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# Potential Correction Factors for Interpreting $CO_2$ Measurements in Buildings

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## ABSTRACT

*Carbon dioxide ($CO_2$) is commonly used to estimate outdoor air ventilation rates and assess indoor air quality in buildings. Many practitioners use a single $CO_2$ measurement (or several measurements over a short period) to do this. This practice is based on the steady-state mass balance relationship provided in ASHRAE Standard 62-1989 (Appendix D) in which a $CO_2$ value of 1,000 ppm would correspond to 15 cfm (7 L/s) of outdoor air per person. The assumptions underlying this result are that occupants continuously exhale $CO_2$ at 0.01 cfm (0.30 L/min), $CO_2$ outdoors is constant at 300 ppm, there is a constant outdoor air ventilation rate, there is a uniform indoor $CO_2$ concentration, and the space under consideration does not mix with other interior spaces at different $CO_2$ concentrations. This procedure may not provide an adequate indicator of indoor air quality and will usually overestimate the true ventilation rate, often by as much 100% to 200%. Major problems occur because (a) measurements probably do not occur at steady state; (2) there are systematic age, sex, and activity differences in $CO_2$ exhalation rates; (3) $CO_2$ levels outdoors are variable; and (4) the ASHRAE level for $CO_2$ of 1,000 ppm is only a partial indicator of indoor air quality. To reduce the potential for overestimation and improve interpretation of a $CO_2$ measurement, guidance that applies correction factors in a 10-step process is proposed for field testing. The correction factors are based on steady-state model calculations and published data. While the guidance does not eliminate sources of error, it is hoped that it provides for more accurate interpretations of $CO_2$ measurements. Field tests of this method have not been performed but must be done to reasonably judge the validity and usefulness of the proposed guidance.*


Disclaimer: The procedure described in this paper is proposed by the author for field validation and does not necessarily represent the position of the EPA.

## INTRODUCTION

Perhaps the most misunderstood aspect of indoor air quality (IAQ) is the role and importance of carbon dioxide. Faced with a potentially confusing array of subject matter relevant to diagnosing indoor air quality complaints in buildings and seeking simple and practical methods, many indoor air quality practitioners are attracted to the idea that a single measurement of $CO_2$ (or several measurements over a short period) can be relied on as a surrogate measure for outdoor air ventilation rates and/or as a general indicator of indoor air quality.

Because occupants are the main source of carbon dioxide ($CO_2$) in buildings, $CO_2$ is highly correlated with human bioeffluent odor, and this correlation forms the basis for ASHRAE's 1,000-ppm guideline. In addition, because of the mass balance relationship between indoor generation rates of a gas and the air change rate in a building, $CO_2$ is also used as a measure of outdoor air ventilation rates. Under limited circumstances, the ASHRAE guideline of 1,000 ppm corresponds to 15 cfm (7 L/s) of outdoor air per occupant. It is common practice, therefore, for practitioners to take spot measurements of $CO_2$ and judge both the adequacy of a building's indoor air quality and the adequacy of its outdoor ventilation rate on the basis of this measurement. In both interpretations, there are significant pitfalls for the diagnostician that can lead to gross errors if not adequately addressed. It appears that where errors do occur, they most often lead to an overestimate of the true outdoor air ventilation rate or a dismissal of indoor air quality problems not closely related to bioeffluent odor. In either case, problems that do exist are either dismissed or undervalued. Because of these problems, practitioners have been advised that $CO_2$ cannot be used in this way except under limited circumstances (Persily 1993).

The sources of error in using spot measurements of $CO_2$ to estimate outdoor air ventilation rates and their potential significance have been addressed by others (ASTM 1996; Levine et al. 1993; Persily 1993). However, it is not clear that explanations

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and warnings about its limitations will curb its use or limit its interpretation. Therefore, this paper poses the possibility that a simple-to-use set of correction factors based on the sources of error may be helpful to IAQ practitioners. When the corrections are applied to measured levels of $CO_2$, the practitioner should be able to estimate outdoor air ventilation rates and assess IAQ with improved accuracy. However, the reader is cautioned that use of these correction factors has not been field tested so it is not known how well they would actually work in real applications.

## RELATIONSHIP BETWEEN $CO_2$ AND OUTDOOR AIR VENTILATION RATES

Given a constant indoor source emission rate, a constant outdoor air concentration, a uniform indoor concentration, and a constant air change rate, the indoor concentration of a contaminant will follow a predictable time path given by the following equation:

$$C(t) - Co = S(1 - e^{-at})/aV \tag{1}$$

where

$C(t)$ = indoor concentration (volumetric proportion) at time $t$,

$Co$ = constant outdoor concentration (volumetric proportion),

$S$ = generation rate of the source (volume per time unit),

$a$ = air change rate (per time unit),

$t$ = time, and

$V$ = volume in the occupied space.

It is assumed that the only source of $CO_2$ in the occupied space is the building occupants and that the outdoor air ventilation rate at night is sufficient to flush out all the $CO_2$ built up during the previous period of occupancy. If these assumptions hold, the indoor concentration of $CO_2$ will equal the outdoor concentration ($CO_2 - Co = 0$) in the early morning up to the time that continuous occupancy begins ($t = 0$). After occupants arrive, they are assumed to represent a constant source of $CO_2$ so that the indoor concentration asymptotically approaches a steady-state condition ($Css$) by the time path defined in Equation 1. The steady-state condition (defined by Equation 1 as $t \rightarrow$ infinity) is given by

$$Css - Co = S/aV. \tag{2}$$

Since the air change rate is equivalent to the outdoor air ventilation rate divided by the volume of the space, Equation 2 becomes

$$Css - Co = S/Q \tag{3}$$

or

$$Css - Co = s/q \tag{4}$$

where $Q$ is the outdoor air ventilation rate (volume per time unit) and where $s$ and $q$ are the per person equivalents of $S$ and $Q$. This is the equation given in Appendix D of ASHRAE Standard 62-1989 (ASHRAE 1989).

Equation 4 is a convenient version of the steady-state model since ASHRAE Standard 62-1989 specifies outdoor air ventilation rates ($q$) on a "per person" basis. Provided that all the assumptions are reasonably met, this equation can be used as the basis for estimating the per person outdoor air ventilation rate in a building as defined by that standard. However, while all of the assumptions are almost never met in the real world, there is the potential to reduce (but not eliminate) some of the sources of error based on available information about $CO_2$ emission rates and mass balance relationships.

## INTERPRETING SPOT MEASUREMENTS OF $CO_2$

### Measured Values of $CO_2$ Relative to Its Steady-State Value

Appendix D of ASHRAE Standard 62-1989 estimates that the activity level associated with general office work is 1.2 met. At that activity level, the per person $CO_2$ generation rate is assumed to be 0.01 cfm (0.30 L/s). ASHRAE also assumes that the outdoor $CO_2$ level is constant at a volumetric proportion of 0.03% (300 ppm). Inserting these values into Equation 2, the relationship between the steady-state indoor concentration ($Css$) and the outdoor air ventilation rate ($q$) is given in Table 1.

**TABLE 1**
**Outdoor Air Ventilation Rates Associated with Steady-State Values of $CO_2$**

| Steady-State $CO_2$ (PPM) | Outdoor Air Ventilation (CFM/Occ) | Outdoor Air Ventilation (L/s)/occ |
|---|---|---|
| 5000 | 2 | 1 |
| 2500 | 5 | 2 |
| 2000 | 6 | 3 |
| 1500 | 9 | 4 |
| 1000 | 15 | 7 |
| 900 | 18 | 8 |
| 800 | 21 | 10 |

Accordingly, the guideline value of 1,000 ppm for $CO_2$, which is specified in the Indoor Air Quality Procedure of ASHRAE Standard 62-1989, corresponds to an outdoor air ventilation rate of approximately 15 cfm (7 L/s) per person, while 800 ppm corresponds to approximately 20 cfm (9 L/s) per person.

Perhaps the most misunderstood aspect of this model is that it applies only to the $CO_2$ concentration at or close to its steady-state value. *If $CO_2$ is measured prior to the time that steady state is substantively achieved, outdoor air ventilation rates will be overestimated.*

As described in Equation 1, steady state is approached asymptotically in a well-defined pattern under the assumptions

## TABLE 2
## Percent of Steady State Achieved at Specific Times

| at = | Percent Steady State | Hours Required at Alternative ACH | | | | |
|---|---|---|---|---|---|---|
| | | ACH=0.25 | ACH=0.5 | ACH=.75 | ACH=1.0 | ACH=2.0 |
| 1 | 63.21% | 4.00 | 2.00 | 1.33 | 1.00 | 0.50 |
| 2 | 86.47% | 8.00 | 4.00 | 2.67 | 2.00 | 1.00 |
| 3 | 95.02% | 12.00 | 6.00 | 4.00 | 3.00 | 1.50 |
| 4 | 98.17% | 16.00 | 8.00 | 5.33 | 4.00 | 2.00 |
| 5 | 99.33% | 20.00 | 10.00 | 6.67 | 5.00 | 2.50 |

of the model (constant source, constant outdoor concentration, constant air change rate, and uniform indoor concentration). With each time constant (the time it takes for *at* to equal 1, 2, 3, etc.) the indoor concentration ($C(t)$) will move from its current position toward its steady-state condition by a proportion equal to ($[1 - 1/e]$ or 63.2%) of the remaining distance to the steady-state level. Thus, after one time constant, the $CO_2$ level achieves 63.2% of its steady-state level. After two time constants, $C(t)$ achieves 87%, etc. The pattern of movement toward steady state with each time constant is given in Table 2.

As a practical matter, assuming that one would want to measure $CO_2$ when it has reached at least 95% of its steady-state value, using measurements of $CO_2$ to assess the outdoor air ventilation rate as in Table 1 would be unreliable unless the building has had stable occupancy for a length of time equal to at least three time constants. At 1 ACH, 95% of steady state is achieved in three hours. At 0.50 ACH, it would take 6 hours to achieve 95% of steady state, and at 0.25 ACH, it would take 12 hours.

It is commonly recommended that $CO_2$ measurements be taken at their peak value when $CO_2$ is closest to its steady-state value. But there is no guarantee that the peak value is close enough to steady state for estimation purposes. Figure 1 shows the time path for $CO_2$ in a typical office building.[1] $CO_2$ begins to rise as occupants enter in the morning and peaks in the late morning before occupants leave for lunch, peaking again in the late afternoon just before they begin to go home. Under some common occupancy patterns, there is scarcely a three-hour time frame of steady occupancy in which $CO_2$ is rising toward steady state. If this were the case, and the air change rate were less than 1 ACH, the $CO_2$ measurement would likely underestimate *Css* and overestimate ventilation rates even if measurements were taken at or close to peak. The extent to which measurements are taken at subpeak levels serves only to magnify this problem.

1. The timing of measurements designed to represent peak values should depend on occupancy schedules.

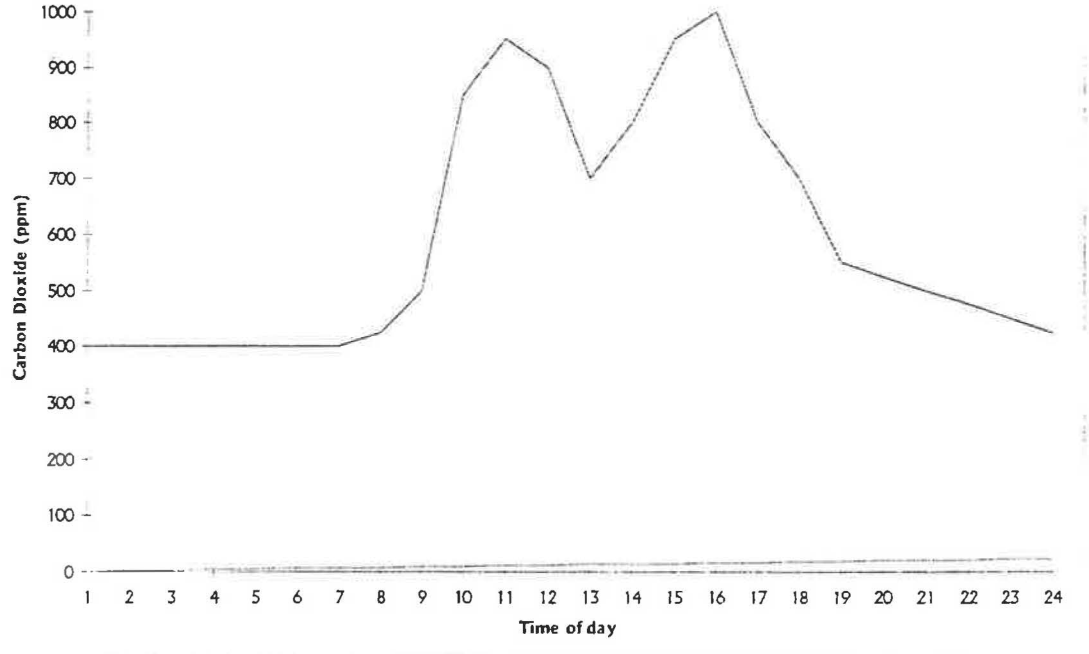


*Figure 1 Carbon dioxide in a typical office building.*

## Adjusting Measured Values for the Time of Measurement

Under the assumptions of the model, the time path to steady state—and therefore the potential error due to premature measurement—depends solely on the air change rate. If the practitioner knew in advance the air change rate, he or she could adjust the measurement for an error factor. But the air change rate is in part what is being determined, so this poses a dilemma. To solve this problem, we calculate air change rates based on the time of measurement and occupant density.

Equation 1 can be rewritten as

$$\{C(t) - Co\}V/(sN) = (1 - e^{-at})/a \tag{5}$$

where

$N$ = number of occupants.

All the variables on the left side of Equation 5 can be measured or determined by the practitioner. Once the left-side value is known and the value of $t$ (length of time since continuous occupancy that the measurement was taken) is specified, the air change can be determined by iterative trial and error. To save the practitioner the trouble of doing this, solutions for various combinations of $a$ and $t$ under the assumptions of the model are provided in Table 3.[2]

For example, suppose that $CO_2$ outside is measured at 350 ppm ($350 \times 10^{-6}$) and is relatively constant, and an inside measurement of 850 ppm ($800 \times 10^{-6}$) was taken at $t$ = two hours. Ordinarily, a reading of 850 ppm would imply that this space is receiving approximately 20 cfm (9 L/s) of outdoor air per person (from Table 1). However, suppose that we estimate the relevant area to be a 5,000-ft$^2$ (464.5-m$^2$) space with a ceiling height of 10 feet (3 m), with 35 occupants (7 occupants per 1,000 ft$^2$ [100 m$^2$]). Assuming the ASHRAE $CO_2$ generation rate of 0.01(60) cfh (or 0.30 [60] L/h) is correct, we can calculate the left side of Equation 5 and then determine the air change rate from

2. Alternatively, the practitioner could solve Equation 3 for the air change rate rather than use Table 3.

**TABLE 3**
**Calculating Air Exchange Rate (a) from Measured Data**
**$\{C(t) - Co\}(V)/(s \times N) = (1/a)(1-e^{-at})$**

| | Time (t) in Hours | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ACH (a) | 0.3 | 0.5 | 0.8 | 1 | 1.3 | 1.5 | 1.8 | 2 | 2.3 | 2.5 | 2.8 | 3 | 3.3 | 3.5 | 3.8 | 4 |
| 0.1 | 0.25 | 0.49 | 0.72 | 0.95 | 1.18 | 1.39 | 1.61 | 1.81 | 2.01 | 2.21 | 2.40 | 2.59 | 2.77 | 2.95 | 3.13 | 3.30 |
| 0.2 | 0.24 | 0.48 | 0.70 | 0.91 | 1.11 | 1.30 | 1.48 | 1.65 | 1.81 | 1.97 | 2.12 | 2.26 | 2.39 | 2.52 | 2.64 | 2.75 |
| 0.3 | 0.24 | 0.46 | 0.67 | 0.86 | 1.04 | 1.21 | 1.36 | 1.50 | 1.64 | 1.76 | 1.87 | 1.98 | 2.08 | 2.17 | 2.25 | 2.33 |
| 0.4 | 0.24 | 0.45 | 0.65 | 0.82 | 0.98 | 1.13 | 1.26 | 1.38 | 1.48 | 1.58 | 1.67 | 1.75 | 1.82 | 1.88 | 1.94 | 2.00 |
| 0.5 | 0.24 | 0.44 | 0.63 | 0.79 | 0.93 | 1.06 | 1.17 | 1.26 | 1.35 | 1.43 | 1.49 | 1.55 | 1.61 | 1.65 | 1.69 | 1.73 |
| 0.6 | 0.23 | 0.43 | 0.60 | 0.75 | 0.88 | 0.99 | 1.08 | 1.16 | 1.23 | 1.29 | 1.35 | 1.39 | 1.43 | 1.46 | 1.49 | 1.52 |
| 0.7 | 0.23 | 0.42 | 0.58 | 0.72 | 0.83 | 0.93 | 1.01 | 1.08 | 1.13 | 1.18 | 1.22 | 1.25 | 1.28 | 1.31 | 1.33 | 1.34 |
| 0.8 | 0.23 | 0.41 | 0.56 | 0.69 | 0.79 | 0.87 | 0.94 | 1.00 | 1.04 | 1.08 | 1.11 | 1.14 | 1.16 | 1.17 | 1.19 | 1.20 |
| 0.9 | 0.22 | 0.40 | 0.55 | 0.66 | 0.75 | 0.82 | 0.88 | 0.93 | 0.96 | 0.99 | 1.02 | 1.04 | 1.05 | 1.06 | 1.07 | 1.08 |
| 1 | 0.22 | 0.39 | 0.53 | 0.63 | 0.71 | 0.78 | 0.83 | 0.86 | 0.89 | 0.92 | 0.94 | 0.95 | 0.96 | 0.97 | 0.98 | 0.98 |
| 1.2 | 0.22 | 0.38 | 0.49 | 0.58 | 0.65 | 0.70 | 0.73 | 0.76 | 0.78 | 0.79 | 0.80 | 0.81 | 0.82 | 0.82 | 0.82 | 0.83 |
| 1.4 | 0.21 | 0.36 | 0.46 | 0.54 | 0.59 | 0.63 | 0.65 | 0.67 | 0.68 | 0.69 | 0.70 | 0.70 | 0.71 | 0.71 | 0.71 | 0.71 |
| 1.6 | 0.21 | 0.34 | 0.44 | 0.50 | 0.54 | 0.57 | 0.59 | 0.60 | 0.61 | 0.61 | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 |
| 1.8 | 0.20 | 0.33 | 0.41 | 0.46 | 0.50 | 0.52 | 0.53 | 0.54 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.56 |
| 2 | 0.20 | 0.32 | 0.39 | 0.43 | 0.46 | 0.48 | 0.48 | 0.49 | 0.49 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| 2.5 | 0.19 | 0.29 | 0.34 | 0.37 | 0.38 | 0.39 | 0.39 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| 3 | 0.18 | 0.26 | 0.30 | 0.32 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 |
| 4 | 0.16 | 0.22 | 0.24 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 5 | 0.14 | 0.18 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |

To use this table, calculate the left side of the equation from collected data. Look for this value in the column corresponding to the time from steady occupancy at which indoor carbon dioxide was measured. The left-hand column is the calculated air exchange rate for the building.

Table 3. The value of the left side of Equation 5, which we call omega ($\Omega$), would be

$$\Omega = \{C(t) - Co\} V/(sN)$$

$$= (500)(10^{-6})(5)(10^{4})/(10595)(10^{-6})(60)(35) = 1.19.$$

To determine the air change rate of this building, enter Table 3 at the column corresponding to $t = 2$ hours seeking the values bounding 1.19. The air change rate at the left-hand column is approximately 0.5-0.6.

The equivalent outdoor air ventilation rate per person (in cfm or L/s) can be calculated from

$$q = aV/(Nx60). \quad (6)$$

In this example, the per person outdoor air ventilation rate, adjusted for the time of measurement, is between 12 and 14 cfm per occupant (which is less than the original, unadjusted estimate of 20 cfm per occupant).

### Significance of Time Factor Corrections

To more fully examine the nature of potential errors due to the time of measurement, numerous calculations were made representing indoor $CO_2$ measurements made at $t = 2.0, 2.5, 3.0$, and 3.5 hours (Tables 4a, 4b, 4c, and 4d) for buildings with occupant densities of 3, 5, 7, and 10 occupants per 1,000 ft$^2$ (92.9 m$^2$). Each column in these tables corresponds to measured values of indoor minus outdoor $CO_2$ (ppm). Just below the measured value is the uncorrected per person outdoor air ventilation rate (cfm per person) indicated by the $CO_2$ measurement if it were made under conditions that are assumed by ASHRAE. The body of the table then provides the steady-state value, the air change rate, and the corrected outdoor air ventilation rate for each of the identified occupant densities. The difference between the uncorrected and corrected values is due solely to the fact that measurements were taken prior to steady-state conditions.

Using the example above where $CO_2$ was measured at 350 ppm outside with 850 ppm inside at $t = 2.0$ hours and an occupant density of 7 occupants/1,000 ft$^2$ (92.9 m$^2$), follow the column in Table 4a corresponding to 500 (850-350) ppm. The uncorrected ventilation rate is 21 cfm per occupant. However, under steady-state conditions, $C(t) - Co$ would be 996 ppm, corresponding to an air change rate of 0.6 and a ventilation rate of 15 cfm per occupant.

Several important practical implications are revealed when examining these tables.

1. *For any given measured value of $C(t) - Co$, the potential for underestimation increases as occupant density falls.* Lowering the source strength ($S$) must be accompanied by a lowering of the air change rate ($a$) in order to maintain the same measured value ($C(t) - Co$)). Thus, in the example above, if the building had 5 occupants per 1,000 ft$^2$ (92.9 m$^2$), the corrected ventilation rate would be approximately 8 rather than 15 cfm per occupant, implying a much greater overestimation of the uncorrected value of 20 cfm per occupant. However, if the building had 10 occupants per 1,000 ft$^2$ (92.9 m$^2$), the corrected ventilation rate would be about the same as the uncorrected value.
2. *At low occupant densities, a building may never violate the 1,000-ppm guideline, even at extremely low per-person outdoor ventilation rates.* Measurements taken in buildings with occupant densities below 5 occupants per 1,000 ft$^2$ (92.9 m$^2$) are not likely to show values of ($C(t) - Co$) above 700 ppm, even when taken at their peak. This is because to achieve this value, assuming peak is at $t = 3.0$ hours, would necessitate air change rates below 0.2 (see Table 4c). In fact, buildings with only three occupants per 1,000 ft$^2$ (92.9 m$^2$) could not achieve levels that high in three hours, even with a zero air change rate. Subpeak measurements at $t$ = two hours would make it impossible to achieve measured values of ($C(t) - Co$) as high as 700 ppm, even at five occupants per 1,000 ft$^2$ (92.9 m$^2$).

   If measured values as high as $C(t) - Co = 700$ ppm or more are encountered in buildings with five or fewer occupants per 1,000 ft$^2$ (92.9 m$^2$), it suggests the possibility that the building has a serious ventilation problem or that the measurements are inaccurate. In either case, the information is valuable.
3. *It is wise to estimate the air change rate in buildings with low occupant densities even when the corrected outdoor air ventilation rate equals or exceeds 15 cfm (7 L/s) per person.* This is because buildings with low occupant densities may satisfy the 15 cfm (7 L/s) per occupant criterion but still have unacceptably low air change rates. The ASHRAE criterion of 15 cfm (7 L/s) of outdoor air per occupant is based on the ventilation needed to control body odor. But while a low air change rate may be sufficient to control body odor (and perhaps other contaminants associated with the number of occupants) it may not be sufficient to control other contaminants. A practitioner might wisely question whether a building with less than 0.5 ACH has sufficient outdoor air ventilation even though it maintains at least 15 cfm (7 L/s) of outdoor air per occupant because of low occupant density.[3]

In general, relying on spot measurements of $CO_2$ to estimate ventilation rates in buildings has a built-in bias that tends to overestimate ventilation rates. The potential to overestimate ventilation rates is greatest at low air change rates—precisely the conditions that cause indoor air quality problems. In addition, if practitioners are not careful to measure peak values, but for convenience or through ignorance measure subpeak levels, the potential to overestimate can be substantially increased. This problem suggests that adjustment factors based on mass balance principles and other measured parameters would assist practitioners in more accurately interpreting $CO_2$ values.

3. For example, the prescriptive method in the proposed ASHRAE Standard 62-1989R would require approximately 0.5 air changes per hour to remove building-related contaminants.

## TABLE 4a

## Interpreting $CO_2$ Values Corrected for Time to Steady State

**t = 2.0 hours**

| | Carbon Dioxide Values (after 2.0 hours) in Parts Per Million (PPM) | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Occupants per 1000 ft²** | **C(t) - Co (ppm)** | **1900** | **1700** | **1500** | **1400** | **1300** | **1200** | **1100** | **1000** | **900** | **800** | **700** | **600** | **500** | **400** | **200** | **100** |
| | **Uncorr. q (cfm/occ)** | **5.53** | **6.18** | **7.00** | **7.50** | **8.08** | **8.75** | **9.55** | **10.50** | **11.67** | **13.13** | **15.00** | **17.50** | **21.00** | **26.25** | **52.50** | **105.00** |
| | ***Uncorr. q ((L/s)/occ)*** | ***2.52*** | ***2.82*** | ***3.20*** | ***3.42*** | ***3.69*** | ***4.00*** | ***4.36*** | ***4.79*** | ***5.33*** | ***5.99*** | ***6.85*** | ***7.99*** | ***9.59*** | ***11.99*** | ***23.97*** | ***47.95*** |
| | Corrected Values | | | | | | | | | | | | | | | | |
| 3 | Steady State (ppm) | | | | | | | | | | | | | | | 1085 | 562 |
| | ACH | | | | | | | | | | | | | | | 0.24 | 0.72 |
| | q (cfm/occ) | | | | | | | | | | | | | | | 13.38 | 40.11 |
| | *q ((L/s)/occ)* | | | | | | | | | | | | | | | *6.11* | *18.32* |
| 5 | Steady State (ppm) | | | | | | | | | | | | | 1608 | 937 | 665 | 511 |
| | ACH | | | | | | | | | | | | | 0.24 | 0.49 | 0.86 | 1.50 |
| | q (cfm/occ) | | | | | | | | | | | | | 8.03 | 16.49 | 28.77 | 49.86 |
| | *q ((L/s)/occ)* | | | | | | | | | | | | | 3.66 | 7.53 | 13.14 | 22.77 |
| 7 | Steady State (ppm) | | | | | | | | | | 4745 | 2132 | 1366 | 996 | 774 | 620 | 503 |
| | ACH | | | | | | | | | | 0.10 | 0.24 | 0.41 | 0.63 | 0.93 | 1.38 | 2.18 |
| | q (cfm/occ) | | | | | | | | | | 2.36 | 5.73 | 9.85 | 15.09 | 22.17 | 32.77 | 51.82 |
| | *q ((L/s)/occ)* | | | | | | | | | | *1.08* | *2.62* | *4.50* | *6.89* | *10.13* | *14.96* | *23.66* |
| 10 | Steady State (ppm) | | | | | | 13107 | 4832 | 2917 | 2061 | 1573 | 1256 | 1030 | 859 | 721 | 605 | 500 |
| | ACH | | | | | | 0.05 | 0.14 | 0.24 | 0.36 | 0.49 | 0.66 | 0.86 | 1.13 | 1.50 | 2.07 | 3.14 |
| | q (cfm/occ) | | | | | | 0.82 | 2.32 | 4.01 | 5.96 | 8.25 | 10.99 | 14.39 | 18.80 | 24.93 | 34.44 | 52.40 |
| | *q ((L/s)/occ)* | | | | | | *0.37* | *1.06* | *1.83* | *2.72* | *3.76* | *5.02* | *6.57* | *8.58* | *11.38* | *15.73* | *23.93* |

## TABLE 4b

## Interpreting $CO_2$ Values Corrected for Time to Steady State

**t = 2.5 hours**

| | Carbon Dioxide Values (after 2.5 hours) in Parts Per Million (PPM) | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Occupants per 1000 ft²** | **C(t) - Co (ppm)** | **1900** | **1700** | **1500** | **1400** | **1300** | **1200** | **1100** | **1000** | **900** | **800** | **700** | **600** | **500** | **400** | **200** | **100** |
| | **Uncorr. q (cfm/occ)** | **5.53** | **6.18** | **7.00** | **7.50** | **8.08** | **8.75** | **9.55** | **10.50** | **11.67** | **13.13** | **15.00** | **17.50** | **21.00** | **26.25** | **52.50** | **105.00** |
| | ***Uncorr. q ((L/s)/occ)*** | ***2.52*** | ***2.82*** | ***3.20*** | ***3.42*** | ***3.69*** | ***4.00*** | ***4.36*** | ***4.79*** | ***5.33*** | ***5.99*** | ***6.85*** | ***7.99*** | ***9.59*** | ***11.99*** | ***23.97*** | ***47.95*** |
| | Corrected Values | | | | | | | | | | | | | | | | |
| 3 | Steady State (ppm) | | | | | | | | | | | | | | 1678 | 778 | 529 |
| | ACH | | | | | | | | | | | | | | 0.14 | 0.40 | 0.82 |
| | q (cfm/occ) | | | | | | | | | | | | | | 7.62 | 21.99 | 45.82 |
| | *q ((L/s)/occ)* | | | | | | | | | | | | | | *3.48* | *10.04* | *20.92* |
| 5 | Steady State (ppm) | | | | | | | | | | | 3576 | 1679 | 1096 | 808 | 631 | 504 |
| | ACH | | | | | | | | | | | 0.10 | 0.23 | 0.40 | 0.62 | 0.95 | 1.54 |
| | q (cfm/occ) | | | | | | | | | | | 3.21 | 7.61 | 13.19 | 20.69 | 31.77 | 51.39 |
| | *q ((L/s)/occ)* | | | | | | | | | | | *1.46* | *3.48* | *6.02* | *9.45* | *14.51* | *23.46* |

## TABLE 4b (Continued)
## Interpreting $CO_2$ Values Corrected for Time to Steady State

**t = 2.5 hours**

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | Steady State (ppm) | | | | | | | 243029 | 5856 | 2921 | 1922 | 1414 | 1104 | 892 | 734 | 609 | 501 |
| | ACH | | | | | | | 0.00 | 0.08 | 0.17 | 0.27 | 0.40 | 0.55 | 0.75 | 1.02 | 1.43 | 2.20 |
| | q (cfm/occ) | | | | | | | 0.04 | 1.89 | 4.01 | 6.47 | 9.42 | 13.06 | 17.74 | 24.18 | 34.02 | 52.28 |
| | *q ((L/s)/occ)* | | | | | | | *0.02* | *0.86* | *1.83* | *2.96* | *4.30* | *5.96* | *8.10* | *11.04* | *15.53* | *23.87* |
| 10 | Steady State (ppm) | | | 16308 | 6852 | 4268 | 2354 | 1892 | 1563 | 1315 | 1120 | 961 | 826 | 709 | 602 | 500 | 400 |
| | ACH | | | 0.04 | 0.10 | 0.16 | 0.31 | 0.40 | 0.50 | 0.62 | 0.77 | 0.95 | 1.20 | 1.54 | 2.09 | 3.15 | 6.30 |
| | q (cfm/occ) | | | 0.66 | 1.60 | 2.65 | 5.11 | 6.60 | 8.31 | 10.34 | 12.80 | 15.88 | 19.95 | 25.69 | 34.81 | 52.48 | 105.00 |
| | *q ((L/s)/occ)* | | | *0.30* | *0.73* | *1.21* | *2.33* | *3.01* | *3.80* | *4.72* | *5.85* | *7.25* | *9.11* | *11.73* | *15.90* | *23.96* | *47.95* |

## TABLE 4c
## Interpreting $CO_2$ Values Corrected for Time to Steady State

**t = 3.0 hours**

| Carbon Dioxide Values (after 3.0 hours) in Parts Per Million (PPM) | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Occupants per 1000 ft²** | **C(t) - Co (ppm)** | **1900** | **1700** | **1500** | **1400** | **1300** | **1200** | **1100** | **1000** | **900** | **800** | **700** | **600** | **500** | **400** | **200** | **100** |
| | **Uncorr. q (cfm/occ)** | **5.53** | **6.18** | **7.00** | **7.50** | **8.08** | **8.75** | **9.55** | **10.50** | **11.67** | **13.13** | **15.00** | **17.50** | **21.00** | **26.25** | **52.50** | **105.00** |
| | ***Uncorr. q ((L/s)/occ)*** | ***2.52*** | ***2.82*** | ***3.20*** | ***3.42*** | ***3.69*** | ***4.00*** | ***4.36*** | ***4.79*** | ***5.33*** | ***5.99*** | ***6.85*** | ***7.99*** | ***9.59*** | ***11.99*** | ***23.97*** | ***47.95*** |
| Corrected Values | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| 3 | Steady State (ppm) | | | | | | | | | | | | | 2506 | 1062 | 693 | 516 |
| | ACH | | | | | | | | | | | | | 0.09 | 0.25 | 0.48 | 0.88 |
| | q (cfm/occ) | | | | | | | | | | | | | 4.76 | 13.77 | 26.74 | 48.72 |
| | *q ((L/s)/occ)* | | | | | | | | | | | | | *2.17* | *6.29* | *12.21* | *22.25* |
| 5 | Steady State (ppm) | | | | | | | | | 9905 | 3056 | 1792 | 1255 | 954 | 758 | 616 | 502 |
| | ACH | | | | | | | | | 0.03 | 0.11 | 0.21 | 0.33 | 0.48 | 0.69 | 1.00 | 1.56 |
| | q (cfm/occ) | | | | | | | | | 1.09 | 3.81 | 7.04 | 10.99 | 16.04 | 22.91 | 33.24 | 52.01 |
| | *q ((L/s)/occ)* | | | | | | | | | *0.50* | *1.74* | *3.21* | *5.02* | *7.33* | *10.46* | *15.18* | *23.75* |
| 7 | Steady State (ppm) | | | | | 37908 | 6967 | 3770 | 2548 | 1899 | 1495 | 1216 | 1010 | 849 | 718 | 604 | 500 |
| | ACH | | | | | 0.01 | 0.07 | 0.13 | 0.20 | 0.28 | 0.37 | 0.48 | 0.62 | 0.80 | 1.06 | 1.45 | 2.20 |
| | q (cfm/occ) | | | | | 0.28 | 1.57 | 3.03 | 4.67 | 6.57 | 8.79 | 11.46 | 14.78 | 19.11 | 25.15 | 34.55 | 52.43 |
| | *q ((L/s)/occ)* | | | | | *0.13* | *0.72* | *1.38* | *2.13* | *3.00* | *4.01* | *5.23* | *6.75* | *8.73* | *11.48* | *15.78* | *23.94* |
| 10 | Steady State (ppm) | | 9059 | 4225 | 3283 | 2657 | 2210 | 1873 | 1609 | 1395 | 1217 | 1065 | 932 | 813 | 704 | 601 | 500 |
| | ACH | | 0.07 | 0.16 | 0.21 | 0.27 | 0.33 | 0.40 | 0.48 | 0.58 | 0.69 | 0.82 | 1.00 | 1.23 | 1.56 | 2.10 | 3.15 |
| | q (cfm/occ) | | 1.20 | 2.68 | 3.52 | 4.45 | 5.50 | 6.67 | 8.02 | 9.59 | 11.46 | 13.73 | 16.62 | 20.47 | 26.01 | 34.93 | 52.50 |
| | *q ((L/s)/occ)* | | *0.55* | *1.22* | *1.61* | *2.03* | *2.51* | *3.05* | *3.66* | *4.38* | *5.23* | *6.27* | *7.59* | *9.35* | *11.88* | *15.95* | *23.97* |

## Measuring $CO_2$ Outdoors

Outdoor values of $CO_2$ can vary widely but are seldom as low as the ASHRAE assumption of 300 ppm. A common observation is that outdoor values are typically 350 ppm, but they often go as high as 500 ppm. Higher outdoor $CO_2$ levels uniformly raise indoor values by an equivalent amount and should be accounted for by the IAQ practitioner. Failure to specifically account for higher outdoor $CO_2$ values will result in the practitioner underestimating true ventilation rates. In general, the error tends to be significant above 15 cfm per person, where misinterpretation is less critical. At lower venti-

**TABLE 4d**

**Interpreting $CO_2$ Values Corrected for Time to Steady State**

t = 3.5 hours

| Occupants per 1000 $ft^2$ | Carbon Dioxide Values (after 3.5 hours) in Parts Per Million (PPM) | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **C(t) - Co (ppm)** | **1900** | **1700** | **1500** | **1400** | **1300** | **1200** | **1100** | **1000** | **900** | **800** | **700** | **600** | **500** | **400** | **200** | **100** |
| | **Uncorr. q (cfm/occ)** | **5.53** | **6.18** | **7.00** | **7.50** | **8.08** | **8.75** | **9.55** | **10.50** | **11.67** | **13.13** | **15.00** | **17.50** | **21.00** | **26.25** | **52.50** | **105.00** |
| | *Uncorr. q ((L/s)/occ)* | *2.52* | *2.82* | *3.20* | *3.42* | *3.69* | *4.00* | *4.36* | *4.79* | *5.33* | *5.99* | *6.85* | *7.99* | *9.59* | *11.99* | *23.97* | *47.95* |
| Corrected Values | | | | | | | | | | | | | | | | | |
| 3 | Steady State (ppm) | | | | | | | | | | | | 3633 | 1424 | 897 | 655 | 509 |
| | ACH | | | | | | | | | | | | 0.06 | 0.17 | 0.32 | 0.53 | 0.91 |
| | q (cfm/occ) | | | | | | | | | | | | 3.15 | 9.34 | 17.58 | 29.57 | 50.29 |
| | *q ((L/s)/occ)* | | | | | | | | | | | | *1.44* | *4.27* | *8.03* | *13.50* | *22.96* |
| 5 | Steady State (ppm) | | | | | | | | 5856 | 2921 | 1922 | 1414 | 1104 | 892 | 734 | 609 | 501 |
| | ACH | | | | | | | | 0.06 | 0.12 | 0.19 | 0.28 | 0.39 | 0.53 | 0.73 | 1.02 | 1.57 |
| | q (cfm/occ) | | | | | | | | 1.89 | 4.01 | 6.47 | 9.42 | 13.06 | 17.74 | 24.18 | 34.02 | 52.28 |
| | *q ((L/s)/occ)* | | | | | | | | *0.86* | *1.83* | *2.96* | *4.30* | *5.96* | *8.10* | *11.04* | *15.53* | *23.87* |
| 7 | Steady State (ppm) | | | 27167 | 8078 | 4663 | 3232 | 2442 | 1940 | 1590 | 1330 | 1129 | 965 | 828 | 709 | 602 | 500 |
| | ACH | | | 0.02 | 0.06 | 0.10 | 0.15 | 0.21 | 0.27 | 0.34 | 0.43 | 0.53 | 0.66 | 0.83 | 1.08 | 1.46 | 2.20 |
| | q (cfm/occ) | | | 0.39 | 1.35 | 2.41 | 3.58 | 4.90 | 6.40 | 8.14 | 10.19 | 12.67 | 15.78 | 19.87 | 25.64 | 34.79 | 52.48 |
| | *q ((L/s)/occ)* | | | *0.18* | *0.62* | *1.10* | *1.64* | *2.24* | *2.92* | *3.72* | *4.65* | *5.79* | *7.21* | *9.07* | *11.71* | *15.89* | *23.96* |
| 10 | Steady State (ppm) | 7517 | 4347 | 2966 | 2529 | 2186 | 1908 | 1678 | 1484 | 1316 | 1169 | 1037 | 917 | 807 | 702 | 600 | 500 |
| | ACH | 0.09 | 0.16 | 0.24 | 0.28 | 0.33 | 0.39 | 0.46 | 0.53 | 0.62 | 0.73 | 0.85 | 1.02 | 1.24 | 1.57 | 2.10 | 3.15 |
| | q (cfm/occ) | 1.45 | 2.59 | 3.94 | 4.71 | 5.57 | 6.53 | 7.62 | 8.87 | 10.34 | 12.09 | 14.25 | 17.01 | 20.73 | 26.14 | 34.98 | 52.50 |
| | *q ((L/s)/occ)* | *0.66* | *1.18* | *1.80* | *2.15* | *2.54* | *2.98* | *3.48* | *4.05* | *4.72* | *5.52* | *6.51* | *7.77* | *9.47* | *11.94* | *15.97* | *23.97* |

lation rates, the higher outdoor air $CO_2$ will partially correct the underestimation that occurs due to the time it takes to reach steady state. The best practice is to measure both indoor and outdoor levels and use the difference in these values to estimate the outdoor air ventilation rate.

## Occupant Gender and Age

Measured values of $C(t) - Co$ will be proportional to the $CO_2$ generation rate. ASHRAE estimates the generation rate to be 0.01 cfm (0.30 L/m) per person for office-type work (1.2 met). This estimate is widely used to represent persons of any age and gender, and it is the basis for the ASHRAE $CO_2$ level. However, the basis for this assumption is not clearly established in the ASHRAE Handbook (1985) or Standard 62 (ASHRAE 1989), so it is worthwhile to examine its applicability and to examine the impact the assumption has on estimates of ventilation using $CO_2$ measurements.

Data from the International Commission on Radiological Protection (ICRP 1975) confirm several parameters used by ASHRAE to obtain the estimated $CO_2$ generation rate. First, ASHRAE assumes that the respiratory quotient (the ratio of $CO_2$ produced to oxygen consumed) is 0.83 for a typical diet. Data from ICRP (1975) confirm this to be true for persons of all ages, both male and female. Second, the data from ICRP demonstrate a consistent ratio of $CO_2$ produced to energy expended for persons of all ages, both male and female.

What remains to investigate, therefore, is whether there are significant differences in energy expended for various activities between males and females and persons of different ages. Since the $CO_2$ generation rate appears to be in constant proportion to energy expenditure (0.16 to 0.17 L/Kcal), differences in energy expenditure associated with gender and age would represent proportional differences in $CO_2$ generation. Third, it appears that the ICRP data support the ASHRAE assumption that 1.2 met would correspond to a $CO_2$ generation rate of approximately 0.01 cfm (0.30 L/m) for adult males. However, it shows important differences for females and other age groups.

Comparisons of energy expenditure (and, hence, $CO_2$ generation rates) by gender and age taken from the ICRP data are provided in Table 5. Females, the young, and the elderly have lower $CO_2$ generation rates than adult males. Therefore, buildings with a high proportion of women, young children, or the elderly may be expected to have lower $CO_2$ levels for any given outdoor air ventilation rate. Unless these lower generation rates

### TABLE 5
### Average Ratios of Energy Expenditure by Gender, Age, and Type of Activity

| Age | Sitting & Standing | | Activities | Ratio to Gen. Office Work |
|---|---|---|---|---|
| | Female to Male Ratio | Ratio to Adult 20-65 yrs | | |
| 1-5 | | 0.57 | Seated Reading/Writing | 0.83 |
| 6-11 | 1.06 | 1.06 | Seated talking | 0.93 |
| 12-19 | 0.84 | 0.99 | Standing talking | 1.00 |
| 20-65 | 0.76 | 1.00 | Casual typing | 0.93 |
| >65 | 0.80 | 0.89 | Regular typing | 1.08 |
| | | | Seated filing | 1.00 |
| | | | Standing filing | 1.14 |
| | | | Walking | 1.43 |
| | | | Cleaning | 1.50 |
| | | | General laboratory | 1.33 |
| | | | Teaching | 1.33 |
| | | | Lifting/Packing | 1.72 |
| | | | Calisthenics | 2.92 |
| | | | Dancing, social | 2.83 |
| | | | Basketball, half court | 5.08 |
| | | | Squash, singles | 5.25 |

are taken into account, measured values of $CO_2$ will overestimate the true ventilation rate for that building.

### Occupant Activity Level

The $CO_2$ generation rate is also affected by activity. ASHRAE estimates that the energy level for the average person in an office setting is 1.2 met units. However, measurements in buildings in which the average energy level is lower than 1.2 met will result in overestimates of the ventilation rate. Conversely, in buildings where the activity level is more strenuous than 1.2 met, measured values of $CO_2$ will underestimate the true ventilation rate. Table 5 also provides energy levels for different types of activities in relation to 1.2 met. Without appropriate adjustment, the practitioner would underestimate the ventilation rate in buildings with higher activity levels or overestimate it in buildings with lower activity levels.

### Overall Significance of $CO_2$ Correction Factors

Table 6 examines the magnitude of errors associated with $CO_2$ measurements of 1,000 ppm for variations of time of measurement ($t$ = two hours, three hours, and steady state), with 20% adjustments below and above the ASHRAE assumed $CO_2$ generation rate. The table shows that substantial errors are possible. The lower the generation rate per person and the lower the occupant density, the lower the air change rate required to reach 1,000 ppm over the designated period and, therefore, the higher the error. High occupant densities and/or high generation rates brought on by activity levels higher than 1.2 met will counteract the overestimation of ventilation rates due to measurements taken prior to steady state. Assuming that buildings do not have air change rates of less than 0.1, errors on the order of 100% to 200% can be readily expected unless they are specifically accounted for by the practitioner.

## POTENTIAL GUIDANCE BASED ON CORRECTIONS TO $CO_2$ MEASUREMENTS

Using this information, it may be possible to provide the practitioner with a set of simple calculations that account for the time of measurement and adjustments to the $CO_2$ generation rate based on gender, age, and type of activity. A simple 10-step process making use of Tables 3 and 5 is proposed for field investigation. An adjustment factor of 0.76 is used for females over males (Table 5). That is, in a building with 100% women, the generation rate would be 76% of the generation rate for males. In a building with some proportion of men and women, the adjustment factor would be a weighted average of no adjustment and the adjustment factor, where the weights are the proportions of men and women, respectively. That is, in an office building with 10% women, the adjustment factor would be 0.90 (1) + 0.76 (.10) = 0.98. The adjustment factor for the generation rate for age and activity levels is also determined using weighted averages and adjustments in Table 5. Once adjustments for gender, age, and activity (met value) are derived in this manner, they can be multiplied to obtain an overall adjustment to the generation rate; that is, $F = (Fg) \times (Fa) \times (Fm)$.

### Proposal to Field Test a 10-Step Process for More Accurate Interpretation of $CO_2$ Measurements

The practitioner would follow the steps below, recording values for each step on the worksheet. In a field test, the results would be compared with more accurate ventilation rate measurement methods. Examples are provided for clarity.

Step 1: {$Ct$)} Indoor $CO_2$ level (ppm). Measure indoor $CO_2$ as close to its anticipated peak value as possible.

Step 2: {$Co$} Outdoor $CO_2$ level (ppm). Measure outdoor $CO_2$ at approximately the same time as indoor $CO_2$ is being measured.

Step 3: {$t$} Time (hours). Estimate the time in hours since the occupants first entered the space. For example, in an office, if people arrive between 8 and 9 a.m., and indoor

## TABLE 6
## Errors in Estimating Ventilation Rates Due to Time of Measurement and Changes in $CO_2$ Generation Rates

| Occ/1000 ft² | | s = 0.008 cfm (0.24 L/min) | | s = 0.010 cfm (0.30 L/min) | | s = 0.012 cfm (0.0.36 L/min) | |
|---|---|---|---|---|---|---|---|
| | | t = 2 | t = 3 | t = 2 | t = 3 | t = 2 | t = 3 |
| 3 | Css (ppm) | * | * | * | * | * | * |
| | a | * | * | * | * | * | * |
| | Corrected q in cfm (L/s) | * | * | * | * | * | * |
| | Error (%) | * | * | * | * | * | * |
| 5 | Css (ppm) | * | * | * | 1792 | * | 1373 |
| | a | * | * | * | 0.21 | * | 0.35 |
| | Corrected q in cfm (L/s) | * | * | * | 7.04 (3.21) | * | 11.75 (5.37) |
| | **Error (%)** | * | * | * | **113%** | * | **28%** |
| 7 | Css (ppm) | * | 1485 | 2132 | 1216 | 1485 | 1117 |
| | a | * | 0.3 | 0.2 | 0.5 | 0.5 | 0.7 |
| | Corrected q in cfm (L/s) | * | 7.0 (3.2) | 5.7 (2.6) | 11.5 (5.2) | 10.6 (4.9) | 15.4 (7.1) |
| | **Error (%)** | * | **113%** | **162%** | **31%** | **41%** | **-3%** |
| 10 | Css (ppm) | 1593 | 1138 | 1256 | 1065 | 1138 | 1033 |
| | a | 0.39 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
| | Corrected q in cfm (L/s) | 6.5 (3,0) | 4.6 | 5 | 13.7 (6.3) | 15.0 (6.9) | 17.2 (7.8) |
| | **Error (%)** | **131%** | **50%** | **136%** | 9% | **0%** | **-13%** |

1. Calculations based on ASHRAE assumptions: Co = 300 ppm, C(t) = 1,000 ppm. Uncorrected per person outdoor air flow rate (q) is 15 cfm per person in all cases. The error is the percent difference between the uncorrected and the corrected per person outdoor air flow rate.
* indicates that the air exchange rate would have to be negative or unrealistically low (below 0.1) for C(t) to reach 1000 ppm in the designated time.

measurements are taken at 11 a.m., then the time of steady occupancy might be estimated to be 2.5 hours.[4]

Step 4: $\{V\}$ Volume of space (ft³). Estimate the volume of the space being represented by the measurements.

Step 5: $\{N\}$ Number of occupants in the space. Determine the number of people that occupy the space during the period of time ($t$).

Step 6: $\{s^*\}$ Adjusted $CO_2$ generation rate per person (cubic feet per hour). The base $CO_2$ generation rate per person is $(10595)(10^{-6})(60) = 0.6357$ cubic feet per hour and represents males aged 20 to 65 with an activity level of 1.2 met. From Table 5, estimate adjustment factors ($F$) based on the proportion ($P$) of females, persons who are younger than 20 or older than 65, and persons engaged in activity that is higher or lower than 1.2 met. Multiply $\{(1 - Pg) + (Pg)(Fg)\} \times \{(1 - Pa) + (Pa)(Fa)\} \times \{(1 - Pm) + Pm(Fm)\} \times 0.6357$.

Step 7: $\{\Omega\}$ The omega factor.[5] Compute $\{\Omega = C(t) - Co\}\, V/(sN)$.

4. At present, the author does not propose how time (t) can be estimated if measurements are taken in the afternoon. Such an estimate would have to account for the lunch break. Developing an approach to adjusting the time variable for afternoon measurements shall await examination of field data.

Step 8: $\{a\}$ Air Change Rate.[6] Determine the air change rate using Table 3.

Step 9: $\{q\}$ The outdoor ventilation rate (cfm per occupant). Estimate the outdoor air ventilation rate per occupant by multiplying the air change rate ($a$) times the space volume ($V$) and dividing by the number of occupants ($N$). Convert the units from hours to minutes: $q = (aV)/60N$.

Step 10: Assess whether the air change rate (step 8) and the outdoor air ventilation rate per person (step 9) are each adequate to ventilate the space due to non-occupant-related and occupant-related contaminants. Assess sources of error.[7]

**Example 1:** Consider a space of 5,000 ft² (464.5 m²) with 10-ft (3-m) ceilings and approximately 20 occupants. The indoor

5. As an alternative to steps 7 and 8, the practitioner may simply solve Equation 1 for the air change rate.
6. Since the air change rate may vary over the course of the day, particularly with VAV systems, the air change rate is, in reality, an estimated average over the time period (t).
7. Potential sources of error include measurement error, sources of CO2 other than occupants, an initial value of CO2 (at t = 0) that is higher than outdoors (e.g., from insufficient outdoor ventilation at night), occupancy or activity levels that vary, and airflows from other spaces with different CO2 concentrations.

$CO_2$ level was measured at 800 ppm at 11:00 a.m. in an office building where people arrive between 8 and 9 a.m. $CO_2$ measured outdoors was 350 ppm. The office building is about 90% women. You are evaluating the outdoor air ventilation rate.

Step 1: $C(t) = 700$ ppm.

Step 2: $Co = 350$ ppm.

Step 3: $t = 2.5$.

Step 4: $V = 50{,}000$ ft$^3$ (1,416 m$^3$).

Step 5: $N = 20$.

Step 6: $s^* = \{(1 - Pg) + (Fg)(Pg)\}s = \{0.10 + (0.76)(0.90)\} \times 0.6357 = 0.4984$.

Step 7: $\Omega = (800 - 350)(10^{-6})(50{,}000)/(0.4984)(20) = 1.74$.

Step 8: $a = 0.3$ ACH (from Table 3).

Step 9: $q = (0.3)(50{,}000)/(20)(60) = 12.5$ cfm per occupant.

Step 10: The measured value of 700 ppm should not be interpreted as suggesting that the space is adequately ventilated at more than 20 cfm per occupant. The adjusted per person outdoor air ventilation rate is less than 15 cfm (7 L/s) per person. In addition, the building is operating at a relatively low air change rate of only 0.4 ACH, bringing into question the ability of the ventilation system to adequately ventilate non-occupant-related contaminants.

**Example 2:** Consider a senior citizens' center of about 2,500 ft$^2$ (232.2 m$^2$) with 10-ft (3-m) ceilings in which there are 5 men and 10 women over the age of 65 engaged in various nonstrenuous social activities similar to light office work. They arrived at 8:30 a.m. $CO_2$ measured at 11:30 was 1,000 ppm indoors and 400 ppm outdoors. You are evaluating the outdoor air ventilation rate.

Step 1: $C(t) = 1{,}000$ ppm.

Step 2: $Co = 400$ ppm.

Step 3: $t = 3$.

Step 4: $V = 25{,}000$ ft$^3$ (708 m$^3$).

Step 5: $N = 30$.

Step 6: $s^*$. Adjustment factor for gender (Table 5) is $0.33 + 0.67(0.80) = 0.87$. The adjustment factor for age (Table 5) is 0.89. The overall adjustment is $0.87 \times 0.89 = 0.77$. The adjusted $CO_2$ generation rate is $0.6357 \times 0.77 = 0.49$ ft$^3$ per person per hour.

Step 7: $\Omega = (1{,}000 - 400)(10^{-6})(25{,}000)/(0.49)(15) = 2.15$.

Step 8: $a = 0.25$ ACH (from Table 3).

Step 9: $q = (0.25)(25{,}000)/(15)(60) = 7$ cfm per occupant.

Step 10: The measurement was taken at $t$ = three hours, which suggests that it is close to its peak value. Therefore, since 1,000 ppm is the threshold for bioeffluent odor, it is not likely that this building will suffer from such an odor problem. However, while the indoor $CO_2$ level of 1,000 ppm would ordinarily suggest that the space is ventilated at about 15 cfm (7 L/s) per occupant, at an air change rate of only 0.25, it would take approximately 12 hours for the indoor $CO_2$ level to reach 95% of its steady-state level. This reading of 1,000 ppm appears to be considerably below its steady-state level. Thus, while bioeffluent odor may not be a problem, other sources of contaminants, combined with the low air change rate, may be causing serious indoor air quality problems.

## RESERVATIONS AND LIMITATIONS

The adjustment factors proposed here are based on a mass balance model and are designed to account for some of the sources of error when using spot measurements of $CO_2$ to estimate outdoor air ventilation rates. However, the potential for substantial error remains and the validity and practicality of the adjustment factors proposed here have not been field tested. Practitioners are cautioned not to interpret these adjustment factors as an improvement over current practice in the absence of real world experience but, rather, to consider the method as a proposal for field testing and validation.

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