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Using CO_2 for Demand-Controlled Ventilation

from the editor…
A popular dictionary defines "ventilation" as the admission of "fresh air … to replace stale or noxious air." In the context of a building, this means introducing outdoor air and circulating it throughout the building to dilute contaminants and odors. Not surprisingly, proper ventilation (in conjunction with proper exhaust) is critical to creating a comfortable indoor environment.

The amount of air needed for "proper" ventilation largely depends on the population of the building. In most commercial applications, the number of people in the building seldom equals the design occupancy. As a result, at least some spaces in the building are overventilated … and that means higher-than-necessary energy costs.

Strategies that control ventilation based on actual occupancy attempt to reduce operating costs by optimizing the rate of outdoor air intake to something less than maximum capacity. This EN discusses the design issues of measuring carbon dioxide for demand-controlled ventilation, with particular attention to ASHRAE Standard 62 as the definitive U.S. reference for ventilation-system design.

Demand-controlled ventilation (DCV) describes a control strategy that responds to the actual "demand" (need) for ventilation by regulating the rate at which the HVAC system brings outdoor air into the building. There are several ways to assess ventilation demand:

- **Occupancy sensors**, which detect the presence or number of people in each monitored space
- **Occupancy schedules**, which allow a building automation system to predict the current population based on the time of day
- **Carbon dioxide (CO_2) sensors**, which monitor the concentration of CO_2 that the occupants continuously produce

Regardless of which method is used, DCV strategies vary the outdoor air intake in response to the current population and to account for natural ventilation (infiltration or open windows, for example). The practice of using carbon dioxide concentrations as an indicator of population or ventilation rate is often called **CO_2-based, demand-controlled ventilation**.

Carbon Dioxide and Indoor Air Quality

Although the 2001 edition of ANSI/ASHRAE Standard 62, *Ventilation for Acceptable Indoor Air Quality,* does not specifically discuss carbon dioxide as a means for demand-based ventilation control, it *does* make the following comment:

> … Comfort (odor) criteria with respect to human bioeffluents are likely to be satisfied if the ventilation results in indoor CO_2 concentrations less than 700 ppm above the outdoor air concentration. [from Section 6.1.3]

Unlike other sections of the standard, this statement is neither a requirement nor a suggestion; it merely *observes*

Which is it: a *difference* of 700 ppm or a *maximum* of 1,000 ppm?

"Comfort (odor) criteria are likely to be satisfied if the ventilation rate is set so that 1,000 ppm of CO_2 is not exceeded." [ASHRAE Standard 62–1989, Section 6.1.3]

The absolute 1,000 ppm value specified in the 1989 edition of Standard 62 was often interpreted as the *ceiling* CO_2 concentration for acceptable indoor air quality. However, that value was based on a specific ventilation rate (15 cfm/person), activity level (1.2 MET), and outdoor CO_2 concentration (300 ppm).

To clarify the meaning of this phrase, Addendum 62f was approved and published in the 1999 edition of the standard. The revised wording of Section 6.1.3 specifically frames the 700 ppm difference between indoor and outdoor CO_2 concentrations as an acceptable level of human bioeffluents. ■

that occupants are unlikely to notice people-related odors if the concentration of CO_2 indoors does not exceed the concentration outdoors by more than 700 ppm.

Assumptions can be misleading. The 700 ppm differential in Standard 62 was derived from *specific values* for ventilation rate and occupant activity; these values are neither appropriate nor accurate for all space types. Here's why …

Carbon dioxide is a byproduct of respiration. The rate at which we produce it varies with diet and health, as well as with the duration and intensity of physical activity. The more exertion an activity entails, as measured in *metabolic equivalent task* (MET) units, the more carbon dioxide we produce; see Figure 1.

Appendix C of Standard 62 provides a steady-state mass balance equation to predict the difference between indoor and outdoor concentrations of carbon dioxide, given constant rates of ventilation and CO_2 generation (occupant activity):

$$C_s - C_o = N / V_o$$

where,

C_s = CO_2 concentration in the space, ppm
C_o = CO_2 concentration in the outdoor air, ppm
N = CO_2 generation rate, cfm/person
V_o = outdoor airflow rate, cfm/person

Note: Unless combustion fumes are present, the outdoor CO_2 concentration in most locations seldom varies more than 100 ppm from the nominal value.[1]

If the rate of CO_2 generation is 0.0105 cfm (0.3 L/min) per person and the ventilation rate is 15 cfm per person, the resulting difference at steady state is 700 ppm:

$$C_s - C_o = 0.0105 / 15 = 0.0007$$

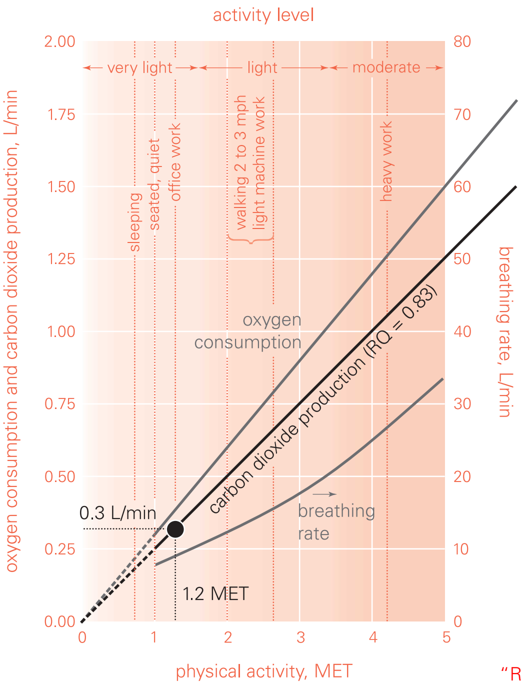
(or 700 ppm)

Based on Section 6.1.3, if the steady-state CO_2 concentration indoors does not exceed the concentration outdoors by more than 700 ppm, we can expect that people-related odors will be unnoticeable to about 80 percent of the occupants (assuming that the space is characterized by a 1.2 MET activity level and a ventilation requirement of 15 cfm per person).

Activity levels of occupants in some spaces are higher than 1.2 MET, just as certain types of spaces require more ventilation airflow than 15 cfm/person to maintain acceptable indoor air quality. For example, Standard 62 currently requires a ventilation rate of 20 cfm/person for an office space. Using the mass balance equation and assuming an activity level of 1.2 MET at steady-state conditions, we can anticipate that the level of CO_2 indoors will exceed the level outdoors by only 525 ppm (0.0105 / 20 = 0.000525). However, if the *actual* indoor CO_2 concentration is 700 ppm higher, the space will be underventilated.

This example illustrates what can happen if you fail to account for the assumptions underlying the 700 ppm value in your ventilation-system designs.

Figure 1. Rates of CO_2 generation for various activities



Based on ANSI/ASHRAE Standard 62–2001, Figure C-2

"RQ = 0.83" represents the volumetric ratio (respiratory quotient) of carbon dioxide production to oxygen consumption for a normal dietary mix of fat, carbohydrate, and protein.

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[1] M. Schell, S. Turner, and R.O. Shim, "Application of CO_2-based demand-controlled ventilation using ASHRAE Standard 62: Optimizing energy use and ventilation," *ASHRAE Transactions,* 1998.

It is also important to recognize that the indoor concentration of CO_2 has limited value as a sign of indoor air quality. Although it provides a good indication of bioeffluents—we produce them at about the same rate as carbon dioxide—the level of CO_2 indoors does *not* reflect the concentrations of other contaminants, such as volatile organic compounds (VOCs) generated by furnishings and cleaning supplies, nor fumes that enter the building through the outdoor-air intake.

A clarification of purpose. The committee who maintains Standard 62 issued official interpretations to more clearly state their intention for the 700 ppm value:[2]

> The reference to 700 ppm CO_2 in Section 6.1.3 is only a point of information. This is not a requirement of ASHRAE 62–2001. Since it is not a requirement it is neither a ceiling value nor a time-weighted average value. Rather, it can be considered an indicator that the outdoor air ventilation may not meet the minimum requirements of the standard. [Interpretation IC 62-2001-05]
>
> The CO_2 level of 700 ppm above outdoors is a guideline based on the perception of human bioeffluents, not a ceiling value for air quality. [Interpretation IC 62-2001-06]

In other words, carbon dioxide does not offer reliable evidence of indoor air quality. But it *can* indicate the correct ratio of human-generated contaminants in the space versus the quantity of ventilation air delivered per person.

By assuming the CO_2 generation rate of the occupants, N, we can establish the indoor–outdoor difference in CO_2 concentrations for a given ventilation rate, V_o. Armed with this information, we can bring less outdoor air into the building during periods of reduced occupancy and still provide the ventilation rate (cfm/person) required by Table 2 of the standard.

Design challenge. Use of the mass balance equation assumes steady-state conditions within the space as well as within the HVAC system—that is, a constant rate of CO_2 generation in the space and the delivery of a constant rate of ventilation airflow to the space.

Is carbon dioxide a contaminant?

The Occupational Safety and Health Administration (OSHA) and the American Conference of Governmental Industrial Hygienists (ACGIH) each established the following concentrations as acceptable limits for carbon dioxide:

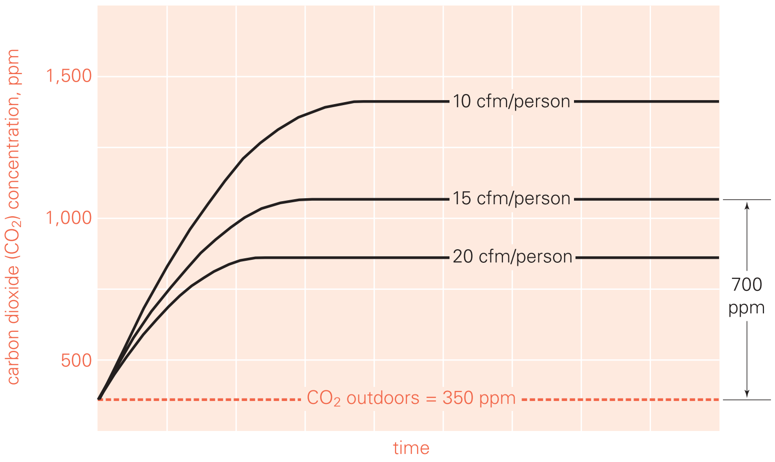
Threshold Limit Value (TLV)[a]	Short-Term Exposure Limit[b]
5,000 ppm	30,000 ppm

[a] Time-weighted average over five 8-hour work days per week
[b] Fifteen minutes

Because typical CO_2 concentrations in commercial and institutional buildings range from 400 ppm to 2,000 ppm, experts do not consider it as a harmful indoor contaminant. To avoid confusion, Table 3 in ASHRAE Standard 62–2001 omits carbon dioxide from the list of indoor contaminants. ■

Figure 2 represents the buildup of carbon dioxide, over time and at different ventilation rates, within an office space. Where each curve levels off, the rate of CO_2 generation (occupant activity) in the space balances the rate of CO_2 removal from the space. The amount of time required to reach the steady-state condition depends on the population density, the volume of the space, and the air circulation rate. It can be as short as a few minutes for a densely occupied space with a low ceiling height, or as long as several hours for a space with a high ceiling and few occupants.

Figure 2. Steady-state indoor CO_2 concentrations at various ventilation rates



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[2] For copies of the interpretations for ASHRAE Standard 62, visit the "Standards" section of the ASHRAE Web site at www.ashrae.org.

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Effective Implementation

How can CO_2-based, demand-controlled ventilation be used to comply with ASHRAE Standard 62? In official interpretation IC 62-2001-34[3], Standing Standard Project Committee (SSPC) 62.1 permits the use of CO_2-based, demand-controlled ventilation to reduce the total supply of outdoor air during periods of reduced occupancy, provided that certain system and control provisions are met. A summary of these provisions follows.

Intermittent occupancy. For most space types, the design ventilation rate is calculated by multiplying the maximum occupancy of the space by the ventilation requirement (cfm/person) for that space type, as listed in Table 2 of the standard. The intermittent occupancy provision of Section 6.1.3.4 permits calculation of the design ventilation rate based on the *average* occupancy of the space, rather than the *maximum* occupancy … but only if the duration of maximum occupancy in that space does not exceed three hours.

> If the total outdoor air supply based on the occupied space is reduced during periods of less occupancy by demand control, it is improper to also apply the variable provision of 6.1.3.4. Concentration of occupant generated contaminants would not then be adequately decreased with reduced occupancy to render the space suitable for future occupancy. [Interpretation IC 62-2001-06]

Using the intermittent occupancy provision instead of implementing DCV sometimes simplifies system control and permits smaller HVAC equipment without sacrificing operating costs appreciably. When using DCV, however, do *not* use this provision to lower the maximum occupancy for the sake of reducing the design ventilation rate.

Dilution. Apart from dilution with ventilation air, carbon dioxide must not be removed from the space by methods such as gas-sorption filtration. When CO_2 is used to indicate occupancy, any means of reducing its concentration (other than dilution with outdoor air) will result in an underventilated space.

Unoccupied periods. It is important to consider the potential for contaminant buildup during unoccupied periods. Potential sources of contamination may include off-gassing from building materials and furnishings, from areas with microbial contamination, or from activities performed by maintenance staff.

> When contaminants are generated in the space or the conditioning system independent of occupants or their

Addendum 62n

At the time this newsletter was published, the Standard 62 committee was considering a proposed addendum to change the minimum ventilation rates to include a people-related component (cfm/person) and a building-related component (cfm/ft^2). Adding these two components together would determine the design ventilation requirement for the space.

The current phrasing of Addendum 62n clarifies the non-zero, base ventilation rate that is required to handle non-occupant sources of contamination. It also further complicates the implementation of a CO_2-based DCV strategy, because the required ventilation rate (on a cfm/person basis) varies as the population in the space changes.

Consider this example: The design ventilation rate, V_z, for a 1,400 ft^2 office space that is designed to accommodate seven people is 119 cfm or 17 cfm/person (119 ÷ 7):

$$V_z = \left(\frac{5\ cfm}{person} \times 7\ people\right) + \left(\frac{0.06\ cfm}{ft^2} \times 1{,}400\ ft^2\right)$$
$$= 119\ cfm$$

When only two people are in this office space, however, the actual ventilation requirement is 94 cfm or 47 cfm/person (94 ÷ 2):

$$V_z = \left(\frac{5\ cfm}{person} \times 2\ people\right) + \left(\frac{0.06\ cfm}{ft^2} \times 1{,}400\ ft^2\right)$$
$$= 94\ cfm$$ ■

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[3] IC 62-2001-34 was originally issued in January 1997 as IC 62-1989-27.

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> activities, supply of outdoor air should lead occupancy so that acceptable conditions will exist at the start of occupancy. [Section 6.1.3.4]

To help achieve an acceptable indoor condition before occupancy, the standard defines minimum requirements for ventilation lead-time.

Non-zero base ventilation rate. SSPC 62.1 counsels designers to account for contaminant sources that aren't related to people by providing a non-zero, base ventilation rate during occupied periods.

> … [G]ood practice and the rationale on which the ventilation rates in Table 2 are based indicates the need for a non-zero base ventilation rate to handle non-occupant sources whenever the space is occupied. [Interpretation IC 62-2001-34]

Regrettably, neither this interpretation nor the 2001 standard offers any guidance for determining the base ventilation rate.

Lag time for ventilation. Depending on the application, Standard 62 allows ventilation to lag occupancy, provided that the ventilation system achieves an acceptable indoor condition within the permissible time frame (Figure 3).

> When contaminants are associated only with occupants or their activities, do not present a short-term health hazard, and are dissipated during unoccupied periods to provide air equivalent to acceptable outdoor air, the supply of outdoor air may lag occupancy. [Section 6.1.3.4]
>
> When spaces such as classrooms, auditoriums, or offices are unoccupied for several hours and then occupied, operation of the ventilation system may be delayed to use the capacity of the air in the space to dilute contaminants. This applies to cases where the inside contaminants are associated only with human occupancy and where contaminants are dissipated by natural means during long vacant periods. [Appendix F, ASHRAE Standard 62–2001]

During the nonsteady-state conditions that are typical of real buildings, the concentration of CO_2 within the space lags behind the actual number of occupants (Figure 2, p. 3). At the beginning of occupancy, the steady-state condition does not yet exist in the space, so the *measured* difference between indoor and outdoor CO_2 concentrations would result in an underventilated space. Considerable time can elapse before the space reaches its steady-state condition—if it ever does. (Most spaces *never* reach equilibrium because of changing occupancy and operation of the HVAC system.)

Although the non-zero base ventilation rate can help meet the permissible lag time for ventilation, the sensors and control system also must respond quickly enough to both the CO_2 concentration and its rate of change to take appropriate action within the required lag time.

Multiple-space system. Each occupied space in a multiple-space system typically requires a different percentage of outdoor air in the primary air that it receives from the air handler. Equation 6-1 (the "multiple-spaces" equation in

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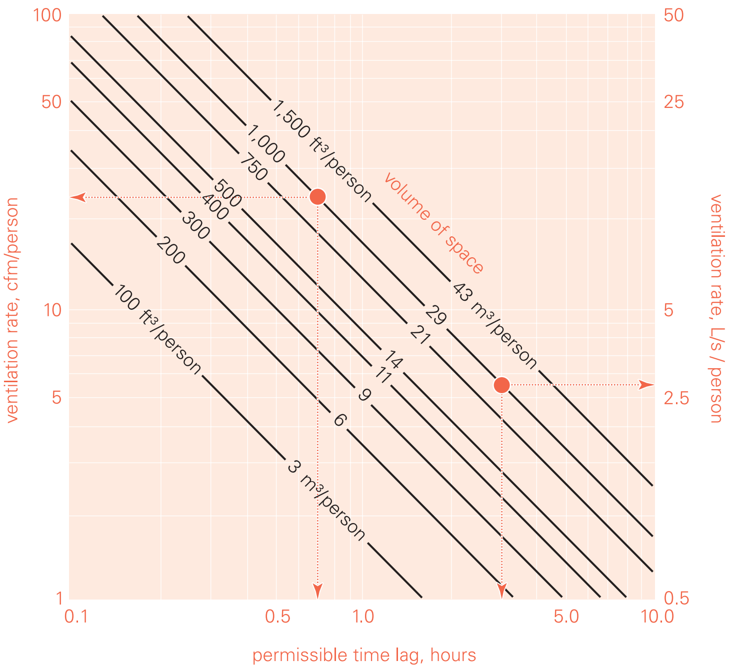
Figure 3. Maximum lag time permissible for ventilation



Based on ANSI/ASHRAE Standard 62–2001, Figure 4

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Section 6.1.3.1) must be used to determine how much outdoor airflow the *system* requires to satisfy the collective ventilation requirement for all spaces. In other words, when using CO_2 as the basis for a demand-controlled ventilation strategy, the CO_2 concentration in the ventilation-critical space must be monitored and maintained to assure that all other noncritical spaces receive sufficient ventilation airflow.

Sensor locations and setpoints must support the ventilation rates listed in Table 2 of the standard. Some designers believe that this provision requires installation of a CO_2 sensor in every space. Obviously, this is true for a *single-zone system*. In applications of this type, install a CO_2 sensor in the space or return-air duct to measure the indoor concentration. Use the difference between the indoor and outdoor concentrations of CO_2 to modulate the position of the outdoor-air damper and thereby provide the proper amount of ventilation.

It can be costly to install a CO_2 sensor in each space of a *multiple-space system,* however, especially for spaces that will always be overventilated regardless of operating conditions. For these applications, consider installing CO_2 sensors only in those spaces, such as conference rooms and reception areas, that experience widely varying patterns of occupancy and are likely to become critically underventilated. Use the sensor in each "critical" space to reset the *system-level* ventilation airflow based on local need.

Because the outdoor concentration of carbon dioxide seldom varies by more than 100 ppm from the nominal value, designers often use the control system to automatically apply a one-time reading or historical value for the outdoor CO_2 concentration in lieu of an outdoor sensor.

Closing Thoughts

Measuring the indoor–outdoor difference in carbon dioxide concentrations makes it possible to reduce the total outdoor airflow during periods of partial occupancy and still meet the requirements of ASHRAE Standard 62.

Demand-controlled ventilation based on carbon dioxide can reduce the cost of operating the HVAC system—especially in applications where contaminant levels result primarily from people and where population varies significantly (in gymnasiums, large meeting rooms, and auditoriums, for example).

Carefully study all of the requirements in IC 62-2001-34 before you adopt a CO_2-based DCV control strategy. ■

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