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Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation[1]

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1. Scope

1.1 This guide describes how measured values of indoor carbon dioxide (CO_2) concentrations can be used in evaluations of indoor air quality and building ventilation.

1.2 This guide describes the determination of CO_2 generation rates from people as a function of body size and level of physical activity.

1.3 This guide describes the experimentally-determined relationship between CO_2 concentrations and the acceptability of a space in terms of human body odor.

1.4 This guide describes the following uses of indoor CO_2 concentrations to evaluate building ventilation–mass balance analysis to determine the percent outdoor air intake at an air handler, the tracer gas decay technique to estimate whole building air change rates, and the constant injection tracer gas technique at equilibrium to estimate whole building air change rates.

1.5 This guide discusses the use of continuous monitoring of indoor and outdoor CO_2 concentrations as a means of evaluating building ventilation and indoor air quality.

1.6 This guide discusses some concentration measurement issues, but it does not include or recommend a method for measuring CO_2 concentrations.

1.7 This guide does not address the use of indoor CO_2 to control outdoor air intake rates.

1.8 *Units*—The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.9 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.10 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1356 Terminology Relating to Sampling and Analysis of Atmospheres

D3249 Practice for General Ambient Air Analyzer Procedures

E741 Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution

2.2 *Other Documents:*

ASHRAE Standard 62.1 Ventilation for Acceptable Indoor Air Quality[3]

3. Terminology

3.1 *Definitions*—For definitions and terms used in this guide, refer to Terminology D1356.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *air change rate, n*—the total volume of air passing through a zone to and from the outdoors per unit time, divided by the volume of the zone (s^{-1}, h^{-1}).[4]

3.2.2 *bioeffluents, n*—gases emitted by people as a product of their metabolism that can result in unpleasant odors.

3.2.3 *single-zone, n*—an indoor space, or group of spaces, wherein the CO_2 concentration is uniform and that only exchanges air with the outdoors.

4. Summary of Guide

4.1 When investigating indoor air quality and building ventilation, a number of tools are available. One such tool is

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), 1791 Tullie Circle, NE, Atlanta, GA 30329, http://www.ashrae.org.

[4] A common way of expressing air change rate units is h^{-1} = air changes per hour.

the measurement and interpretation of indoor and outdoor CO_2 concentrations. Using CO_2 concentrations to evaluate building indoor air quality and ventilation requires the proper use of the procedures involved, as well as consideration of several factors related to building and ventilation system configuration, occupancy patterns, non-occupant CO_2 sources, time and location of air sampling, and instrumentation for concentration measurement. This guide discusses ways in which CO_2 concentrations can be used to evaluate building indoor air quality and ventilation.

4.2 Section 6 discusses the rate at which people generate CO_2 and the factors that affect this rate.

4.3 Section 7 discusses the use of indoor concentrations of CO_2 as an indicator of the acceptability of a space in terms of perceptions of human body odor.

4.4 Section 8 describes the use of mass balance analysis to determine the percent outdoor air intake at an air handler based on the measured CO_2 concentrations in the supply, return, and outdoor air intake airstreams.

4.5 Section 9 describes the use of the tracer gas decay technique to determine building air change rates using occupant-generated CO_2 as a tracer gas. The tracer gas decay technique is described in detail in Test Method E741, and this section discusses the application of this test method to the special case of occupant-generated CO_2 after the occupants have left the building.

4.6 Section 10 describes the use of the constant injection tracer gas technique with occupant-generated CO_2 to estimate outdoor air ventilation rates. This technique is sometimes referred to as equilibrium analysis, and Section 10 discusses the use of this technique and the assumptions upon which it is based.

4.7 Section 11 discusses the use of continuous monitoring of CO_2 concentrations as a means of evaluating indoor air quality and ventilation in buildings. In this discussion, continuous refers to real-time concentration measurement recorded with a datalogging device, generally over several days.

4.8 Section 12 discusses CO_2 concentration measurement issues, including measuring outdoor concentrations, sample locations for indoor concentration measurements, establishing the uncertainty of measured concentrations, and calibration.

5. Significance and Use

5.1 Indoor CO_2 concentrations have been described and used by some people as an indicator of indoor air quality. These uses have included both appropriate and inappropriate interpretations of indoor CO_2 concentrations. Appropriate uses include estimating expected levels of occupant comfort in terms of human body odor, studying occupancy patterns, investigating the levels of contaminants that are related to occupant activity, and screening for the sufficiency of ventilation rates relative to occupancy. Inappropriate uses include the application of simple relationships to determine outdoor air ventilation rates per person from indoor CO_2 concentrations without verifying the assumptions upon which these relationships are based, and the interpretation of indoor CO_2 concentrations as a comprehensive indicator of indoor air quality.

5.2 Outdoor air ventilation rates affect contaminant levels in buildings and building occupants' perception of the acceptability of the indoor environment. Minimum rates of outdoor air ventilation are specified in building codes and indoor air quality standards, for example, ASHRAE Standard 62. The compliance of outdoor air ventilation rates with relevant codes and standards are often assessed as part of indoor air quality investigations in buildings. The outdoor air ventilation rate of a building depends on the size and distribution of air leakage sites, pressure differences induced by wind and temperature, mechanical system operation, and occupant behavior. Given all of this information, ventilation rates are predictable; however, many of these parameters are difficult to determine in practice. Therefore, measurement is required to determine outdoor air change rates reliably.

5.3 The measurement of CO_2 concentrations has been promoted as a means of determining outdoor air ventilation rates per person. This approach, referred to in this guide as equilibrium analysis, is based on a steady-state, single-zone mass balance of CO_2 in the building and is sometimes presented with little or no discussion of its limitations and the assumptions on which it is based. As a result, in some cases, the technique has been misused and indoor CO_2 concentration measurements have been misinterpreted.

5.4 When the assumptions upon which equilibrium analysis is based are valid, the technique can yield reliable measurements of outdoor air ventilation rates. In addition, indoor CO_2 concentrations can be used to determine other aspects of building ventilation when used properly. By applying a mass balance at an air handler, the percent outdoor air intake in the supply airstream can be determined based on the CO_2 concentrations in the supply, return, and outdoor air. This percentage can be multiplied by the supply airflow rate of the air handler to yield the outdoor air intake rate of the air handler. In addition, the decay of indoor CO_2 concentrations can be monitored in a building after the occupants have left to determine the outdoor air change rate of the building.

5.5 Continuous monitoring of indoor and outdoor CO_2 concentrations can be used to study some aspects of ventilation system performance, the quality of outdoor air, and building occupancy patterns.

6. CO_2 Generation Rates

6.1 Human metabolism consumes oxygen and generates CO_2 at rates that depend on the level of physical activity, body size, and diet.

6.2 The rate of carbon dioxide generation of an individual V_{CO2} in L/s per person, at an air temperature of 273 K and an air pressure of 101 kPa, is given by Eq 1, the derivation of which is described in detail in Ref (**1**):[5]

$$V_{CO_2} = RQ\ BMR\ M\ 0.000569 \quad (1)$$

[5] The boldface numbers in parentheses refer to a list of references at the end of this standard.

where:

RQ	=	respiratory quotient, dimensionless (defined in 6.3),
BMR	=	basal metabolic rate, MJ/day, and
M	=	metabolic rate per unit of surface area, met (dimensionless).

For other values of air temperature T and pressure P, V_{CO2} is given by Eq 2.

$$V_{CO_2} = RQ\ BMR\ M\ (T / P)\ 0.000211 \quad (2)$$

6.3 The respiratory quotient, RQ, is the ratio of the volumetric rate at which CO_2 is produced by an individual to the rate at which oxygen is consumed. The value of RQ depends primarily on diet (**2**). Based on data on human nutrition in the United States, primarily the ratios of fat, protein, and carbohydrate intake, RQ equals about 0.85 (**3**).

6.4 Values of BMR are a function of sex, age, and body mass. Equations for the calculation of BMR are given in Table 1 (**4**).

6.5 The variable M (in dimensionless units of met) is used to describe the ratio of the human energy use associated with a particular physical activity to the BMR of an individual as discussed in detail in Ref (**1**). There are two primary references for obtaining met levels for different physical activities (**5, 6**). Tables 2 and 3 contain met levels for many common indoor activities drawn from those two references.

6.6 Table 4 lists CO_2 generation rates for ranges of ages and met levels estimated using the body mass data for males and females in the EPA Exposure Factors Handbook (**7**), assuming RQ is equal to 0.85.

6.7 To reflect the importance of variations in body size, that is, mass, in estimating CO_2 generation rates, Fig. 1 and Fig. 2 show the variation in V_{CO2} with age and body mass for females and males, respectively. Each plot displays V_{CO2} for 13 age ranges from < 1 y to ≥ 80 y and for six met levels from 1 to 4. The plotted generation rates are calculated using RQ equal to 0.85. Each vertical box-whisker plot displays the range of CO_2 generation rates from the 10^{th} percentile value of body mass up to the 90^{th} as indicated in the key to each figure.

6.8 In using Eq 1 and Table 4 to estimate CO_2 generation rates for the occupants in a given building, it is important to consider the ages, sizes and met levels of the individual occupants, as well as the ranges in each of these variables in the building population. When applying these calculations to occupied buildings, this information should be obtained via observations of the occupants to achieve more accurate estimates of the CO_2 generation rates.

7. CO_2 as an Indicator of Body Odor Acceptability

7.1 This section describes the use of CO_2 to evaluate indoor air quality in terms of human body odor acceptability and therefore, the adequacy of the ventilation rate to control body odor. The material in this section is based on a number of experimental studies in both chambers and real buildings and describes the most well-established link between indoor CO_2 concentrations and indoor air quality.

7.2 At the same time people are generating CO_2 they are also producing odor-causing bioeffluents. Similar to CO_2 generation, the rate of bioeffluent generation depends on the level of physical activity. Bioeffluent generation also depends on personal hygiene such as the frequency of baths or showers. Because both CO_2 and bioeffluent generation rates depend on physical activity, the concentrations of CO_2 and the odor intensity from human bioeffluents in a space exhibit a similar dependence on the number of occupants and the outdoor air ventilation rate.

7.3 Experimental studies have been conducted in chambers and in occupied buildings in which people evaluated the acceptability of the air in terms of body odor (**8-12**). These experiments studied the relationship between outdoor air ventilation rates and odor acceptability, and the results of these studies were considered in the development of most ventilation standards and guidelines (including ASHRAE Standard 62.1). This entire section is based on the results of these studies.

7.3.1 These studies concluded that about 7.5 L/s of outdoor air ventilation per person will control human body odor such that roughly 80 % of unadapted persons (visitors) will find the odor at an acceptable level. These studies also showed that the same level of body odor acceptability was found to occur at a CO_2 concentration that is about 650 ppm(v) above the outdoor concentration.

7.3.2 Fig. 3 shows the percent of unadapted persons (visitors) who are dissatisfied with the level of body odor in a space as a function of the CO_2 concentration above outdoors (**13**). This figure accounts only for the perception of body odor and does not account for other environmental factors that may influence the dissatisfaction of visitors to the space, such as the concentrations of other pollutants and thermal parameters. Based on the relationship in Fig. 3, the difference between indoor and outdoor CO_2 concentrations can be used as an indicator of the acceptability of the air in a space in terms of body odor and, therefore, as an indicator of the adequacy of the ventilation rate to control the level of body odor. However, the relationship between percent dissatisfied and CO_2 concentration is also dependent on the personal hygiene of the occupants

TABLE 1 Equations for Calculating BMR (4)

NOTE 1—m is body mass in units of kg.

Age (y)	BMR: MJ/day	
	Males	Females
<3	0.249 m – 0.127	0.244 m – 0.130
3 to 10	0.095 m + 2.110	0.085 m + 2.033
10 to 18	0.074 m + 2.754	0.056 m + 2.898
18 to 30	0.063 m + 2.896	0.062 m + 2.036
30 to 60	0.048 m + 3.653	0.034 m + 3.538
≥60	0.049 m + 2.459	0.038 m + 2.755

TABLE 2 Metabolic Rates (*M* in Met) for Various Physical Activities (5)

Activity	M (Met)	Range
Calisthenics – light effort	2.8	
Calisthenics – moderate effort	3.8	
Calisthenics – vigorous effort	8.0	
Child care		2.0 to 3.0
Cleaning, sweeping – moderate effort	3.8	
Custodial work – light	2.3	
Dancing – aerobic, general	7.3	
Dancing – general	7.8	
Health club exercise classes – general	5.0	
Kitchen activity – moderate effort	3.3	
Lying or sitting quietly		1.0 to 1.3
Sitting reading, writing, typing	1.3	
Sitting at sporting event as spectator	1.5	
Sitting tasks, light effort (for example, office work)	1.5	
Sitting quietly in religious service	1.3	
Sleeping	0.95	
Standing quietly	1.3	
Standing tasks, light effort (for example, store clerk, filing)	3.0	
Walking, less than 2 mph, level surface, very slow	2.0	
Walking, 2.8 mph to 3.2 mph, level surface, moderate pace	3.5	

TABLE 3 Metabolic Rates (*M* in Met) for Additional Physical Activities (6)

Activity	Males		Females	
	Average	Range	Average	Range
Aerobic dancing – low intensity	3.51		4.24	
Aerobic dancing – high intensity	7.93		8.31	
Calisthenics	5.44			
Child care (unspecified)			2.5	
Climbing stairs	5.0			
Dancing	5.0		5.09	
Eating and drinking	1.4		1.6	
Housework (unspecified)			2.8	2.5 to 3.0
Office worker – Filing	1.3		1.5	
Office worker – Reading	1.3		1.5	
Office worker – Sitting at desk	1.3			
Office worker – Standing/moving around	1.6			
Office worker – Typing	1.8		1.8	
Office worker – Writing	1.4		1.4	
Reading	1.22		1.25	
Sleeping	1.0		1.0	
Sitting quietly	1.2		1.2	
Sitting on a bus/train	1.2			
Standing	1.4		1.5	
Walking around/strolling	2.1	2.0 to 2.2	2.5	2.1 to 2.9
Walking quickly	3.8			
Walking slowly	2.8	2.8 to 3.0	3.0	

of a space, that is, their frequency of bathing, as well as the societal expectations of the visitors to the space. The individuals involved in the experiments on which Fig. 3 is based were office workers and university students with modern habits of personal hygiene from the United States, Denmark, and Japan. If the occupants of a space have different levels of personal hygiene and if the visitors have different expectations, then Fig. 3 would not necessarily apply.

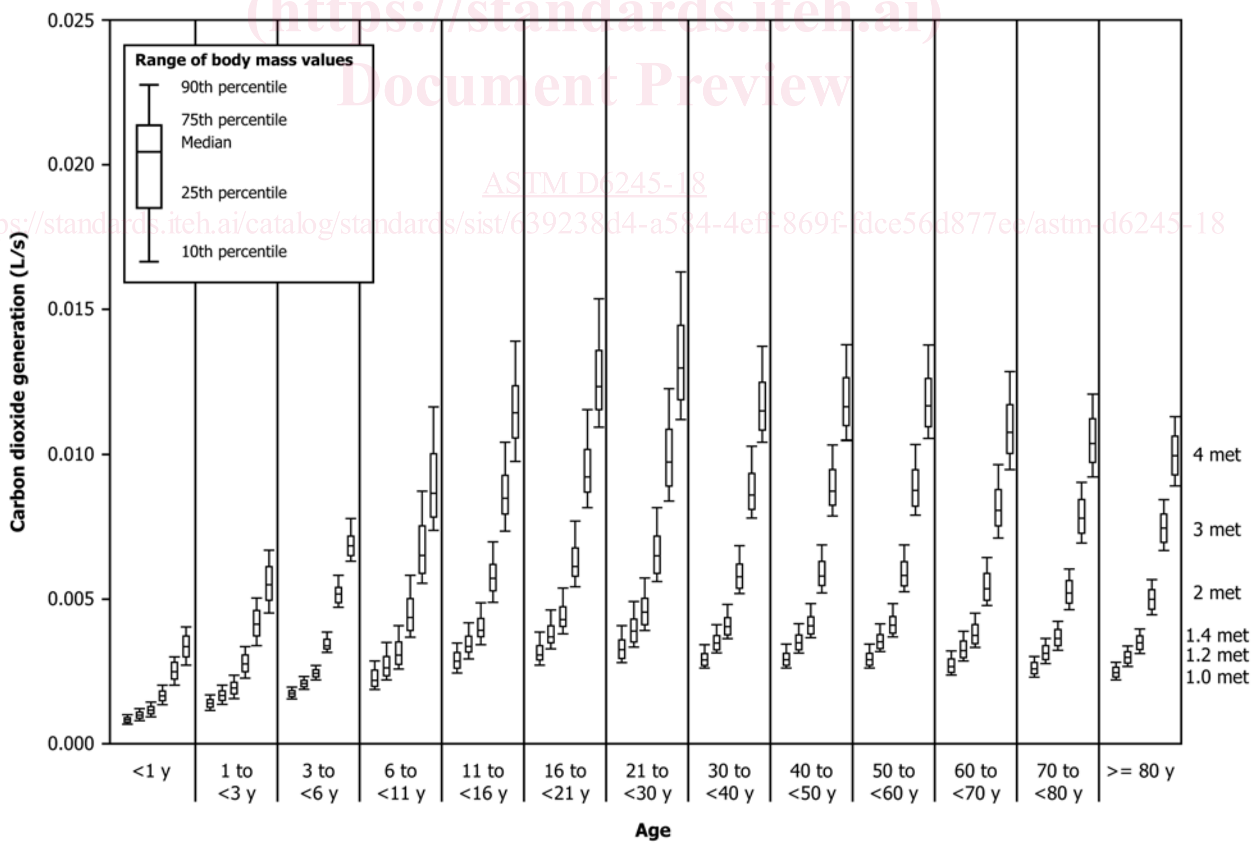
7.3.3 The experimentally observed relationship between percent dissatisfied and CO_2 concentrations in Fig. 3 was not strongly dependent on the level of physical activity (**8, 10, 12**). In addition, the relationship did not require that the indoor CO_2 concentration be at equilibrium.

7.3.4 The relationship described in Fig. 3 can also be derived based on the experimentally-determined relationship between percent dissatisfied and outdoor air ventilation rates in L/s. Based on a typical level of CO_2 generation per person and an assumption that the indoor CO_2 concentrations are at equilibrium, the outdoor air ventilation rates determined experimentally to result in a particular value of percent dissatisfied can be converted into indoor CO_2 concentrations to derive the relationship in Fig. 3.

7.3.5 The cited research has shown that if the difference between the indoor and outdoor CO_2 concentrations is less than about 650 ppm(v), then at least 80 % of unadapted persons (visitors) will find the level of body odor acceptable. This concentration difference corresponds to the indoor CO_2 concentration at equilibrium at a ventilation rate of 7.5 L/s per person. This ventilation rate also corresponds to 80 % acceptability based on experiment. The 650 ppm(v) concentration difference, combined with an outdoor CO_2 concentration of 350 ppm(v), is the basis of the commonly-referenced guideline value for CO_2 of 1000 ppm(v). Note that outdoor CO_2 concentrations have been increasing (**14**) and therefore an indoor-outdoor concentration difference of 650 ppm(v) would translate to a higher indoor concentration than 1000 ppm(v).

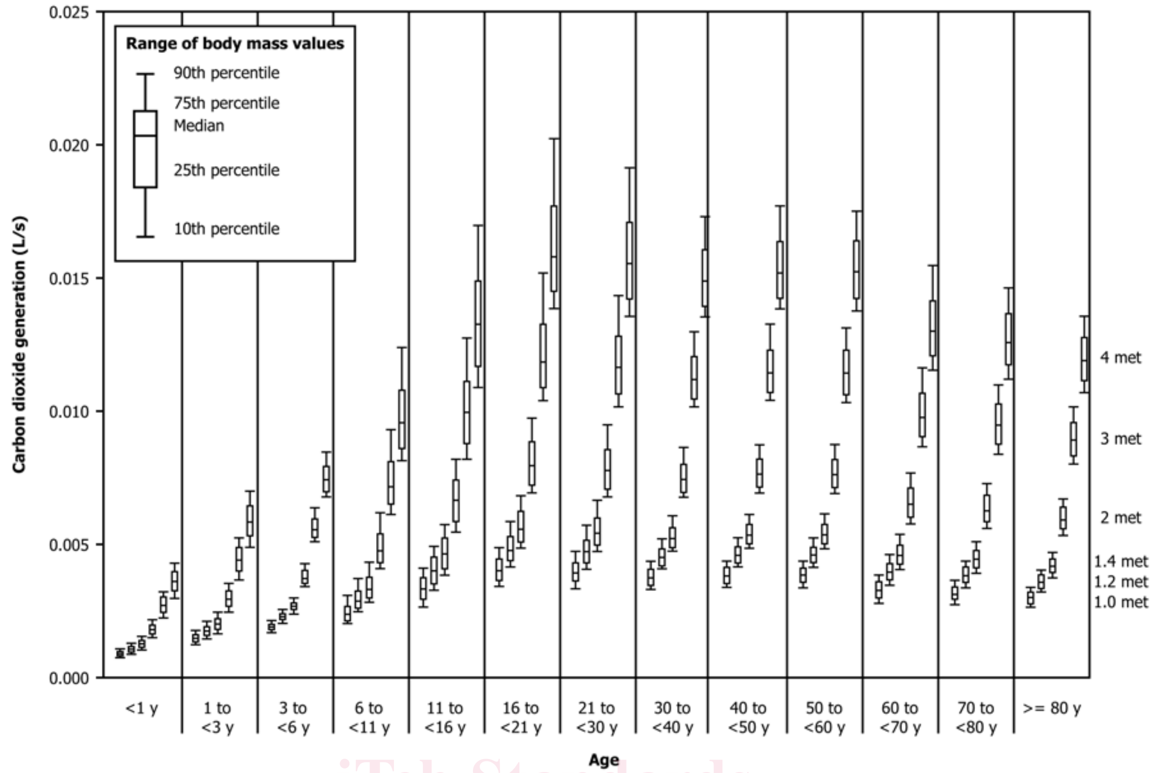
TABLE 4 Carbon Dioxide Generation Rates as a Function of Occupant Sex, Age, and Met Level (Based on Body Mass Data in (7)

Age (y)	Mean Mass (kg)	BMR (MJ/day)	CO_2 Generation Rate (L/s)						
			Level of Physical Activity (Met)						
			1.0	1.2	1.4	1.6	2.0	3.0	4.0
Males									
<1	8.0	1.86	0.0009	0.0011	0.0013	0.0014	0.0018	0.0027	0.0036
1 to <3	12.8	3.05	0.0015	0.0018	0.0021	0.0024	0.0030	0.0044	0.0059
3 to <6	18.8	3.90	0.0019	0.0023	0.0026	0.0030	0.0038	0.0057	0.0075
6 to <11	31.9	5.14	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0100
11 to <16	57.6	7.02	0.0034	0.0041	0.0048	0.0054	0.0068	0.0102	0.0136
16 to <21	77.3	7.77	0.0037	0.0045	0.0053	0.0060	0.0075	0.0113	0.0150
21 to <30	84.9	8.24	0.0039	0.0048	0.0056	0.0064	0.0080	0.0120	0.0160
30 to <40	87.0	7.83	0.0037	0.0046	0.0053	0.0061	0.0076	0.0114	0.0152
40 to <50	90.5	8.00	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0155
50 to <60	89.5	7.95	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0154
60 to <70	89.5	6.84	0.0033	0.0040	0.0046	0.0053	0.0066	0.0099	0.0133
70 to <80	83.9	6.57	0.0031	0.0038	0.0045	0.0051	0.0064	0.0095	0.0127
≥80	76.1	6.19	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
Females									
<1	7.7	1.75	0.0008	0.0010	0.0012	0.0014	0.0017	0.0025	0.0034
1 to <3	12.3	2.88	0.0014	0.0017	0.0020	0.0022	0.0028	0.0042	0.0056
3 to <6	18.3	3.59	0.0017	0.0021	0.0024	0.0028	0.0035	0.0052	0.0070
6 to <11	31.7	4.73	0.0023	0.0027	0.0032	0.0037	0.0046	0.0069	0.0092
11 to <16	55.9	6.03	0.0029	0.0035	0.0041	0.0047	0.0058	0.0088	0.0117
16 to <21	65.9	6.12	0.0029	0.0036	0.0042	0.0047	0.0059	0.0089	0.0119
21 to <30	71.9	6.49	0.0031	0.0038	0.0044	0.0050	0.0063	0.0094	0.0126
30 to <40	74.8	6.08	0.0029	0.0035	0.0041	0.0047	0.0059	0.0088	0.0118
40 to <50	77.1	6.16	0.0029	0.0036	0.0042	0.0048	0.0060	0.0090	0.0119
50 to <60	77.5	6.17	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
60 to <70	76.8	5.67	0.0027	0.0033	0.0038	0.0044	0.0055	0.0082	0.0110
70 to <80	70.8	5.45	0.0026	0.0032	0.0037	0.0042	0.0053	0.0079	0.0106
≥80	64.1	5.19	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0101



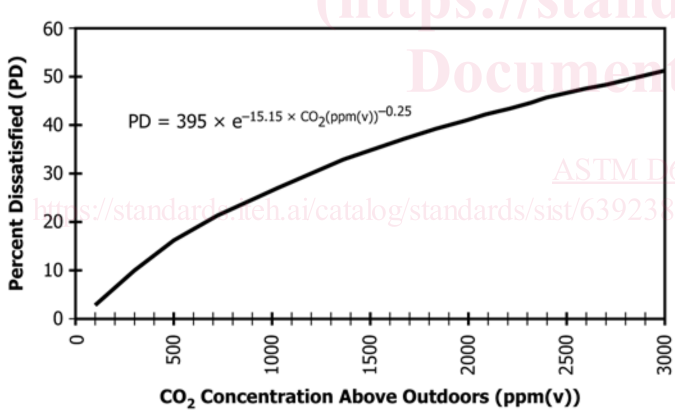
NOTE 1—Each age bin contains box-whisker plots at 1 met, 1.2 met, 1.4 met, 2 met, 3 met, and 4 met. (Based on body size data in (7).)

FIG. 1 Variation in Carbon Dioxide Generation Rate Associated with Age, Body Mass, and Level of Physical Activity for Females



NOTE 1—Each age bin contains box-whisker plots at 1 met, 1.2 met, 1.4 met, 2 met, 3 met, and 4 met. (Based on body size data in (7).)

FIG. 2 Variation in Carbon Dioxide Generation Rate Associated with Age, Body Mass, and Level of Physical Activity for Males.



NOTE 1—This figure applies to spaces where human bioeffluents are the only sensory contaminants in the air.

FIG. 3 Percent of Visitors Dissatisfied as a Function of CO_2 Concentration (13)

7.4 People adapt to bioeffluents over time, and adapted persons (occupants) will find a space acceptable at a higher level of body odor than unadapted persons (visitors). For adapted persons (occupants), the ventilation rate per person to provide the same acceptance is approximately one-third of the value for unadapated persons (visitors), and the corresponding CO_2 concentrations above outdoors are three times higher. While such a reduction in the ventilation rate may result in levels of body odor that are acceptable to adapted persons, the concentrations of other contaminants with indoor sources will increase which may result in poorer indoor air quality.

7.5 The use of CO_2 concentration differences as an indicator of body odor acceptability requires that the outdoor CO_2 concentration be measured. Paragraph 12.4 discusses these measurements.

7.6 The existence of other sources will increase CO_2 concentrations, and these elevated concentrations could be interpreted as a lower level of acceptability in terms of body odor. The existence of removal mechanisms will decrease CO_2 concentrations, and lead to the conclusion that the acceptability in terms of body odor is higher than its actual value. There is no practical way to adjust for the existence of significant sources or removal mechanisms, and therefore, CO_2 concentrations measured in these circumstances can not generally be used as a reliable indicator of body odor acceptability. Situations in which there might be significant indoor CO_2 sources are predominantly restricted to industrial processes. Significant indoor removal can occur when there are large numbers of plants in a building. However, no clear guidance exists on when CO_2 removal by plants is an issue.[6] Nonetheless, the user needs to be aware of the possibilities of indoor CO_2 source and removal mechanisms and avoid the misinterpretation of indoor CO_2 concentrations when these situations exist.

7.7 The use of CO_2 concentrations as an indicator of human body odor is distinct from any health effects associated with the

[6] An indication of the importance of this removal mechanism may be obtained by measuring the indoor concentration after the building has been unoccupied for some period of time. If the concentration is well below the outdoor concentration, then removal may be significant.