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Interpretation of 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 CO2 measurement (or several measurements over a short period of time) to do this. This practice is based on the stead-state mass balance relationship provided in ASHRAE 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, and there is perfect mixing. 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% - 200%. Major problems occur because (a) measurements probably do not represent steady-state, (2) there are systematic age and sex and activity differences in CO_2 exhalation rates, (3) CO_2 levels outdoors is variable, and (4) the ASHRAE level for CO_2 of 1,000 ppm is only a partial indicator of indoor air quality. To overcome these problems, guidance to assist practitioners in interpreting their measurements, along with a 10 step process which applies correction factors is presented. The correction factors are based on steady-state model calculations and published data. The corrected CO_2 value should provide for more accurate interpretations.

Disclaimer: This procedure is still in draft form, has not been reviewed or validated in the field, and does not necessarily represent the position of EPA.

Key Words: air quality, comfort, commercial, odor, office building, ventilation.

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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 CO2 measurement (or several measurements over a short period of time) to do this. This practice is based on the stead-state mass balance relationship provided in ASHRAE 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, and there is perfect mixing. 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% - 200%. Major problems occur because (a) measurements probably do not represent steady-state, (2) there are systematic age and sex and activity differences in CO_2 exhalation rates, (3) CO_2 levels outdoors is variable, and (4) the ASHRAE level for CO_2 of 1,000 ppm is only a partial indicator of indoor air quality. To overcome these problems, guidance to assist practitioners in interpreting their measurements, along with a 10 step process which applies correction factors is presented. The correction factors are based on steady-state model calculations and published data. The corrected CO_2 value should provide for more accurate interpretations..

Introduction

Perhaps the most misunderstood aspect of indoor air quality 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 of time) can be relied on as a 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 level. In addition, because of the mass balance relationship between indoor generation rates of a gas and the air exchange rate in a building, CO_2 is also used as a measure of outdoor air ventilation rates. Under limited circumstances , the ASHRAE level 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 which 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 which do exist are either dismissed or under-valued. 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 CO2 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 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, use of these correction factors has not been field tested so it is not known how well they actually works in real applications.*

Relationship Between $C0_2$ and Outdoor Air Ventilation Rates

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

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

Where

C(t) = the indoor concentration(volumetric proportion) at time t
Co = the constant outdoor concentration (volumetric proportion)
S = the generation rate of the source (volume/per time unit)
a = the air exchange rate (per time unit), and
V = the volume in the occupied space

Since the dominant sources of $C0_2$ in buildings are the building occupants, it is assumed that in the early morning before occupants arrive, the indoor concentration of C02 is the same as that outdoors. Accordingly, after occupants arrive, they are assumed to represent a constant source of $C0_2$ so that the indoor concentration would asymptotically approach a steady state condition (Css) by the time path defined in equation (1). The steady state condition, (defined by Equation 1 as t--> infinity) is given by

$$Css - Co = S/aV \qquad (2)$$

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

$$Css - Co = S/Q \qquad (3)$$

or

$$Css - Co = s/q \qquad (4)$$

where Q = 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.

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. Providing 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, since the assumptions are often not met in the real world, adjustments may be needed to insure that $C0_2$ measurements are properly interpreted to avoid misrepresentation of the true ventilation rate.

Interpreting spot measurements of CO_2

Measured values of CO_2 relative to its steady state value

Appendix D of ASHRAE 62-1989 estimates that at the activity level associated with general office work is 1.2 met. At that activity level, the per person $C0_2$ generation rate is assumed to be 0.01 cfm (0.30 L/s). ASHRAE also assumes that the outdoor $C0_2$ level is constant at a volumetric proportion of .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. Accordingly, the threshold value of 1,000 ppm for C02 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 $C0_2$ concentration at or close to its steady state value. *If $C0_2$ is measured prior to the time that steady state is substantively achieieved, 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 of the model (constant source, constant outdoor air concentration, constant air exchange rate and perfect mixing), with each time constant (the time it takes for ta 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 {(l-l/e) or 63.2%} of the remaining distance to the steady state level. Thus, after one time constant, the $C0_2$ level achieves 63.2% of its steady state level. After 2 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 $C0_2$ when it has reached at least 95% of its steady state value, using measurements of $C0_2$ to assess the outdoor air ventilation rate as per Table 1 would be unreliable unless the building has had stable occupancy for a lenght of time equal to at least three time constants. At 1ACH, 95% of steady state is achieved in 3 hours. At 0.50 ACH, it would take 6 hours to achieve 95% of steady state, and at 0.25 ACH, it would take12 hours.

It is commonly recommended that $C0_2$ measurements be taken at their peak value when $C0_2$ is closest to its steady state value. But this does not guarantee that the peak value will adequately represent steady state for estimation purposes. Figure 1 shows the time path for $C0_2$ in a typical office building[1]. $C0_2$ begins to rise as occupants enter in the morning, and peaks late morning before occupants leave for lunch, peaking again late afternoon just before they begin leaving to go home. In general, there is scarcely a 3 hour time frame of steady occupancy in which CO_2 is rising toward steady state. Thus, CO_2 measurements in buildings with air exchange rates below 1 ACH will likely underestimate Css, and over estimate ventilation rates even if measurements were taken at or close to peak. The extent to which measurements are taken at sub-peak levels serves only to magnifiy this problem.

Adjusting measured values for the time of measurement

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

Equation 1 can be rewitten as

[1] The timing of measurements designed to represent peak values should depend on occupancy schedules, vary from building to building.

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

where

N = number of occupants

All the variables on the left side of equation can be measured or determined by the practitioner. Once the left side value is known, and the time the measurement was taken is specified, the air exchange rate of the building 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" are provided in Table 3.

For example, suppose that CO_2 outside is measured at 350 ppm (350×10^{-6}) and is relatively constant, and an inside measurement of 850 ppm (800×10^{-6}) was taken at t = 2 hours. Ordinarily, a reading of 850 ppm would imply that this space is receiving approximately 20 cfm (9L/s) of outdoor air per person (from Table 1). However, suppose that we estimate the relevant area to be a 5,000 square foot space with a ceiling height of 10 feet, 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 exchange rate from Table 3. The value of the left side of equation 5, which we call omega ('Ω) 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 exchange rate of this building, enter Table 3 at the column corresponding to t = 2 hours seeking the values bounding 1.12. The air exchange 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

$q = aV/(N \times 60)$ (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 square feet. 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) implied by the measured value using ASHRAE assumptions. The body of the table then provides the steady state value, the air exchange 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 soley to the fact that measurements were taken prior to steady state conditions.

Using the example above where CO_2 was measured at 850 ppm outside and 350 ppm inside at t = 2.0 hours and an occupant density of 7 occupants/1,000 ft^2, follow the column on 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 exchange 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 exchange rate (a) in order to maintain the same measured value (C(t)- Co)). Thus, in the example above, if the building had 5 occupants/1,000 sf, 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/1,000 square feet, 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 level even at extremely low per-person outdoor ventilation rates.* Measurements taken in buildings with occupant densities below 5 occupants per 1,000 ft^2 (100 $m^{2)}$ 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 neccesitate air exchange rates below 0.2 (see Table 4c). In fact, buildings with only 3 occupants per 1,000 ft^2 (100 m^2) could not achieve levels that high in 3 hours, even with a zero air exchange. Sub-peak measurements at t = 2 hours would make it impossible to achieve measured values of (C(t) - Co) as high as 700 ppm, evan at 5 occupants/1,000 ft^2 (100 m^2).

If measured values as high as C (t) - Co = 700 ppm or more are encountered in buildings with 5 or less occupants per 1,000 square feet, it suggests the possibility that the building has a serious ventilation problem, or that the measurements are innacurate. In either case, the information is valuable.

3. *It is wise to estimate the air exchange rate in low occupant density buildings even*

when the corrected outdoor air ventilation rate equals or exceeds 15 cfm (7 L/s) per person. This is because low occupant density buildings may satisfy the 15 cfm (7 L/s)per occupant criteria but still have unacceptably low air exchange rates. The ASHRAE criteria 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 exchange rate may be sufficient to control body odor (and perhaps other contamninants associated with the numnber 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.

In general, relying on spot measurements of $C0_2$ to estimate ventilation rates in buildings has a built in bias which tends to overestimate ventilation rates. *The potential to overestimate ventilation rates is greatest at low air exchange rates--precisely the conditions which cause indoor air quality problems.* In addition, if practitioners are not careful to measure peak values, but for convenience or through ignorance measure sub-peak levels, the potential to overestimate can be substantially increased. This problem suggests the need for adustment factors based to assist practitioners in interpreting $C0^2$ values.

Measuring $C0_2$ Outdoors

Outdoor values of CO_2 can vary widely, but are seldom as low as the ASHRAE assumption of 300ppm. A common observation is that outdoor values are typically 350 ppm, but 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 ventilation rates, the higher outdoor air CO_2 will partially correct the underestimation which 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 estirnate 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 0.01cfm (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 $C0_2$ level. However, the basis for this assumption is not clearly established in ASHRAE (1985) or ASHRAE (1969), 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 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 (0.16-0.17 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 .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 are taken into account, measured values of C02 will overestimate the true ventilation rate for that building.*

Occupant Activity Level

The CO_2 generation rate is also effected 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 activitiesin relation to 1.2 met. Without appropriate adjustment, the practitioner would under-estimate the ventilation rate 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 errorsassociated with CO_2 measurements of 1,000 ppm for variations of time of measurement (t = 2 hours, 3 hours and at steady state), and 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 is the air exchange rate required to reach 1,000 ppm over the designated period, and therefore, the higher is 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 exchange rates below 0.1, errors in the order of 100% - 200% can be readily expected unless they are specifically accounted for by the practioner.

Potential Guidance based on Corrections to CO_2 Measurements

Using the information above, it is now possible to provide the practioner with a set of simple calculations which account for the time of measurement, and adjustments to the CO_2 generation rate based on gender, age, and type of activity. A simple ten step process making use of Tables 3, and 5) is proposed below. An adjustment factor of 0.76 is used for females over males (Table5). 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 a 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 are also determined using weighted averages and adjustments in Tables 7 and 8. 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) x (Fa) x (Fm).

Proposed 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 the worksheet presented as Figure 2. 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 (e.g. late morning, before lunch, or late afternoon, prior to leaving).

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 of steady occupancy. For example, in an office, if people arrive between 8-9am, and indoor measurements are taken at 11 am, then the time of steady occupancy might be estimated to be 2.5 hours.

Step 4: {V} Volume of space (cubic feet). Estimate the volume of the space being represented by the measurements (e.g. the space served by the air handling unit and generally protected from airflows from other spaces).

Step 5: {N} Number of occupants in the space. Determine the number of people which occupy the space during the perod of time (t).

Step 6: {s*} Adjusted CO_2 generation rate per person (cubic feet per hour). The base CO_2 generation rate is $(10595)(10^{-6)}($ 60) = 0.6357 cubic feet per hour and represents males aged 20-65 with an activity level of 1.2 met. From Tables 6, 7, and 8, 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 which is higher or lower than 1.2 met. Multiply {(1-Pg) + (Pg)(Fg)} x {(1-Pa) +(Pa)(Fa)} x {(1- Pm) + Pm(Fm)) x 0.6357.

Step 7: {σ} The omega factor. Compute σ =C(t) - Co}V/(sN)

Step 8: {a} Air Exchange Rate. Determine the air exchange 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 exchange 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

Step10: Assess whether the air exchange rate (step 7) and the outdoor air ventilation rate per person (Step 9) are each adequate to ventilate the space due to occupant related and non-occupant related contaminants.

Example 1: Consider a space of 5,000 square feet, with 10 foot ceilings, and approximately 20 occupants. The indoor CO_2 level was measured at 800 ppm at 11:00 am in an office building where people arrive between 8 and 9 am. 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 cubic feet
Step 5: N = 20
Step 6: s* = (1 - Pg) +(Fg)(Pg) x s = 0.10 +(0.76)(0.10) x 0.6357 = 0.4984
Step 7: σ = (800 - 350)(10^{-6}) (50,000)/(0.4984)(20) = 1.74
Step 8: a = 0.4 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 over 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 exchange rate of only 0.4ach, 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 square feet with 10 foot ceilings in which there are 5 men and 10 women over the age of 65 engaged in various non-strenuous social activities similar to light office work. The arrived at 830 am. 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
Step 5: N = 30
Step 6: s*. Adjustment factor for gender (Table 5) is 0.33 + 0.67(0.76) = 0.84. The adjustment factor for age (Table 5) is 0.89. The overall adjustment is 0.84 x 0.89 = 0.75. The adjusted CO_2 generation rate is 0.6357 x 0.75 = 0.4768 ft^3 per person per hour.
Step 7: $\Omega = (1{,}000 - 400)(10^{-6})(25{,}000)/(0.4768)(15) = 2.09$
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 = 3 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 exchange 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 exchange rate, may be causing serious indoor air quality problems.

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Table 1: Outdoor Air Ventilation Rates Associated with Steady State Values of CO2

Steady State CO2 (PPM)	*Outdoor Air Ventilation*	
	(CFM/Occ)	*L/s/occ*
5000	2	*1*
2500	5	*2*
2000	6	*3*
1500	9	*4*
1000	***15***	*7*
900	18	*8*
800	***21***	*10*

Table 2: Percent of Steady State Achieved at Specified 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

Table 3: Calculating air Exchange Rate (a) from Measured Data

$$\frac{\{C(t) - Co\}(V)}{s \times N} = (1/a)(1-e^{-at})$$

ACH (a) \ Time (t) in Hours	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5	3.75	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 caluclated air exchange rate for the building.

Table 4a: Interpreting CO2 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 thou sq ft	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 CO2 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 thou sq	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*
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 CO2 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 thou sq ft	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*

Table 4d: Interpreting CO2 Values Corrected for Time to Steady State

t = 3.5 hours

Carbon Dioxide Values (after 3.5 hours) in Parts Per Million (PPM)

Occupants per thou sq ft	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*

Table 5: Average Ratios of Energy Expenditure by Gender, Age, and Type of Activity

Age	Sitting & Standing Female to Male Ratio	Sitting & Standing Ratio to Adult 20-65 yrs	Activities	Ratio to General Office Work (1.2 met)
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
			Calesthenics	2.92
			Dancing, social	2.83
			Basketball, half court	5.08
			Squash, singles	5.25

Table 6: Errors in Estimating Ventilation Rates due to Time of Measurement and Changes in CO2 Generation Rates

Occ/1000 sq ft		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 ecxhange rate would have to be negative or unrealistically low (below 0.1) for C(t) to reach 1000 ppm in the designated time.

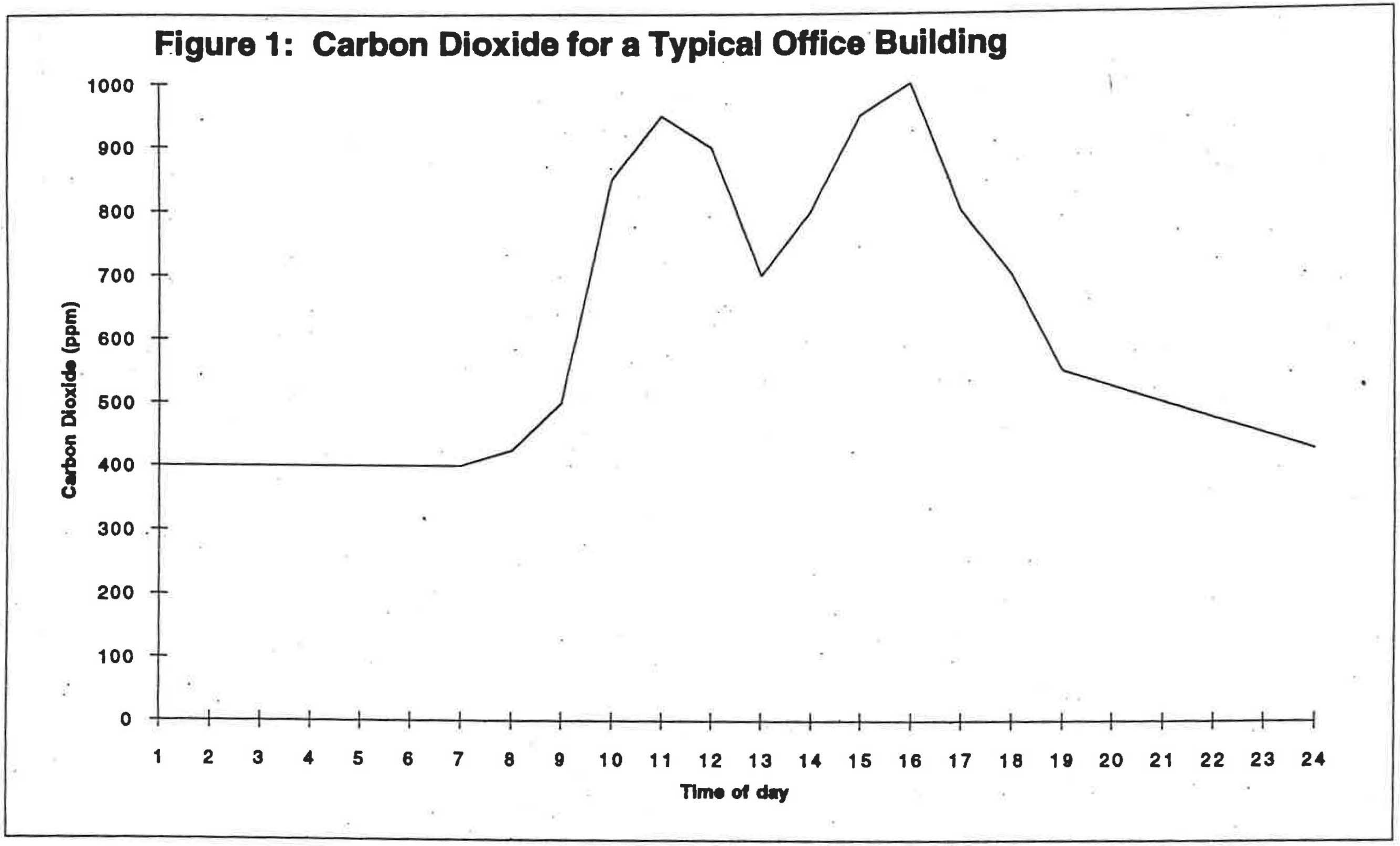

Figure 1: Carbon Dioxide for a Typical Office Building
Carbon Dioxide (ppm)
1000
900
800
700
600
500
400
300
200
100
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time of day

Figure 2: Carbon Dioxide Worksheet

Step 1. [C(t)] Indoor Level ________ **ppm**

Step 2. [Co] Outdoor Level ________ **ppm**

Step 3. [t] Time ________ **hours**

Step 4. [V] Volume of space ________ **ft^3 (m^3)**

Step 5. [N] Number of occupants ________

Step 6. [s*] Adjusted generation rate

Gender adjustment ___________ **x**

Age adjustment ___________ **x**

Activity adjustment _______ **x 0.66 (18)** _____ **ft^3/hr (m^3/hr)**

Step 7. [Ω] Omega factor ________

$$\frac{[C(t) - Co]\,(10^{-6})V}{s^{*}N}$$

Step 8. [a] Air echange rate (Table 3) ________

Step 9 [q] Outdoor air ventilation per occ. ________ **cfm/occ**

Step 10. Evaluation