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Abstract

Indoor carbon dioxide (CO_2) concentrations have been used for decades to evaluate indoor air quality (IAQ) and ventilation and more recently have factored into discussions of the risk of airborne infectious disease transmission. However, many applications of indoor CO_2 reflect a lack of understanding of the connection between indoor CO_2 concentrations, ventilation and IAQ. In many cases, an indoor concentration of 1000 ppm_v has been used as a metric of IAQ and ventilation without an understanding of its basis or significance. After many attempts to dissuade practitioners and researchers from using this or some other single concentration as a metric of ventilation and IAQ, an approach has been developed to determine a space-specific CO_2 concentration that can be used as an indicator of the outdoor ventilation rate. The concept, as described in this report, is to estimate the CO_2 concentration that would be expected in a specific space given its intended ventilation rate per person, the number of occupants and the rate at which they generate CO_2. A calculation method is described to estimate the CO_2 concentration in a space at selected times after occupancy starts, which provides a more meaningful ventilation metric than a single value for all spaces. An online tool (*QICO2*, Quick Indoor CO_2) has been developed to perform these calculations, and this report contains a User Guide for that tool.

Key Words: carbon dioxide; indoor air quality; metric; standards; ventilation.

Disclaimer

Users are warned that this software is intended for use only by persons competent in the field of particle exposure analysis and is intended only to supplement the judgement of the qualified user. The computer programs described in this report are prototype methodologies for computing particle exposure in buildings. The calculations are based upon a simplified model of the complexity of real buildings. These simplifications must be understood and considered by the user.

1 Introduction

Indoor CO_2 concentrations have been prominent in discussions of ventilation and IAQ since the 18th century, when Lavoisier thought that CO_2 build-up rather than oxygen depletion was responsible for "bad air" indoors [1]. About one hundred years later, von Pettenkofer suggested that biological contaminants from human occupants were causing indoor air problems, not CO_2. Since that time, discussions and research on CO_2 in relation to IAQ and ventilation have focused on the impacts of CO_2 on building occupants, how CO_2 concentrations relate to occupant perception of bioeffluents, and the use of indoor CO_2 to estimate ventilation rates and to control outdoor air ventilation [2, 3].

Indoor CO_2 concentrations are relevant to the outdoor air ventilation rates per person specified in standards, guidelines and building regulations [4-6]. These outdoor air requirements reflect more than 100 years of research, which first focused on the amount of ventilation needed to control odor associated with the byproducts of human metabolism, i.e., bioeffluents [1, 7]. This research found that about 7.5 L/s to 9 L/s per person of ventilation air diluted body odor to levels judged to be acceptable by about 80 % of individuals entering the room from relatively clean air, i.e., unadapted visitors. Some of these experiments also included measurements of CO_2 concentrations, allowing examination of the relationship between CO_2 concentrations and body odor acceptability. These experiments showed that CO_2 concentrations about 700 ppm_v above outdoors corresponded to the same levels of body odor acceptability as found for roughly 8 L/s per person of ventilation. For an outdoor CO_2 concentration of 300 ppm_v, this concentration difference corresponds roughly to the commonly-cited indoor value of 1000 ppm_v. (Note that outdoor concentrations have increased to over 400 ppm_v since these odor acceptability studies were done [8].) This body of research supports 1000 ppm_v of CO_2 as a reflection of body odor acceptability perceived by unadapted visitors to a building. However, there are many important indoor air contaminants that are not associated with the number of occupants, for which CO_2 is not a good indicator.

ASHRAE Standard 62-1981 contained an indoor CO_2 limit of 2500 ppm_v for use when applying the performance approach to complying with the standard, i.e., the Indoor Air Quality Procedure. That limit was changed without explanation to 1000 ppm_v in the 1989 version of the standard. That value has been viewed by many to be a de facto IAQ standard without a sound understanding of its basis as an indicator of body odor acceptability to unadapted building occupants [2, 7]. Reference 2 notes the existence of anecdotal discussions associating CO_2 concentrations in this range with occupant symptoms such as stuffiness and discomfort. While several studies have shown associations of elevated CO_2 concentrations with sick building syndrome symptoms, absenteeism and other effects [9-11], those studies did not control for other contaminants and environmental conditions. Therefore, the observed associations between CO_2 concentrations and symptom rates are more likely due to lower ventilation rates elevating the concentrations of other more important indoor contaminants [3, 12, 13].

Indoor CO_2 concentrations are typically well below values of interest based on health concerns, though recent work has shown evidence of impacts on human performance. Two studies of individuals completing computer-based tests showed statistically significant decreases in decision-making performance at CO_2 concentrations as low as 1000 ppm_v [14, 15]. However, other studies have not shown performance impacts at similar concentrations [16, 17]. Based on the inconsistency of these studies, it is premature to conclusively link CO_2 concentrations in this range with such occupant impacts [3, 12, 18, 19].

While indoor CO_2 is not a comprehensive indicator of IAQ and typical indoor concentrations have not been shown to have significant impacts on occupant health and comfort, this paper proposes using CO_2 as an indicator or metric of outdoor air ventilation rates. As discussed below, indoor CO_2 concentrations depend primarily on the rate at which the occupants generate CO_2, the outdoor air ventilation rate of the space, the time since occupancy began, and the outdoor CO_2 concentration. If these factors are properly accounted for, indoor CO_2 concentrations can serve as meaningful indicators of ventilation. This report describes the use of CO_2 concentrations as a metric of ventilation rates and an online tool, *QICO2* (Quick Indoor CO_2), developed to support these calculations. Note that while indoor CO_2 concentrations have been discussed as an indicator of the risk of airborne infectious disease transmission [20], this discussion and the metric concepts and the *QICO2* tool do not consider infection risks. However, if one has determined a ventilation rate to manage these risks, this metric concept and the online tool can be used to assess whether a space is being ventilated at that risk-based ventilation rate.

2 Theory and Background

The underlying model on which the discussion in this report is based is a single-zone mass balance of a ventilated space. This model is also used in *QICO2*, which is described in the User Guide section of this report. While a single-zone mass balance model is a simplification and will not apply in all buildings and spaces, it is widely used when considering indoor air contaminants. This section also describes the rate at which building occupants generate CO_2 and the ventilation requirements in ASHRAE Standards 62.1 and 62.2, which serve as the basis for the input format of *QICO2*.

2.1 Single Zone Mass Balance

The ventilation metric described in this report employs a single-zone mass balance of CO_2 in the space of interest, which can be expressed as follows:

$$V\frac{dC}{dt} = Q\,(C_{out} - C) + G, \tag{1}$$

where V is the volume of the space being considered (L), C is the CO_2 concentration in the space (ppm_v)[1], C_{out} is the outdoor CO_2 concentration, t is time (s), Q is the volumetric flow of air into the space from outdoors and from the space to the outdoors (L/s), and G is the CO_2 generation rate in the space (L/s). Note that, in general, Q, C_{out} and G are functions of time, but they are assumed to be constant in this discussion. Also, air density differences between indoors and out are ignored by using the same value of Q for the airflow into the space and out. Finally, this single zone formulation ignores concentration differences within the single zone, differences in concentrations between building zones and CO_2 transport between zones. These assumptions are not always valid, which must be considered by users of this analysis approach and *QICO2*.

The solution to Equation 1 can be expressed as follows:

$$C(t) = C(0)e^{-\frac{Q}{V}t} + C_{ss}\left(1 - e^{-\frac{Q}{V}t}\right), \tag{2}$$

where $C(0)$ is the indoor concentration at $t = 0$ and C_{ss} is the steady-state indoor concentration. Note that the indoor concentration will only reach steady-state if conditions, specifically Q and G, are constant for a sufficiently long period of time, which can be many hours depending on the air change rate Q/V. A constant value of G requires that the occupancy and the intensity of

[1] In this work, CO_2 concentrations are expressed in ppm_v rather than using the SI unit of µL/L, which is equivalent.

occupant activity remain constant, but in many spaces occupancy will be too short or too variable for steady-state to be achieved. A convenient means of assessing whether steady-state is likely to be achieved is by considering the time constant of the system, which is equal to the inverse of the air change rate. One can consider that the system is essentially at steady-state after three time constants, at which time the concentration (relative to outdoors) will have reached 95 % of its steady-state value. For example, for a space with an air change rate of 1.0 h^{-1}, steady-state will exist after three hours. For a space with an air change rate of 0.5 h^{-1}, it will take six hours. Assuming steady-state has been achieved, Equation 2 can be solved for C_{ss} as follows:

$$C_{ss} = {}^{G}/_{Q}, \tag{3}$$

If G and Q are both expressed in L/s, the value on the right side of the equation can be multiplied by 10^6 to convert C_{ss} to units of ppm_v.

2.2 CO_2 Generation from Building Occupants

The ventilation and IAQ fields have long used the following equation to estimate CO_2 generation rates from building occupants [21]:

$$V_{CO2} = \frac{0.00276\, A_D\, M\, RQ}{(0.23RQ + 0.77)} \tag{4}$$

where V_{CO2} is the CO_2 generation rate per person (L/s); A_D is the DuBois surface area of the individual (m^2); M is the level of physical activity, sometimes referred to as the metabolic rate or met level (dimensionless); and RQ is the respiratory quotient (dimensionless). The respiratory quotient RQ is the ratio of the volumetric rate at which CO_2 is produced to the rate at which oxygen is consumed.

More recently, an approach to estimating CO_2 generation rates from building occupants based on concepts from the fields of human metabolism and exercise physiology has been described [22]. This approach uses the basal metabolic rate (*BMR*) of the individual of interest, which is the energy needed to sustain the basic functions of human life, including the function of cells, the brain and the cardiac and respiratory systems, as well as the maintenance of body temperature. The *BMR* of an individual is a function of their sex, age and body mass, which when multiplied by their level of physical activity *M*, yields their rate of energy expenditure. The rate of energy expenditure can then be related to oxygen consumption, and then CO_2 generation via the value of *RQ*, which depends primarily on diet. The noted reference provides equations to estimate *BMR* as well as data on met levels for different activities. Assuming *RQ* equals 0.85, the CO_2 generation rate of an individual can be estimated by the following equation:

$$\mathrm{V_{CO2}} = \mathrm{BMR\ M\ ({}^{T}/_{P})\ 0.000179} \tag{5}$$

where T is the air temperature (K) and P is the air pressure (kPa). This updated approach for estimating CO_2 generation rates from individuals offers important advantages. First, Equation 4 is based on a 1981 reference that provides no explanation of its basis, while the new approach is derived using established principles of human metabolism and energy expenditure. Also, the new approach characterizes body size using mass rather than surface area, which in practice is estimated and not measured. Body mass is easily measured, and data on body mass distributions for various populations are readily available [23]. The new approach also explicitly accounts for the sex and age of the individuals being considered, which is not the case with Equation 4. Data on met levels for various activities are available from a number of sources [24-27].

2.3 Ventilation requirements in ASHRAE Standards 62.1 and 62.2

The calculations in this report and *QICO2* use ventilation rates based on ANSI/ASHRAE Standard 62.1 and Standard 62.2, which apply to non-residential and residential buildings respectively [4, 5]. *QICO2* allows for other ventilation requirements to be specified as discussed in the User Guide.

ASHRAE Standard 62.1 contains outdoor air ventilation requirements, which are listed in Table 6.1 under the prescriptive Ventilation Rate Procedure [5]. That table contains minimum ventilation rates in the form of a People Outdoor Air Rate R_p (L/s·person) and an Area Outdoor Air Rate R_a (L/s·m^2) for a number of Occupancy Categories. Those two values are combined to yield the outdoor air requirement to the breathing zone V_{bz} of a space per the following equation:

$$V_{bz}=R_p \times P_z+R_a \times A_z \quad (6)$$

where P_z is the number of people in the zone and A_z (m^2) is the net occupiable floor area of the zone. For example, in the case of Office Space, R_p = 2.5 L/s·person and R_a = 0.3 L/s·m^2. For an office with a floor area of 100 m^2 and an occupancy of 5 individuals, the outdoor air requirement under Standard 62.1 would result in a per person ventilation rate of 8.5 L/s. The standard requires that the breathing zone outdoor airflow be adjusted to account for air distribution in the space to determine the zone outdoor airflow. Zone outdoor airflows are then used to determine the required outdoor air intake at the air handler, with adjustments for multizone recirculating systems and occupant variations over time (referred to as diversity in the standard). Adjustments for zone air distribution, multizone systems and occupant diversity are not considered here.

ASHRAE Standard 62.2 applies to residential occupancies and contains an outdoor air ventilation requirement for a dwelling unit expressed as follows [4]:

$$Q_{tot}=0.15A_{floor}+3.5(N_{br}+1), \quad (7)$$

where Q_{tot} is the total required ventilation rate (L/s), A_{floor} is the floor area (m^2) and N_{br} is the number of bedrooms. The value of Q_{tot} is used in this analysis without any of the adjustments allowed by Standard 62.2, such as a credit for air infiltration. For example, in a house with a floor area of 200 m^2 and 3 bedrooms, the ventilation requirement is 44 L/s.

The adequacy of the minimum outdoor air ventilation requirements in both ASHRAE standards has been debated for decades and those discussions continue. However, these requirements are taken as a given in this discussion and in *QICO2*, which allows the user to specify ventilation rates based on these standards or to input other rates if they prefer.

2.4 Indoor CO_2 Metrics

While a single CO_2 concentration metric that characterizes overall IAQ would be attractive, indoor CO_2 concentrations only reflect occupant exposure to contaminants that are associated with the number of occupants in a space [3]. However, there are many indoor air contaminants that do not correlate with occupancy, such as chemical emissions from building materials and furnishings and contaminants that enter from outdoors. Instead, a CO_2 metric can be used to evaluate outdoor air ventilation rates relative to a design value or a requirement in a standard, but such a metric must be based on the space in question and its occupancy. Relevant space information includes the required outdoor air ventilation rate, geometry (floor area and ceiling height), and the number of occupants and their characteristics that impact the rate at which they generate CO_2 (sex, age, body mass and level of physical activity). This information can then be used to calculate the expected CO_2 concentration at a point in time, and that value can serve as a ventilation metric for a given space. A measured CO_2 concentration that is above the metric value at a given time would indicate that the ventilation rate is below the intended value. Such a space-specific metric has advantages over using a single value for all spaces, such as the often misinterpreted value of 1000 ppm_v.

2.4.1 CO_2 Metric Examples for Commercial Buildings

In order to demonstrate this CO_2 metric approach, indoor CO_2 concentrations were calculated for the space types listed in Table 1, which includes several commercial/institutional building spaces covered by ASHRAE Standard 62.1. (Residential cases are discussed in Section 2.4.2.) All of these cases are included in *QICO2*, but users can modify these cases or create their own. The space types considered were selected from the longer list of commercial/institutional building space types in ASHRAE Standard 62.1. The second column of Table 1 is the occupant density, expressed as number of people per 100 m^2 of floor area (corresponding to the default values in Standard 62.1). The third and fourth columns are the outdoor air ventilation rate in L/s per person and h^{-1} based on Standard 62.1, with the conversion to h^{-1} using a ceiling height of 3 m for all spaces except those identified in the note to the table. The fifth column contains information on the occupants (number, sex, age, body mass and met level) used to calculate their CO_2 generation rates, with the average per person generation rate in the last column. In some cases the number of occupants of a particular type is listed as an integer value plus one-half in order for the total number to match the Standard 62.1 occupant density. Most of the average CO_2 generation rates range from 0.004 L/s to 0.005 L/s per person. Higher values are seen in spaces where the occupants are assumed to be more active, i.e., Public assembly/Lobby and Retail/Sales. The average generation rate in the hotel bedroom is below 0.004 L/s given that the occupants are assumed to be sleeping. The assumptions reflected in Table 1 are not intended to be representative but rather to provide example cases for discussion.

For each space type the time required to achieve steady-state and the steady-state CO_2 concentration were calculated using the assumptions listed in Table 1. These values are presented in the third and fourth columns in Table 2, along with the CO_2 concentration (above the outdoor concentration) that would occur one hour after the space is fully occupied (in the fifth column). A value of t_{metric} is listed for each space type in the second column of the table. This value is the length of time over which the particular space type may be expected to be fully occupied, and the CO_2 concentration at that time is listed in the last column of the table. The values of t_{metric} reflect the judgement of the authors and should not be considered as representative for wide application. Note that for spaces where the occupancy is not expected to be constant long enough for a steady-state concentration to occur, the CO_2 concentration will not have achieved steady-state at t_{metric}. The calculations presented herein assume all of the occupants enter the space at the same time, which is not necessarily the case in an actual building.

Table 1: CO_2 concentration calculations for commercial/institutional buildings

		Outdoor air ventilation			
Space Type	**Occupant density (#/100 m^2)**	**L/s per person**	**h^{-1}**	**Occupants (age, body mass in kg, met level)**	**Average CO_2 generation per person (L/s)**
Classroom (5 to 8 y)	25	7.4	2.2	12 males (8 y, 23 kg, 2 met); 12 females (8 y, 23 kg, 2 met); 1 male (35 y, 85 kg, 3 met)	0.0047
Classroom (>9 y)	35	6.7	2.8	17 males (15 y, 65 kg, 1.7 met); 17 females (15 y, 60 kg, 1.7 met); 1 male (35 y, 85 kg, 2.5 met)	0.0063
Lecture classroom	65	4.3	2.5	32 males (20 y, 80 kg, 1.3 met); 32 females (20 y, 70 kg, 1.3 met); 1 female (35 y, 75 kg, 2 met)	0.0049
Lecture hall (fixed seats)	150	4.0	4.3	74.5 males (20 y, 80 kg, 1.3 met); 74.5 females (20 y, 70 kg, 1.3 met); 1 female (35 y, 75 kg, 2 met)	0.0049
Restaurant dining room	70	5.1	3.2	33 males (35 y, 85 kg, 1.5 met); 33 females (35 y, 75 kg, 1.5 met); 2 males (35 y, 85 kg, 3 met); 2 females (35 y, 75 kg, 3 met)	0.0058
Conference meeting room	50	3.1	1.9	25 males (35 y, 85 kg, 1.4 met); 25 females (35 y, 75 kg, 1.4 met)	0.0051
Hotel/motel bedroom	10	5.5	0.7	1 male (35 y, 85 kg, 1.0 met); 1 female (35 y, 75 kg, 1.0 met)	0.0036
Office space	5	8.5	0.5	2.5 male (35 y, 85 kg, 1.4 met); 2.5 female (35 y, 75 kg, 1.4 met)	0.0051
Public assembly/ Auditorium	150	2.7	1.9	75 males (35 y, 85 kg, 1.3 met); 75 females (35 y, 75 kg, 1.3 met)	0.0047
Public assembly/Lobby	150	2.7	2.9	75 males (35 y, 85 kg, 2 met); 75 females (35 y, 75 kg, 2 met)	0.0073
Retail/Sales	15	7.8	1.1	7.5 male (35 y, 85 kg, 2.5 met); 7.5 female (35 y, 75 kg, 2.5 met)	0.0091

Commercial/Institutional space types, default occupancies and outdoor air ventilation requirements from ASHRAE Standard 62.1-2019; ceiling height assumed to equal 3 m except as follows (Lecture classroom 4 m; Lecture hall with fixed seats 5 m, Restaurant dining room 4 m, Public assembly 7.5 m, Lobby 5 m, and Retail/Sales 4 m).

The time for the CO_2 concentration (relative to outdoors) to reach 95 % of steady-state in Table 2 is linked to the air change rate in Table 1, i.e., it is three times the inverse of that rate. For most of the spaces, the time to steady-state is less than 1.5 h. In those cases, the three calculated CO_2 concentrations are generally within 100 ppm_v of each other, making the timing of a measurement for comparison to a metric value less critical than in other spaces. For spaces with longer times required to achieve steady-state, the three CO_2 concentrations cover a broader range. For such spaces, the concentration after 1 h of occupancy will be a stronger function of time than the values at t_{metric} or at steady-state. Of particular note is the Office space, which takes almost 6 h to reach steady-state due in large part to its low occupant density that leads to a low air change rate. As a result, the three concentrations values are quite different, covering a range of almost 3 to 1. It's unlikely for a typical office space to be at full occupancy for 6 h given lunch schedules and other occupancy variations; therefore, the t_{metric} value of 2 h and the corresponding concentration of about 383 ppm_v above outdoors are more relevant in practice.

Table 2: Calculated CO_2 concentrations for commercial/institutional buildings

Space Type	t_{metric} (h)	Time to steady-state (h)*	CO_2 concentration above outdoors (ppm_v) Steady-state	1 h	t_{metric}
Classroom (5 to 8 y)	2	1.4	631	563	624
Classroom (>9 y)	1	1.1	937	882	882
Lecture classroom	1	1.2	1154	1058	1058
Lecture hall (fixed seats)	1	0.7	1226	1210	1210
Restaurant dining room	1	0.9	1133	1087	1087
Conference meeting room	1	1.6	1642	1386	1386
Hotel/motel bedroom	6	4.5	661	319	648
Office space	2	5.9	599	239	383
Public assembly/ Auditorium	1	1.5	1750	1500	1500
Public assembly/Lobby	1	1.0	2692	2547	2547
Retail/Sales	2	2.9	1165	759	1023

* Time to achieve 95 % of steady-state CO_2 concentration, i.e., three time constants

The use of these concentration-time combinations as metrics of per person ventilation rates requires consideration of occupancy schedules. If the concentration calculation starts as soon as the space contains any occupants, but the actual occupancy increases from unoccupied to the assumed full occupancy over time, the calculated concentration at a given time will be less than it would have been than if the space was fully occupied all at once. Therefore, if the 1 h concentration value is used as a metric, the space could be below this criterion even though it would not be the case over the long term. However, if the concentration calculation is delayed until the space is fully occupied, then the actual concentration increase will have a "head start" on that calculation and may exceed the metric value. This situation would make the metric conservative, i.e., some spaces might "fail" even though they would pass if the space achieved full occupancy at a single instant in time. Note also that if the early occupants are different from the full occupants (in terms of their CO_2 generation rates), it will also complicate application of this approach.

If the space is not at the occupancy level assumed in Table 1, which could be the case for retail or lobby spaces, one could estimate the fraction of the assumed occupancy and reduce the metric value by multiplying by that fractional value. In fact, when applying this metric approach, the actual occupant density should be used instead of the default values from Standard 62.1. Also, it may not be practical to apply these metrics to spaces with particularly transient and short-term occupancies, such as retail and lobbies spaces. Nevertheless, users of this approach need to characterize the space occupancy and the occupancy schedule before applying it.

Application of this CO_2 metric approach requires one to report, at a minimum, the following information: space type, occupant density, time at which full occupancy starts, time of CO_2 concentration measurement, and measured indoor and outdoor CO_2 concentrations. These measurements could then be compared with the values in Table 2, or to space-specific values determined by the user, as an indication of whether the ventilation rate per person complies with the value in Standard 62.1 or some other ventilation requirement of interest.

2.4.2 CO_2 Metric Examples for Residential Buildings

This section extends the concepts discussed above to residential spaces, which can be challenging given the variations in dwelling and family size and in occupant characteristics, as well as the often unpredictable durations of occupancy relative to some commercial and institutional spaces. However, the hours associated with sleep provide helpful options for these analyses in bedrooms. Equation (1) can again be used to calculate the CO_2 concentrations for a given space based on assumptions about the CO_2 generation rates and ventilation rate of the space. This section describes the pre-defined residential cases in *QICO2*, starting with descriptions of the occupancy and the ventilation scenarios covered by these cases followed by information on the two house sizes considered. The calculated concentrations for these residential cases are not presented in this report, but they can be accessed using *QICO2*.

Pre-Defined Families

Three residential occupancies are available in the tool as listed in Table 3: a *Baseline Family* with 4 members (2 adults and 2 children), a *Large Family* with 2 additional children, and a *Small Family* with 2 adults and no children. The sex, age, body mass and level of physical activity are described for each family, including the CO_2 generation rate in L/s for each person and the average generation rate for all of the defined occupants. These generation rates are assumed to exist for the whole house during non-sleeping hours when occupants are assumed to be more active, and for bedrooms when occupants are sleeping.

Table 3: Occupancy assumptions for residential CO_2 calculations

Case	Occupants (age, body mass in kg, met level)	CO_2 generation per person (L/s)	Average CO_2 generation per person (L/s)
Baseline family of 4			
Whole house	1 male (40 y, 85 kg, 1.3 met); 1 female (40 y, 75 kg, 1.3 met); 1 male (6 y, 23 kg, 2 met); 1 female (10 y, 40 kg, 1.7 met)	0.0053 0.0042 0.0045 0.0046	0.0046
Primary Bedroom	1 male (40 y, 85 kg, 1 met); 1 female (40 y, 75 kg, 1 met);	0.0041 0.0032	0.0036
Child Bedrooms	1 male (6 y, 23 kg, 1 met); 1 female (10 y, 40 kg, 1 met)	0.0023 0.0027	0.0025
Additional occupants in larger family of 6			
Whole house	1 male (8 y, 32 kg, 2 met); 1 female (4 y, 14 kg, 2 met)	0.0054 0.0034	0.0046*
Primary Bedroom	No change		0.0036
Child Bedrooms	1 male (8 y, 32 kg, 1 met); 1 female (4 y, 14 kg, 1 met)	0.0027 0.0017	0.0023*
Smaller family of 2 (no children)			
Whole house	Only adults		0.0047
Primary Bedroom	Only adults		0.0036

* Average CO_2 generation rate accounts for all 6 occupants in whole house and all 4 children in child bedrooms.

Ventilation Cases

For each occupancy in Table 3, CO_2 concentrations can be calculated in *QICO2* for the following ventilation scenarios, which are explained below:

Whole house:

- Ventilation rate requirement from ASHRAE Standard 62.2
- Ventilation rate of 0.5 h^{-1}

Bedrooms:

- 62.2/Perfect Distribution: Bedroom ventilation rate is the Standard 62.2 rate divided by the number of house occupants, multiplied by the number of bedroom occupants
- 62.2/Uniform Distribution: Bedroom ventilation rate is the Standard 62.2 rate divided by the whole house floor area, multiplied by the bedroom floor area
- 0.5/Perfect Distribution: Bedroom ventilation rate is 0.5 h^{-1} times the house volume divided by the number of house occupants and then multiplied by the number of occupants in each bedroom
- 0.5/Uniform Distribution: Bedroom ventilation rate is 0.5 h^{-1} times the house volume divided by the whole house floor area, and then multiplied by the bedroom floor area
- 10 L/s per person/Perfect Distribution: Bedroom ventilation rate is 10 L/s multiplied by the number of bedroom occupants

For whole house analysis, predefined cases are provided in *QICO2* based on the ventiation requirements calucated using ASHRAE Standard 62.2 or using a whole house ventilation rate of 0.5 h^{-1}. The four bedroom cases, are based on two idealized air distribution scenarios each being applied to the Standard 62.2 and 0.5 h^{-1} whole house rates. The first distribution scenario, Perfect Distibution is meant to correspond to a ventlation system that supplies outdoor air directly to each bedroom and is calculated by dividing the whole house rate by the number of occupants in the house. That normalized value then is multiplied by the number of occupants in each bedroom to determine the ventilation to each bedroom. Uniform Distribution is provided to represent buildings ventilated by infiltration only, an exhaust-only ventilation system or a mechanical ventilation system that is integrated into a forced-air distribution system. In the Unfiorm Distribution scenario, the whole house rate is divided by the floor area of the house. That normalized value is then multipled by the floor area of each bedroom to determine the outdoor air ventilation provided to each bedroom. Both of these distribution cases are idealized, but they are included to account for the potential impacts of air distribution.The last bedroom ventilation rate, 10 L/s per person/Perfect Distribution, assumes 10 L/s of outdoor air is supplied for each person in each bedroom. That rate is based on ventilation recommendations in CEN [6] and [28].

Pre-Defined Cases in QICO2

Based on the three families and ventilation scenarios just described, Table 4 presents the dimensions (ceiling heights and floor areas) for the two example houses and their bedrooms.

Table 4: House and bedroom sizes

	Ceiling height (m)	House floor area (m^2)	Primary bedroom floor area (m^2)	Child bedrooms floor area (m^2)
Large House	2.74	250	30	20
Small house	2.44	100	20	15

Table 5 lists the pre-defined cases by house size, family size and ventilation scenario, along with ventilation rate information. The second and third columns contain the outdoor air ventilation rate in L/s per person and h^{-1}, and the fourth column is the time required to reach 95 % of the steady-state CO_2 concentration (relative to outdoors), i.e., three times the inverse of the air change rate. Of the four cases with whole house air change rates based on Standard 62.2, three are about 0.3 h^{-1} and the small house/baseline family case is just over 0.4 h^{-1}. The bedroom air change rates cover a range of almost 10 to 1 in the large house/baseline family and the small house/small family cases (and a smaller range in the other two). In these two occupancies, delivering 0.5 h^{-1} directly to the bedrooms under Perfect Distribution results in air change rates above 2 h^{-1} and well over 15 L/s per person. Uniform Distribution to the bedrooms results in less than 5 L/s per person in several cases. These air change rates impact the time required to achieve steady-state, which are 6 h or less for the bedroom cases other than for 62.2/Uniform. For the whole house, the time to 95 % of steady-state is always 6 h for 0.5 h^{-1} and ranges from about 7 h to 11 h for the 62.2 cases.

Table 5: Ventilation rates for the residential cases

	Outdoor air ventilation		Time to steady-state (h)**
Case*	**L/s per person**	**h^{-1}**	
Large House/Baseline family			
Whole house – 62.2	12.9	0.27	11.1
Whole house – 0.5 h^{-1}	23.8	0.50	6.0
62.2/PBR/Perfect	12.9	1.13	2.7
62.2/CBR/Perfect	12.9	0.85	3.5
62.2/PBR/Uniform	3.1	0.27	11.1
62.2/CBR/Uniform	4.1	0.27	11.1
0.5 h^{-1}/PBR/Perfect	23.8	2.08	1.4
0.5 h^{-} CBR/Perfect	23.8	1.56	1.9
0.5 h^{-1}/PBR/Uniform	5.7	0.50	6.0
0.5 h^{-1}/CBR/Uniform	7.6	0.50	6.0
10 L/s per person/PBR/Perfect	10.0	0.88	3.4
10 L/s per person/CBR/Perfect	10.0	0.66	4.6
Large House/Large family			
Whole house – 62.2	9.8	0.31	9.8
Whole house – 0.5 h^{-1}	15.9	0.50	6.0
62.2/PBR/Perfect	9.8	0.85	3.5
62.2/CBR/Perfect	9.8	0.64	4.7
62.2/PBR/Uniform	3.5	0.31	9.8
62.2/CBR/Uniform	4.7	0.31	9.8
0.5 h^{-1}/PBR/Perfect	15.9	1.39	2.2
0.5 h^{-} CBR/Perfect	15.9	1.04	2.9
0.5 h^{-1}/PBR/Uniform	5.7	0.50	6.0
0.5 h^{-1}/CBR/Uniform	7.6	0.50	6.0
10 L/s per person/PBR/Perfect	10.0	0.88	3.4
10 L/s per person/CBR/Perfect	10.0	0.66	4.6
Small House/Baseline family			
Whole house – 62.2	7.3	0.43	7.0
Whole house – 0.5 h^{-1}	8.5	0.50	6.0
62.2/PBR/Perfect	7.3	1.07	2.8
62.2/CBR/Perfect	7.3	0.71	4.2
62.2/PBR/Uniform	2.9	0.43	7.0
62.2/CBR/Uniform	4.4	0.43	7.0
0.5 h^{-1}/PBR/Perfect	8.5	1.25	2.4
0.5 h^{-} CBR/Perfect	8.5	0.83	3.6
0.5 h^{-1}/PBR/Uniform	3.4	0.50	6.0
0.5 h^{-1}/CBR/Uniform	5.1	0.50	6.0
10 L/s per person/PBR/Perfect	10.0	1.48	2.0
10 L/s per person/CBR/Perfect	10.0	0.98	3.1
Small House/Small family			
Whole house – 62.2	11.0	0.32	9.2
Whole house – 0.5 h^{-1}	16.9	0.50	6.0
62.2/PBR/Perfect	11.0	1.62	1.8
62.2/PBR/Uniform	2.2	0.32	9.2
0.5 h^{-1}/PBR/Perfect	16.9	2.50	1.2
0.5 h^{-1}/PBR/Uniform	3.4	0.50	6.0
10 L/s per person/PBR/Perfect	10.0	1.45	2.0

* PBR and CBR stand for Primary bedroom and child bedroom, respectively.
** Time to achieve 95 % of steady-state CO_2 concentration, i.e., three time constants

3 On-Line Tool *QICO2*

This section describes the online tool *QICO2* for implementing the CO_2 concentration calculations just described. Section 0 contains a User Guide that presents the specific inputs and outputs of *QICO2* ,which is available at https://pages.nist.gov/CONTAM-apps/webapps/CO2Tool/#/. *QICO2* implements contaminant calculations that are similar to the more general CONTAM airflow and contaminant transport model for multizone building systems, but they are simplified in this single zone application for which ventilation rates are an input [29]. After providing the required inputs, or selecting one of the predefined cases, *QICO2* allows the user to estimate indoor CO_2 concentrations in a ventilated space at steady-state, 1 h after occupancy and at a selected value of t_{metric}. These calculated concentrations can be compared with measured CO_2 concentrations in a building or space to evaluate whether the intended or required ventilation rate is actually being achieved.

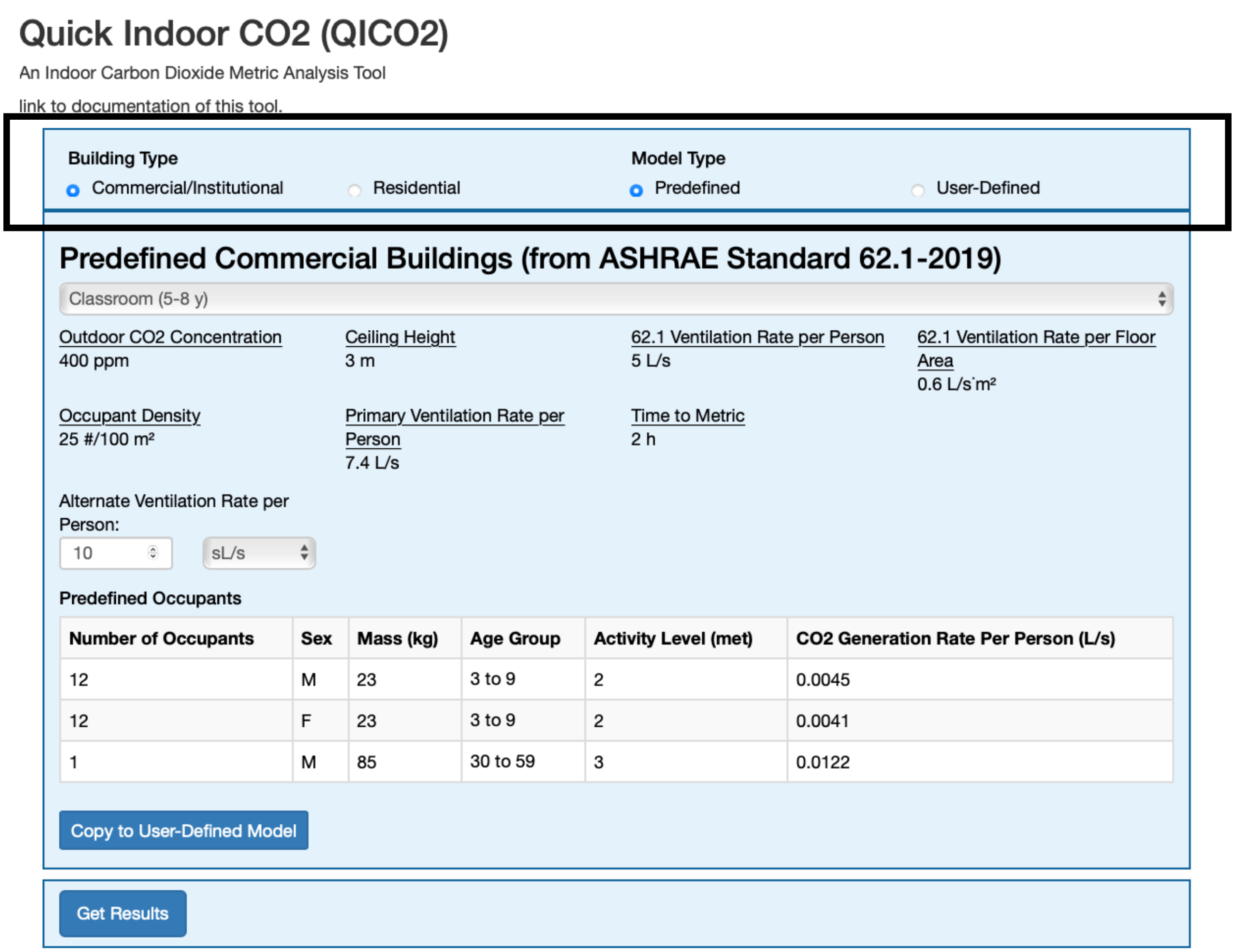


Figure 1: QICO2 Interface (Opening Screen for Commercial Buildings)

Figure 1 shows the first screen encountered when using the tool, where the user selects whether to analyze a commercial/institutional building or a residential building and whether to use a predefined case or to define their own (using the selections within the outlined box). For commercial/institutional buildings, the default case shown in Figure 1, the tool allows the user to choose from several predefined cases selected from the commercial and institutional space types listed in ASHRAE Standard 62.1-2019. The predefined cases use the default values in the standard for outdoor ventilation requirements and occupant density, i.e., number of occupants per 100 m^2 of floor area. The tool makes assumptions about the occupants in each space, i.e., sex, body mass, age and activity level in met, needed to calculate the CO_2 generation rate in the space based on Persily and de Jonge [22]. These assumptions can be modified by selecting User-Defined under Model Type, which brings up an alternative input screen shown in Figure 2. If desired, an Alternate Ventilation Rate per Person can be input to allow comparison of the results to those obtained with the Primary ventilation rate.

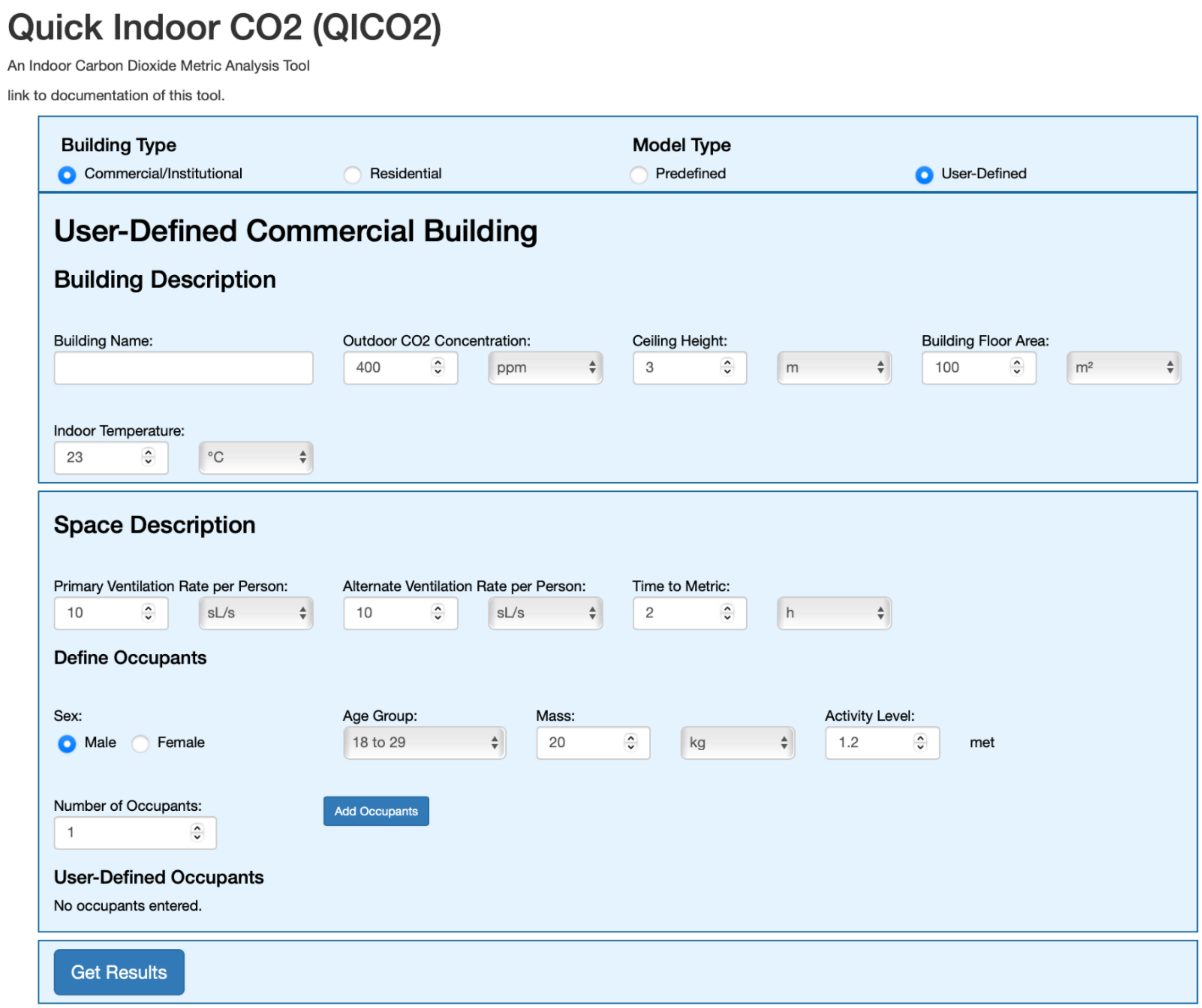


Figure 2: QICO2 Interface (Used-Defined Case for Commercial Buildings)

The residential building input screen is shown in Figure 3, where users can select a predefined case from those listed in Table 5 of this report for either a whole building or a bedroom analysis. Predefined cases exist for whole buildings that use the ventilation requirement in Standard 62.2-2019 or an air change rate of 0.5 h^{-1}. To analyze a bedroom case, users need to select a ventilation requirement from Standard 62.2, 0.5 h^{-1} or 10 L/s per person. (Note that QICO2 displays volumetric airflow rates as sLs, i.e., L/s under standard conditions, based on its use of the CONTAM approaches to unit conversion and display.) Predefined cases exist for Primary and Child bedrooms. The user also needs to define the air distribution as Perfect or Uniform as described above. Under Perfect Distribution, they have the option of having some of the ventilation air bypass the bedrooms entirely, to account for supply vents in other portions of the house. An Alternate Ventilation Rate per Person input can also be input to enable comparison of the results with those based on the Primary ventilation rate.

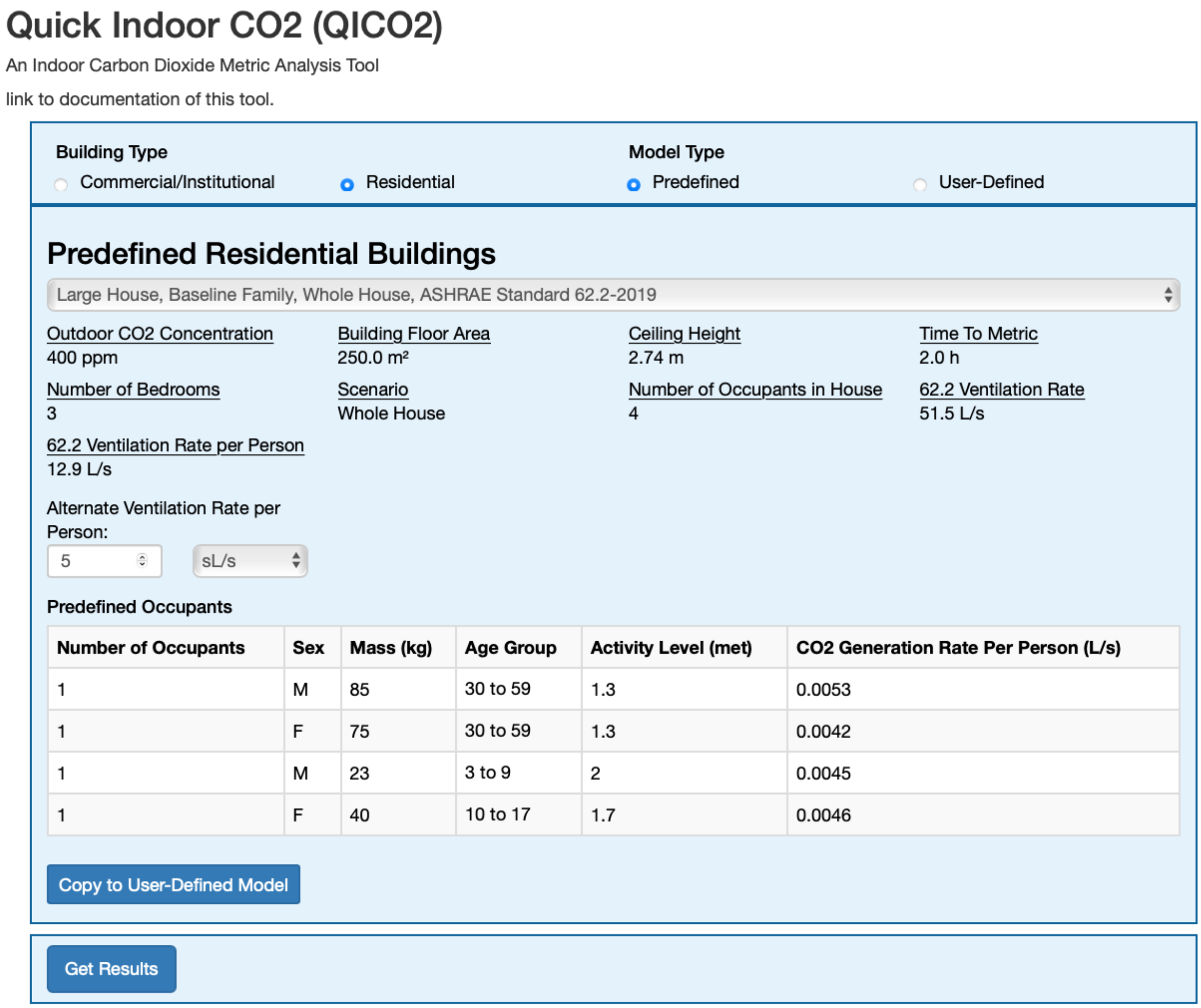
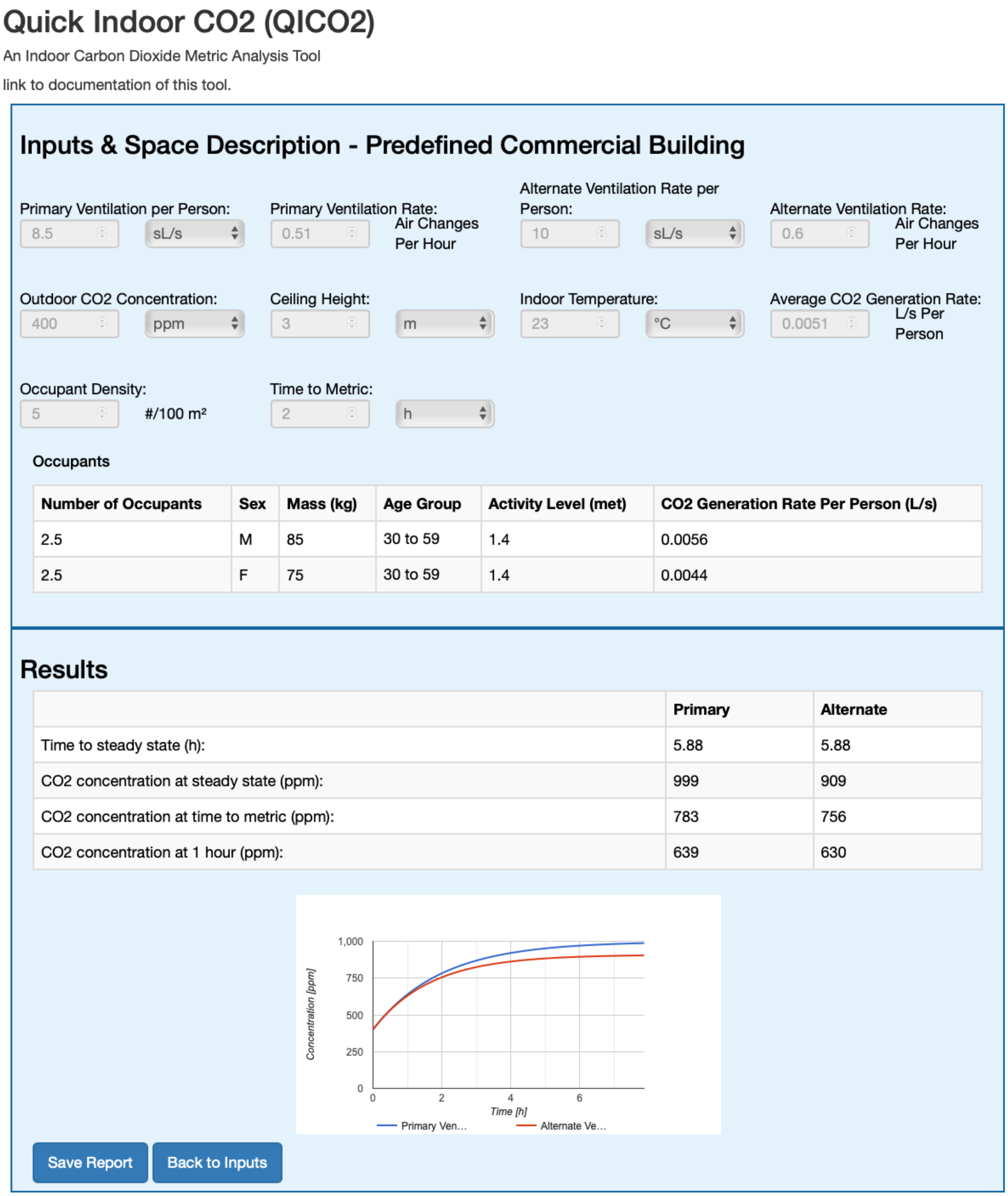


Figure 3: QICO2 Interface (Inputs for Residential Buildings)

Once the user has completed the inputs, selecting Get Results on the bottom of the Inputs page brings up the Results screen shown in Figure 4. The Results screen summarizes the inputs and displays a plot of the indoor CO_2 concentration versus time and a table of the concentration values at steady-state, t_{metric} and 1 h after occupancy for both the Primary and Alternate ventilation rates.



Quick Indoor CO2 (QICO2)

An Indoor Carbon Dioxide Metric Analysis Tool

link to documentation of this tool.

Inputs & Space Description - Predefined Commercial Building

Primary Ventilation per Person: 8.5 sL/s
Primary Ventilation Rate: 0.51 Air Changes Per Hour
Alternate Ventilation Rate per Person: 10 sL/s
Alternate Ventilation Rate: 0.6 Air Changes Per Hour

Outdoor CO2 Concentration: 400 ppm
Ceiling Height: 3 m
Indoor Temperature: 23 °C
Average CO2 Generation Rate: 0.0051 L/s Per Person

Occupant Density: 5 #/100 m²
Time to Metric: 2 h

Occupants

Number of Occupants	Sex	Mass (kg)	Age Group	Activity Level (met)	CO2 Generation Rate Per Person (L/s)
2.5	M	85	30 to 59	1.4	0.0056
2.5	F	75	30 to 59	1.4	0.0044

Results

	Primary	Alternate
Time to steady state (h):	5.88	5.88
CO2 concentration at steady state (ppm):	999	909
CO2 concentration at time to metric (ppm):	783	756
CO2 concentration at 1 hour (ppm):	639	630

Figure 4: QICO2 Interface (Results)

The tool can be applied by comparing the calculated CO_2 concentrations to measured values, with a measured value that is higher serving as an indication that the actual ventilation rate is below the assumed or desired ventilation rate. For comparisons with a calculated whole house value, the measured CO_2 concentration should be a volume-weighted, whole house average based on the concentrations measured in each room. Since the calculations assume constant occupancy, the measurement needs to occur while occupancy is constant, which can be limited in duration. Ideally, a constant occupancy period that lasts for t_{metric} occurs for the building or space being considered, and the calculated value at that time will then provide a more reliable ventilation indicator. If constant occupancy does not last that long, the t_{metric} value in the calculator can be modified.

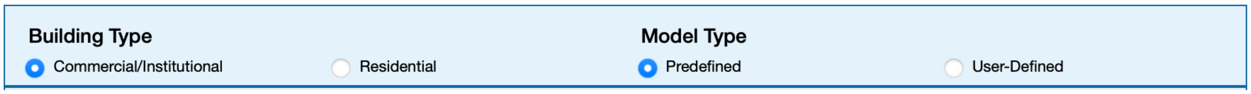
In the case of bedrooms, the calculated CO_2 concentrations can again be compared to measured values in the bedroom. Given the more stable bedroom occupancy during sleeping, that comparison should occur several hours after the bedroom is occupied for sleeping. The tool has a default value of t_{metric} for bedrooms of 6 h, which should work well for comparing the concentrations. In making these comparisons, a measured CO_2 concentration that is higher serves as an indication that the actual ventilation rate is below the assumed or desired ventilation rate. Note that these comparisons neglect the impact of interzone transport on the bedroom CO_2 concentration, which will be impacted by factors such as operation of central HVAC systems, open bedroom doors, and transfer grilles in doors and other interior partitions. Also, the calculation assumes that the bedroom CO_2 concentration starts at the outdoor concentration. However, the initial concentration in the bedroom may be higher than outdoors due to previous occupancy of the house, in which case the calculated concentration will be lower than it would if the actual initial concentration were considered. This situation would result in the calculated metric value being conservative, meaning it would lead to a conclusion that the ventilation rate is lower than it may actually be.

4 *QICO2* User Guide

This section of the report serves as a User Guide for *QICO2*, providing detailed explanations of the inputs and outputs.

4.1 Inputs

In the upper box of the opening screen, the user selects both the Building Type and the Model Type as shown below:



Building Type

Commercial/Institutional: Selecting this Building Type causes the remaining inputs to be consistent with the format of the ventilation requirements in ASHRAE Standard 62.1 as described in Section 2.3 of this report. It also makes available the Predefined Commercial Buildings with selected Occupancy Categories drawn from the standard and based on the examples described earlier in this report.

Residential: Selecting this Building Type populates the Predefined Residential Buildings with selected residential scenarios drawn from the example cases described earlier in this report with whole house ventilation rates using the ventilation requirements in ASHRAE Standard 62.2 or 0.5 air changes per hour, as well as 10 L/s per person for the bedroom cases.

Model Type

Predefined: Selecting this Model Type allows the user to select from a list of predefined building types for the Commercial/Institutional Building case or for the Residential Building case.

User-Defined: Selecting this Model Type allows the user to define the space, its ventilation requirements and its occupants as they see fit. These inputs can be generated starting from a Predefined Case by clicking Copy to User-Defined Model at the bottom of the Predefined input screen, which will switch the tool to the User-Defined Commercial Building or Residential Building mode depending on the selected Building Type. The user can then modify the copied inputs.

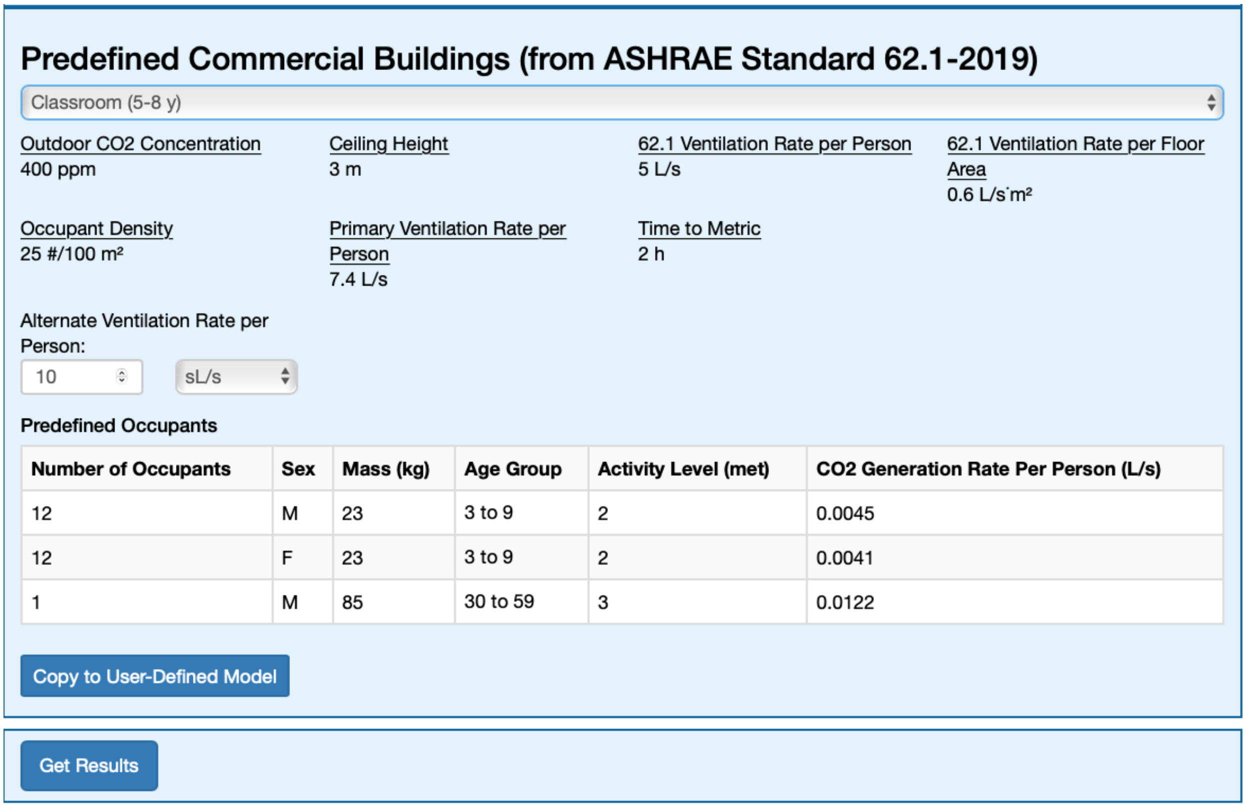
Commercial/Institutional Buildings

Predefined: The user can select from a list of 11 predefined options based on ASHRAE 62.1-2019 as described in Table 1 of this report:

Classroom (5 to 8 y)
Classroom (>9 y)
Lecture Classroom
Lecture Hall (fixed seats)
Restaurant Dining Room
Conference Room
Hotel/Motel Bedroom
Office Space
Public Assembly/Auditorium
Public Assembly/Lobby
Retail/Sales

In each case, the rest of the input screen (shown below for the Classroom (5 to 8 y) is populated with values of the ventilation requirements and default occupant density from ASHRAE

Standard 62.1-2019, various other inputs and the occupant characteristics needed to calculate the CO_2 generation rate in the space. The predefined cases use an air temperature of 23 °C to calculate the CO_2 emission rates from the occupants. If users want to change this value, this can be done via a user-defined case.



Specifically, each predefined case is defined by the inputs listed below:

Outdoor CO_2 Concentration: 400 ppm_v default.

Ceiling Height: 3 m default.

62.1 Ventilation Rate per Person (L/s•m^2): Depends on predefined case selected.

62.1 Ventilation Rate per Floor Area (L/s•m^2): Depends on predefined case selected.

Floor area (m^2): 100 m^2 default.

62.1 Occupant Density (# per 100 m2): Depends on predefined case selected. This value times the floor area equals the number of predefined occupants that are defined under Predefined Occupants in this window.

Ventilation Rate per Person (L/s•person): The total outdoor air ventilation requirement per Standard 62.1 based on the number of occupants and the floor area (as presented in Equation 6). Depends on predefined case selected.

Time to Metric (h): Length of time over which the particular space type may be expected to be fully occupied. Depends on predefined case selected.

Alternate Ventilation Rate per Person (L/s•person)**:** User input to compare results to those of the predefined case. 10 L/s default.

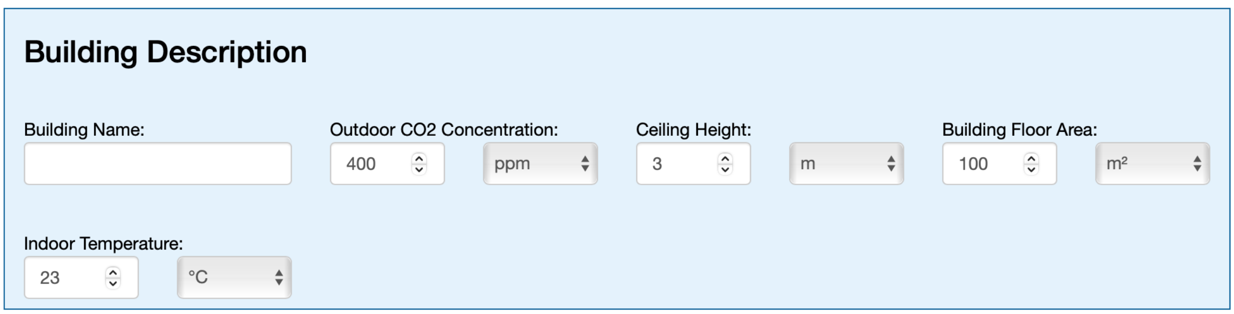
Predefined Occupants*:** Depends on predefined case selected. For each case, there is one row for each type of occupant that includes the ***Number of Occupants, their ***Sex***, their ***Mass*** in kg, their ***Age Group*** and their ***Activity Level*** in met. The Age Group options are based on the ranges in Persily and DeJonge [22], which uses correlations from the literature to estimate *BMR* in the following age ranges: <3 y; 3 to 10 y; 10 to 18 y; 18 to 30 y; 30 to 60 y; and >60y. For each row of occupant types, the ***CO_2 Generation Rate Per Person*** in L/s is displayed to the right of the ***Activity Level***.

As noted above, the user can select Copy to User-Defined Model to copy the inputs for the Predefined case into a User-Defined case and then to modify the inputs to match their space of interest. The user can then select Get Results to access the results page.

User-Defined: If instead of using one of the Predefined cases, the user prefers to define their own case, they need to provide the inputs described below. Alternatively, the user has the option of starting with a Predefined case and copying those inputs into a User-Defined case and proceeding to modify them.

Building Description

The user must provide the Building inputs shown below and described as follows.



Building Name: A text string for the convenience of the user.

Outdoor CO_2 Concentration: 400 ppm_v default.

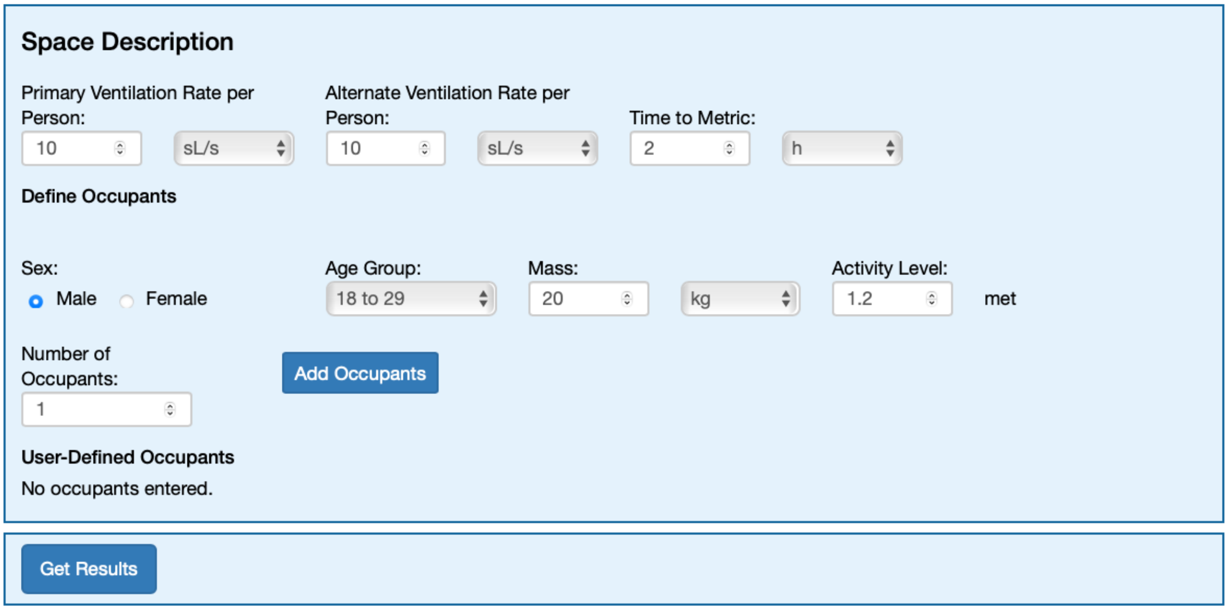
Ceiling Height: 3 m default.

Building Floor Area: 100 m^2 default.

Indoor Temperature: 23 °C default.

Space Description

The user must select the Space inputs shown in the screen below.



Primary Ventilation Rate per Person: 10 L/s default, unless the User-Defined case is pre-populated from a Predefined case with a different value.

Alternate Ventilation Rate per Person: 10 L/s default, unless the User-Defined case is pre-populated from a Predefined case with a different value.

Time to Metric (h): Length of time over which the particular space type may be expected to be fully occupied. 2 h default, unless the User-Defined case is pre-populated from a Predefined case with a different value.

User-Defined Occupants**:** There is one row for each type of occupant that includes the ***Number of Occupants***, their ***Sex***, their ***Mass*** in kg, their ***Age Group*** and their ***Activity Level*** in met. The Age Group options are based on the ranges in Persily and DeJonge [22], which uses correlations from the literature to estimate *BMR* in the following age ranges: <3 y; 3 to 10 y; 10 to 18 y; 18 to 30 y; 30 to 60 y; and >60y. For each row of occupant types, the ***CO_2 Generation Rate Per Person*** in L/s is displayed to the right of the ***Activity Level***.

The user can add additional occupants by selecting [Add Occupants] and then entering the Number, Sex, Mass, Age Group and Activity Level. The user can select [Remove these occupants] to delete previously defined occupants from the summary list.

Residential Buildings

Predefined: The user can select from the 43 options listed in Table 5 of this report.

Large House, Baseline Family, Whole House, ASHRAE Standard 62.2-2019
Large House, Baseline Family, Whole House, 0.5 Air Changes per Hour
Large House, Large Family, Whole House, ASHRAE Standard 62.2-2019
Large House, Large Family, Whole House, 0.5 Air Changes per Hour
Small House, Baseline Family, Whole House, ASHRAE Standard 62.2-2019
Small House, Baseline Family, Whole House, 0.5 Air Changes per Hour
Small House, Small Family, Whole House, ASHRAE Standard 62.2-2019
Small House, Small Family, Whole House, 0.5 Air Changes per Hour

Large House, Baseline Family, Primary Bedroom, ASHRAE Standard 62.2-2019 Perfect Distribution
Large House, Baseline Family, Child Bedroom, ASHRAE Standard 62.2-2019 Perfect Distribution
Large House, Baseline Family, Primary Bedroom, ASHRAE Standard 62.2-2019 Uniform Distribution
Large House, Baseline Family, Child Bedroom, ASHRAE Standard 62.2-2019 Uniform Distribution
Large House, Baseline Family, Primary Bedroom, 0.5 Air Changes per Hour Perfect Distribution
Large House, Baseline Family, Child Bedroom, 0.5 Air Changes per Hour Perfect Distribution
Large House, Baseline Family, Primary Bedroom, 0.5 Air Changes per Hour Uniform Distribution
Large House, Baseline Family, Child Bedroom, 0.5 Air Changes per Hour Uniform Distribution
Large House, Baseline Family, Primary Bedroom, 10 L/s per person
Large House, Baseline Family, Child Bedroom, 10 L/s per person

Large House, Large Family, Primary Bedroom, ASHRAE Standard 62.2-2019 Perfect Distribution
Large House, Large Family, Child Bedroom, ASHRAE Standard 62.2-2019 Perfect Distribution
Large House, Large Family, Primary Bedroom, ASHRAE Standard 62.2-2019 Uniform Distribution
Large House, Large Family, Child Bedroom, ASHRAE Standard 62.2-2019 Uniform Distribution
Large House, Large Family, Primary Bedroom, 0.5 Air Changes per Hour Perfect Distribution
Large House, Large Family, Child Bedroom, 0.5 Air Changes per Hour Perfect Distribution
Large House, Large Family, Primary Bedroom, 0.5 Air Changes per Hour Uniform Distribution
Large House, Large Family, Child Bedroom, 0.5 Air Changes per Hour Uniform Distribution
Large House, Large Family, Primary Bedroom, 10 L/s per person
Large House, Large Family, Child Bedroom, 10 L/s per person

Small House, Baseline Family, Primary Bedroom, ASHRAE Standard 62.2-2019 Perfect Distribution
Small House, Baseline Family, Child Bedroom, ASHRAE Standard 62.2-2019 Perfect Distribution
Small House, Baseline Family, Primary Bedroom, ASHRAE Standard 62.2-2019 Uniform Distribution
Small House, Baseline Family, Child Bedroom, ASHRAE Standard 62.2-2019 Uniform Distribution
Small House, Baseline Family, Primary Bedroom, 0.5 Air Changes per Hour Perfect Distribution
Small House, Baseline Family, Child Bedroom, 0.5 Air Changes per Hour Perfect Distribution
Small House, Baseline Family, Primary Bedroom, 0.5 Air Changes per Hour Uniform Distribution
Small House, Baseline Family, Child Bedroom, 0.5 Air Changes per Hour Uniform Distribution
Small House, Baseline Family, Primary Bedroom, 10 L/s per person
Small House, Baseline Family, Child Bedroom, 10 L/s per person

Small House, Small Family, Primary Bedroom, ASHRAE Standard 62.2-2019 Perfect Distribution
Small House, Small Family, Primary Bedroom, ASHRAE Standard 62.2-2019 Uniform Distribution
Small House, Small Family, Primary Bedroom, 0.5 Air Changes per Hour Perfect Distribution
Small House, Small Family, Primary Bedroom, 0.5 Air Changes per Hour Uniform Distribution
Small House, Small Family, Primary Bedroom, 10 L/s per person

In each case, the rest of the input screen (shown below for Large House, Baseline Family, Whole House, ASHRAE 62.2-219) is populated with values of the ventilation requirements from

ASHRAE Standard 62.2-2019, various other inputs and the occupant characteristics needed to calculate the CO_2 generation rate in the space. The predefined cases use an air temperature of 23 °C to calculate the CO_2 emission rates from the occupants. If users want to change this value, this can be done via a user-defined case.

Predefined Residential Buildings

Large House, Baseline Family, Whole House, ASHRAE Standard 62.2-2019

Outdoor CO2 Concentration: 400 ppm
Building Floor Area: 250.0 m²
Ceiling Height: 2.74 m
Time To Metric: 2.0 h
Number of Bedrooms: 3
Scenario: Whole House
Number of Occupants in House: 4
62.2 Ventilation Rate: 51.5 L/s
62.2 Ventilation Rate per Person: 12.9 L/s

Alternate Ventilation Rate per Person: 5 sL/s

Predefined Occupants

Number of Occupants	Sex	Mass (kg)	Age Group	Activity Level (met)	CO2 Generation Rate Per Person (L/s)
1	M	85	30 to 59	1.3	0.0053
1	F	75	30 to 59	1.3	0.0042
1	M	23	3 to 9	2	0.0045
1	F	40	10 to 17	1.7	0.0046

Copy to User-Defined Model

Get Results

Specifically, each predefined case is defined by the inputs listed below:

Outdoor CO_2 Concentration: 400 ppm_v default.

Building Floor Area (m^2): Depends on predefined case selected.

Ceiling Height (m): Depends on predefined case selected.

Time to Metric (h): Length of time over which the particular space type may be expected to be fully occupied. Default of 2 h for whole house analysis and 6 h for bedrooms.

Number of Bedrooms: Depends on predefined case selected.

Scenario: Whole House or Bedroom, depends on predefined case selected.

Number of Occupants in House: Depends on predefined case selected.

62.2 Ventilation Rate (L/s): The total outdoor air ventilation requirement for the whole house per Standard 62.2 based on the number of bedrooms and the floor area if the predefined case uses Standard 62.2. If the Predefined case uses 0.5 Air Changes per Hour, this field changes to Air Changes per Hour.

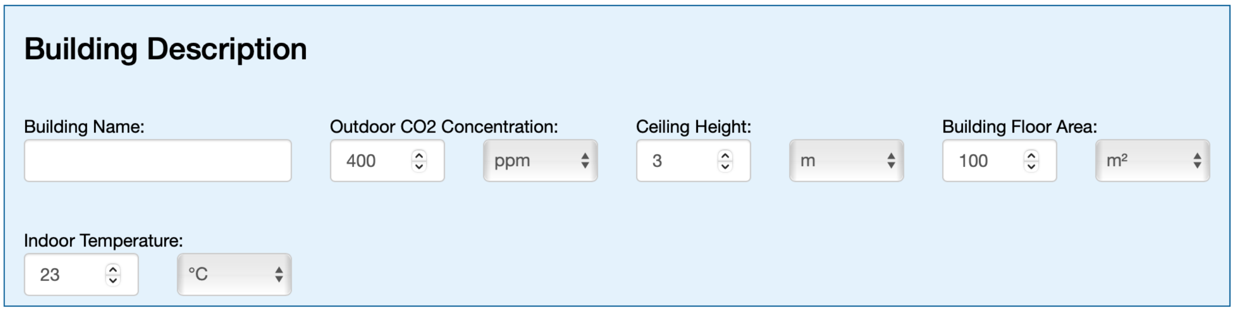
Primary Ventilation Rate per Person (L/s•person): The whole building ventilation rate divided by the Number of Occupants.

Alternate Ventilation Rate per Person (L/s•person)**:** User input to compare results to the those of the predefined case. 5 L/s default.

The user can select Copy to User-Defined Model to copy the inputs for the Predefined case into a User-Defined case and then modify the inputs to better match their space of interest. The user can then select Get Results to move to the results page.

User-Defined: If instead of selecting from the Predefined cases, the user prefers to define their own case, they need to provide the inputs described below. Alternatively, the user has the option of starting with a Predefined case and copying those inputs into a User-Defined case and proceeding to modify them.

Building Description
The user must provide the Building inputs shown below and described as follows.



Building Name: A text string for the convenience of the user.

Outdoor CO_2 Concentration: 400 ppm_v default.

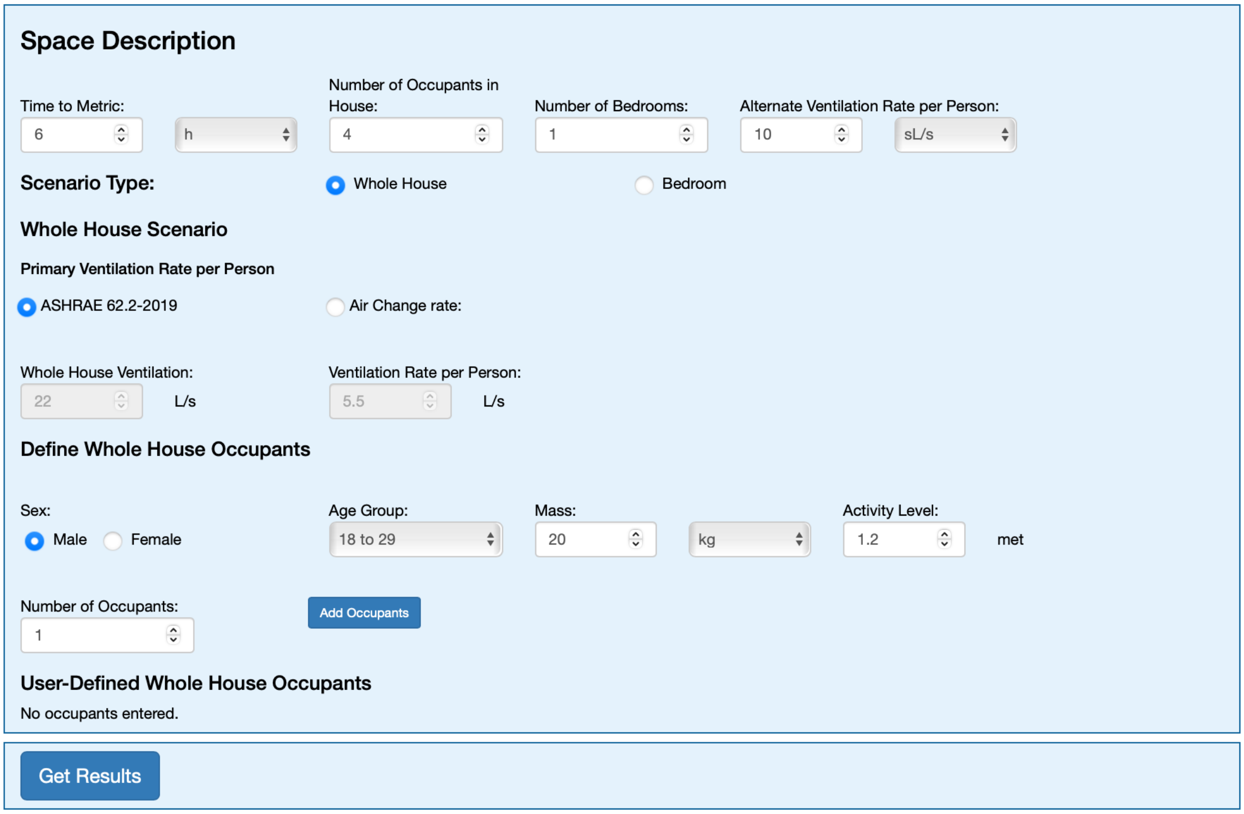
Ceiling Height: 3 m default.

Building Floor Area: 100 m^2 default.

Indoor Temperature: 23 °C default.

Space Description
The user-defined entries under Space Description depend on whether one is analyzing a Whole House or a Bedroom.

Space Description – Whole House
If the user selects Whole House, the following screen appears.



Time to Metric (h): Length of time over which the particular space type may be expected to be fully occupied. 6 h default for Whole House cases.

Number of Occupants: 4 default.

Number of Bedrooms: 1 default.

Scenario: Whole House.

Alternate Ventilation Rate per Person: 10 L/s per person default.

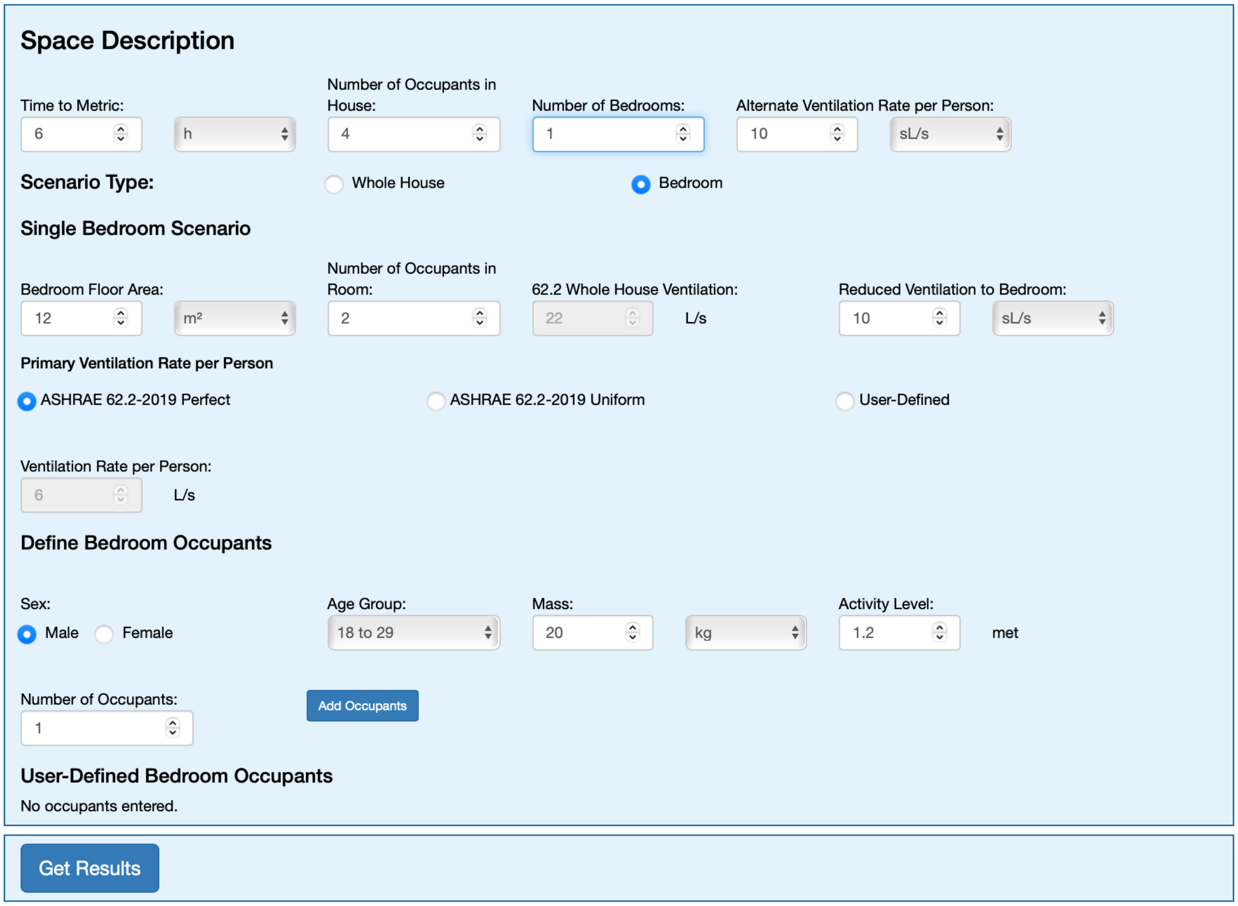
Primary Ventilation Rate per Person: The user must select either ASHRAE 62.2-2019 or Air change Rate. If the former, the Whole House Ventilation Rate in L/s and the Ventilation Rate per person in L/s will be calculated from the Number of Occupants and the Number of Bedrooms per the requirements of the standard. If Air Change Rate is selected, the user enters the air change rate in unit of h^{-1}, with the default being 0.5 h^{-1}. The tool then calculates the Ventilation Rate per Person.

User-Defined Occupants**:** The user must define ***Number of Occupants***, their ***Sex***, their ***Mass*** in kg, their ***Age Group*** and their ***Activity Level*** in met. The Age Group options are based on the ranges in Persily and DeJonge [22], which uses correlations from the literature to estimate *BMR* in the following age ranges: <3 y; 3 to 9 y; 10 to 17 y; 18 to 29 y; 30 to 59 y; and >= 60 y. The default is a single occupant: male, 18 to 29 y, 20 kg and 1.2 met. The total number of user-defined occupants must equal the ***Number of Occupants*** entered earlier. If not, the tool will display a warning of this error when the user attempts to Get Results and will not proceed until the numbers match.

After defining each type of occupant, the user selects Add Occupants to add them to the list of User-Defined Whole House Occupants. By selecting Remove these occupants, the user can delete previously defined occupants from the summary list.

Space Description – Bedroom

If the user selects Bedroom under Space Description, the following screen appears.



The user must first enter the following parameters for the whole house:

Time to Metric (h): Length of time over which the particular space type may be expected to be fully occupied. 6 h default.

Number of Occupants: 4 default.

Number of Bedrooms: 1 default.

Scenario: Bedroom.

Alternate Ventilation Rate per Person: 10 L/s per person default.

The user then enters the following parameters for the bedroom being considered:

Bedroom Floor Area: 12 m^2 default.

Number of Occupants in Bedroom: 2 default.

Reduced Ventilation to Bedroom: 10 L/s default. This value accounts for ventilation system supply air that is not provided to the bedrooms.

Primary Ventilation Rate per Person: The user selects either ASHRAE 62.2-2019 Perfect, ASHRAE 62.2-2019 Uniform, or User-Defined.

If they select ASHRAE 62.2-2019 Perfect, then bedroom ventilation rate is equal to the Standard 62.2 ventilation rate determined from the whole house floor area and total number of bedrooms multiplied by the ratio of the number of occupants in the bedroom to the number of occupants in the whole house (as discussed earlier in this report). In this case, the user can reduce the total ventilation rate by a specified amount (Reduced Ventilation to Bedrooms) to account for supply ventilation provided to other portions of the house other than the bedrooms.

If they select ASHRAE 62.2-2019 Uniform, then bedroom ventilation rate is equal to the Standard 62.2 ventilation rate multiplied by the ratio of the bedroom floor area to the whole house floor area (also discussed earlier in this report).

If they select User-Defined former, they enter the L/s per person, with a default value of 10 L/s.

User-Defined Occupants*:** The user must define ***Number of Occupants, their ***Sex***, their ***Mass*** in kg, their ***Age Group*** and their ***Activity Level*** in met. The Age Group options are based on the ranges in Persily and DeJonge [22], which uses correlations from the literature to estimate *BMR* in the following age ranges: <3 y; 3 to 9 y; 10 to 17 y; 18 to 29 y; 30 to 59 y; and >= 60 y. The default is a single occupant: male, 18 to 29 y, 20 kg and 1.2 met.

After defining each type of occupant, the user selects Add Occupants to add them to the list of User-Defined Whole House Occupants. By selecting Remove these occupants , the user can delete previously defined occupants from the summary list.

4.2 Outputs

As noted above, the user can select the Get Results button from any of the input screens, at which point the tool performs its calculation for the defined inputs. Once the Results button is clicked, the Results screen is displayed as shown below. The Results screen contains a greyed-out summary of the inputs for the case, with the results themselves shown in the lower portion of the Results screen. The Results include a table of the Time to steady state (h) and the calculated CO_2 concentrations (ppm) at steady-state, time to metric and 1 hour for both the Primary and Alternative ventilation rate. Note that *QICO2* displays concentrations in the Results as ppm rather than ppm_v as used earlier in this report. The CO_2 concentrations are also plotted against time for those two ventilation rates.

Quick Indoor CO2 (QICO2)

An Indoor Carbon Dioxide Metric Analysis Tool

link to documentation of this tool.

Inputs & Space Description - Predefined Commercial Building

Primary Ventilation per Person: 8.5 sL/s

Primary Ventilation Rate: 0.51 Air Changes Per Hour

Alternate Ventilation Rate per Person: 10 sL/s

Alternate Ventilation Rate: 0.6 Air Changes Per Hour

Outdoor CO2 Concentration: 400 ppm

Ceiling Height: 3 m

Indoor Temperature: 23 °C

Average CO2 Generation Rate: 0.0051 L/s Per Person

Occupant Density: 5 #/100 m²

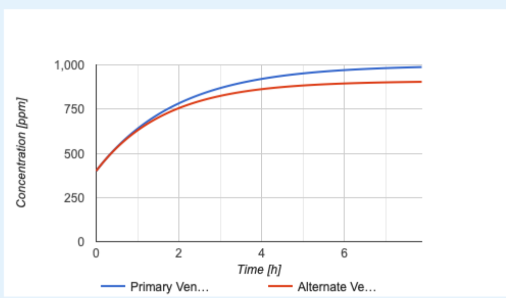
Time to Metric: 2 h

Occupants

Number of Occupants	Sex	Mass (kg)	Age Group	Activity Level (met)	CO2 Generation Rate Per Person (L/s)
2.5	M	85	30 to 59	1.4	0.0056
2.5	F	75	30 to 59	1.4	0.0044

Results

	Primary	Alternate
Time to steady state (h):	5.88	5.88
CO2 concentration at steady state (ppm):	999	909
CO2 concentration at time to metric (ppm):	783	756
CO2 concentration at 1 hour (ppm):	639	630



Save Report Back to Inputs

The user can select Save Report to generate a text file that summarizes the input data and contains the calculated concentration data as a function of time. The text file format is contained in Appendix B. If desired, the user can select Back to Inputs to return to the Inputs screen and revise the inputs, or to consider another case.

5 Conclusions

This report describes the calculation and application of space-specific CO_2 concentrations that can serve as metrics of ventilation rates. An online tool, *QICO2*, is described for making these calculations. While this report and the *QICO2* tool contains example calculations for several example spaces, the analysis of more space types and a wider range of input values would be useful to the future development of this metric concept, as would its application by practitioners.

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Appendix A: Output file format

If the user selects Save Report a text file will be generated that summarizes the input data and contains the calculated concentration data as a function of time.The displayed file contains concentration data for 0.25 h of simulation but the actual file contains 4 h.

The output file for Comnmercial/Institutional cases is called Predefined_Commercial_Building_0_Results.txt if it is generated by one of the Predefined cases, or Building Name_Results.txt, where Building Name is whatever the user enters. The output file is formatted as follows:

```
Predefined Commercial Building,
Inputs + Space Description,
,Co (ppm),HCeil (m),tmetric (h),Q (L/s person),Qalt (L/s person),OccDens (#/100 m²),
,400,3.0,2.0,7.4,10.0,25,

Occupants,
,Nocc,Sex,Mass (kg),Age Group,Activity Level (met),
,12,M,23.0,3 to 9,2,
,12,F,23.0,3 to 9,2,
,1,M,85.0,30 to 59,3,

,tss (h),Css (ppm),Cm (ppm),C1h (ppm),
Primary Results,1.4,1031,1024,963,
Alternate Results,1.4,867,866,844,

Plot Data,
,Time (h),C (ppm),Calt (ppm),
,0.00,400,400,
,0.02,423,423,
,0.03,445,444,
,0.05,466,465,
,0.07,487,485,
,0.08,507,503,
,0.10,526,521,
,0.12,544,538,
,0.13,562,554,
,0.15,579,569,
,0.17,595,584,
,0.18,611,598,
,0.20,626,611,
,0.22,641,623,
,0.23,655,635,
,0.25,669,646,
```

The output file for Residential cases is called Predefined_Residential_Building_0_Results.txt if it is generated by one of the Predefined cases, or Building Name_Results.txt, where Building Name is whatever the user enters. The output file is formatted as follows:

```
Predefined Residential Building,
Inputs + Space Description,
,Co (ppm),HCeil (m),tmetric (h),Q (L/s person),Qalt (L/s person),Bfl (m²),
,400,2.7,2.0,12.9,5.0,250,

Scenario,Method,NOccH,Nbr,
Whole House,62.2,4,3,

Occupants,
,Nocc,Sex,Mass (kg),Age Group,Activity Level (met),
,1,M,85.0,30 to 59,1.3,
,1,F,75.0,30 to 59,1.3,
,1,M,23.0,3 to 9,2,
,1,F,40.0,10 to 17,1.7,

,tss (h),Css (ppm),Cm (ppm),C1h (ppm),
Primary Results,11.1,760,551,485,
Alternate Results,11.1,4112,590,496,

Plot Data,
,Time (h),C (ppm),Calt (ppm),
,0.00,400,400,
,0.02,402,402,
,0.03,403,403,
,0.05,405,405,
,0.07,406,406,
,0.08,408,408,
,0.10,410,410,
,0.12,411,411,
,0.13,413,413,
,0.15,414,415,
,0.17,416,416,
,0.18,417,418,
,0.20,419,419,
,0.22,421,421,
,0.23,422,423,
,0.25,424,424,
```