Residential Application of an Indoor Carbon Dioxide Metric

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ABSTRACT

Indoor carbon dioxide (CO_2) concentrations have been used for decades to evaluate indoor air quality (IAQ) and ventilation. However, many of these applications reflect a lack of understanding of the connection between indoor CO_2, ventilation rates and IAQ. In particular, a concentration of 1800 mg/m^3 (1000 ppm$_v$) has been used as a metric of IAQ and ventilation without an appreciation of its basis or application. After many years of trying to dissuade practitioners and researchers from using CO_2 as a metric of ventilation and IAQ, the first author developed an approach to determine CO_2 levels that can be used as more meaningful indicators. This approach is based on the fact that space types differ in their recommended or required ventilation rates, occupancy and other features that impact indoor CO_2 concentrations. Rather than employ a single CO_2 concentration for all spaces and occupancies, this alternative approach involves the estimation of space-specific CO_2 concentrations. The concept considers the steady-state CO_2 concentration that would be expected in a given space type based on its intended or expected ventilation rate per person, the time to achieve steady-state, the number of occupants as well as the rate at which they generate CO_2, and the occupancy schedule as it pertains to the likelihood that steady-state will be achieved.

This alternative approach was described in a previous AIVC conference paper, with sample calculations presented for several commercial and institutional building spaces. Those calculations yielded potential CO_2 concentration metrics, along with corresponding measurement times after full occupancy. Based on these analyses, it was stressed that reported CO_2 concentrations for comparison to these or other metrics need to be associated with a measurement time relative to the start of occupancy as well as information about the space in question and its occupancy. Since this previous work, an online calculator has been developed to allow users to perform these calculations, and that calculator is described here. In addition, this paper applies the approach to residential buildings, which are more challenging based on their varying configurations and the large fraction of time that occupants spend in bedrooms.

KEYWORDS

Building performance; carbon dioxide; indoor air quality; metrics; residential; ventilation

1 INTRODUCTION

Indoor air quality (IAQ) is characterized by the chemical and physical constituents of air that impact occupant health, comfort and productivity. The number of airborne contaminants in most indoor environments is quite large, and their impacts on building occupants are known for only a very small number of contaminants. The large number of contaminants, and their wide variation among and within buildings and over time, makes it extremely challenging to quantify IAQ, let alone to distinguish between good and bad IAQ based on a single metric. There have been efforts to define IAQ metrics, but none have been shown to capture the health and comfort impacts of IAQ very well or have become accepted in the field (Jackson et al., 2011; Hollick and Sangiovanni, 2000; Moschandreas et al., 2005; Teichman et al., 2015).

The indoor concentration of carbon dioxide (CO_2) has been widely promoted as a metric of IAQ and ventilation, in many cases without a clear explanation of what it is intended to characterize, or a description of its application or its limitations (Persily, 1997). Nevertheless, many practitioners use 1800 mg/m^3 (roughly 1000 ppm$_v$) as a metric, often erroneously basing it on ASHRAE Standard 62.1 (ASHRAE, 2016a). However, that standard has not contained an indoor CO_2 limit for almost 30 years (Persily, 2015a). There have been many papers and presentations that have attempted to clarify the meaning of indoor CO_2 concentrations, some advocating that they not be used at all in IAQ and ventilation evaluations. However, these calls to stop poorly informed applications of indoor CO_2 are not succeeding. Instead, efforts to educate designers, practitioners and others need to continue, and this paper expands on a previously-described approach to using indoor CO_2 concentrations as a metric of ventilation rate per person that thoroughly considers the parameters that determine indoor CO_2 levels (Persily, 2018). That previous discussion presented the approach and outlined its application to a number of commercial and institutional building spaces. This paper expands the consideration to residential buildings and describes an on-line calculator that allows the estimation of indoor CO_2 concentrations in applying this approach.

2 BACKGROUND

Indoor CO_2 concentrations have been prominent in discussions of ventilation and IAQ since the 18th century (Klauss et al., 1970). Since that time, discussions of CO_2 in relation to IAQ and ventilation have evolved, focusing on the impacts of CO_2 concentrations on building occupants, how these concentrations relate to occupant perception of bioeffluents, the use of indoor CO_2 concentrations to estimate ventilation rates, and the control outdoor air ventilation rates based on indoor CO_2 concentrations (Persily, 2015b; Persily, 1997).

Indoor CO_2 concentrations are directly related to the outdoor air ventilation rates per person specified in standards, guidelines and building regulations (ASHRAE, 2016a; ASHRAE, 2016b; CEN, 2007b; CEN, 2009). These outdoor air requirements reflect research on the amount of ventilation needed to control odor associated with the byproducts of human metabolism, as well as other contaminants emitted by building materials and furnishings (Persily, 2015a). This research has found that about 7.5 L/s to 9 L/s per person of ventilation air dilutes body odor to levels judged to be acceptable by individuals entering a room from clean air, i.e., unadapted visitors. This research also supports 1800 mg/m^3 of CO_2 as a reflection of body odor acceptability perceived by unadapted visitors. Of course, there are many other important indoor air contaminants that are not associated with the number of occupants, and CO_2 concentration is not a good indicator of those contaminants.

Indoor CO_2 concentrations are typically well below values of interest based on health concerns (Persily, 2017). Some recent work has shown evidence of impacts on human performance, as well as other health impacts, at levels on the order of 1800 mg/m^3 (Azuma et al., 2018; Snow et al., 2019), while other studies have not shown performance impacts at similar concentrations. It is therefore premature to conclusively link CO_2 concentrations in this range with such occupant impacts until more research is done.

While indoor CO_2 concentrations are not meaningful indicators of overall IAQ, a previous paper describes the use of CO_2 as an indicator or metric of outdoor air ventilation rates per person (Persily, 2018). As discussed in that paper, 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. For the purposes of these discussions, outdoor air ventilation refers to the total rate at which outdoor air enters the building or space of interest, including mechanical and natural ventilation as well as infiltration.

The cited paper describes the single-zone mass balance theory to calculate indoor CO_2 concentrations from these parameters per the following equation:

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

where C is the CO_2 concentration in the space in mg/m^3, $C(0)$ is the indoor concentration at t = 0, t is time in hours, Q is the volumetric flow of air into the space from outdoors and from the space to the outdoors in m^3/h, and V is the volume of the space being considered in m^3. The steady-state CO_2 concentration C_{ss} is given by:

$$C_{ss} = C_{out} + {}^{G}/_{Q}, \quad (2)$$

where C_{out} is the outdoor CO_2 concentration and G is the CO_2 generation rate in the space in mg/h. Q, C_{out} and G are in general functions of time but are assumed constant in this analysis. Also, air density differences between indoors and out are being ignored by using the same value of Q for the airflow into and out of the space. Finally, this single zone formulation ignores concentration differences within and between building zones and CO_2 transport between zones and assumes there are no other indoor sources of CO_2 other than occupants.

Note that the indoor concentration will only get sufficiently close to steady-state if conditions, specifically Q and G, are constant for a long enough period of time. In particular, a constant value of G requires that the occupancy 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 comparing the duration of constant occupancy to the time constant of the space. The time constant is equal to the inverse of Q/V in Equation 1, i.e., the inverse of the air change rate, and the indoor concentration will be about 95 % of steady-state after three time constants. For example, for an air change rate of 1 h^{-1}, steady-state will exist after 3 hours. For an air change rate of 0.5 h^{-1}, it will take 6 hours.

Table 1: Calculated CO_2 concentrations

			CO_2 concentration above outdoors (mg/m^3)		
Space Type	**t_{metric} (h)**	**Time to steady-state (h)***	**Steady-state**	**1 h**	**t_{metric}**
Classroom (5 to 8 y)	2	1.4	1060	940	1040
Classroom (>9 y)	2	1.1	1580	1490	1580
Lecture classroom	1	0.9	1940	1870	1870
Restaurant	2	0.7	1871	1850	1870
Conference room	1	1.6	2526	2130	2130
Hotel/motel bedroom	6	4.5	1080	520	1060
Office space	2	5.9	985	390	630
Auditorium	1	0.6	2900	2880	2880
Lobby	1	0.6	4467	4430	4430
Retail/Sales	2	2.1	1546	1170	1450

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

In the previous work on this CO_2 metric concept, several space types were selected from the commercial/institutional building space types or "Occupancy Categories" in Table 6.2.2.1 of ASHRAE Standard 62.1 (ASHRAE, 2016a). For these spaces, shown in Table 1, CO_2 concentrations above outdoors were calculated at steady-state, after 1 h of occupancy, and at a time t_{metric}, which was selected as a time over which the particular space type may be expected to be fully occupied. That time is in the first column of Table 1, while the time to reach steady-state is in the second column. The assumed occupant densities, occupant characteristics and CO_2 generation rates are described in Persily (2018).

Based on the previous work, including the desire for a CO_2 metric to capture ventilation deficiencies and to be less sensitive to the timing of the concentration measurement, Table 2 summarizes potential CO_2 metric values for these spaces along with the corresponding measurement time. Given the transient nature of indoor CO_2 concentrations, it is critical that a concentration CO_2 metric be linked to a measurement time. Therefore, reported CO_2 concentrations relative to these and any other metrics need to include the time that has passed since the space reached full occupancy. Consideration of additional spaces and different input values would possibly yield other conclusions about potential metrics. Such analyses will be facilitated by the online tool described below.

Table 2: Potential CO_2 concentration metrics

Space Type	**CO_2 concentration metric, above outdoors (mg/m^3)**	**Corresponding time (h after full occupancy)**
Classroom (5 to 8 y)	1000	2
Classroom (>9 y)	1500	1
Lecture classroom	2000	1
Restaurant dining room	2000	1
Conference meeting room	2000	1
Hotel/motel bedroom	1000	6
Office space	600	2
Public assembly/Auditorium	3000	1
Public assembly/Lobby	4500	1
Retail/Sales	1500	2

3 CO_2-BASED VENTILATION METRIC FOR RESIDENTIAL SPACES

This paper 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 many hours associated with sleep provide helpful options for these analyses in bedrooms. The approach taken is again to use Equation (1) 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. In order to explore these dependencies for residential spaces, indoor CO_2 concentrations were calculated for the occupancies listed in Table 3, which describes 3 families: a baseline with 4 members (2 adults and 2 children), a larger family with 2 additional children, and a smaller 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 calculated using the methodology in Persily and de Jonge (2017), as well as the average CO_2 generation rate per person. These generation rates are presented for the whole house during non-sleep hours when occupants are assumed to be more active, and for bedrooms when occupants are sleeping. For occupant characteristics that differ from those considered here, the online tool described below is enables analysis of different occupancies. For each occupancy in Table 3, CO_2 concentrations were calculated for the following ventilation scenarios:

Whole house:

- Ventilation rate requirement from ASHRAE Standard 62.2 (ASHRAE, 2016b)
- 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

Table 3: Occupancy Assumptions for CO_2 concentration 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)	0.0049 0.0038 0.0042 0.0042	0.0043
Master Bedroom	1 male (40 y, 85 kg, 1.3 met); 1 female (40 y, 75 kg, 1.3 met);	0.0037 0.0029	0.0033
Child Bedrooms	1 male (6 y, 23 kg, 2 met); 1 female (10 y, 40 kg, 1.7 met)	0.0021 0.0025	0.0023
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)	0.0050 0.0031	0.0042*
Master Bedroom	No change		0.0033
Child Bedrooms	1 male (8 y, 23 kg, 2 met); 1 female (4 y, 40 kg, 1.7 met)		0.0022*
Smaller family of 2 (no children)			
Whole house	Only adults		0.0043
Master Bedroom	Only adults		0.0033

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

The Standard 62.2 whole house ventilation requirement Q_{tot} in L/s is calculated using Equation (4.1b) from the standard, i.e.,

$$Q_{tot} = 0.15A_f + 3.5(N_{br} + 1), \qquad (2)$$

where A_f is the floor area in 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 the infiltration credit. The whole house air change rate of 0.5 h^{-1} is included as it is recommended in several international standards and guidelines (CEN, 2007a; Concannon, 2002).

For the bedroom cases, two idealized air distribution scenarios are applied to the Standard 62.2 and 0.5 h^{-1} whole house rates. In the first, Perfect Distribution, the whole house rate is divided by the number of occupants in the house. That normalized value is multipled by the number of occupants in each bedroom to determine the ventilation to each bedroom. Perfect Distibution may correspond to a ventlation system that supplies outdoor air directly to each bedroom based on the number of occupants. Under Uniform Distribution, the total ventilaiton rate is normalized by the floor area of the entire house, and the ventilation rate of each bedroom is that normalized rate multiplied by its floor area. Uniform distribution may correspond to a building ventilated by infiltration only, an exhaust-only ventilation system or a mechanical ventilation system that is integrated into a forced-air distribution system. 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 recommendations in CEN (2007a) and (2009).

Table 4 presents the dimensions (ceiling heights and floor areas) for the houses considered.

Table 4: House and bedroom sizes for cases considered

	Ceiling height (m)	**House floor area (m^2)**	**Master bedroom floor area (m^2)**	**Child bedrooms floor area (m^2)**
Large House	2.44	250	30	20
Small house	2.74	200	20	15

Table 5 presents ventilation rates and calculated CO_2 concentrations (above outdoors). The second and third columns contain the outdoor air ventilation rate in L/s per person and h^{-1} for the whole house and bedroom cases. The fourth column is the time to reach a steady-state CO_2 concentration, i.e., three times the inverse of the air change rate. The table does not include t_{metric}, which as described earlier is a time over which a particular space may be expected to be fully occupied. Throughout these analyses, t_{metric} is 2 h for the whole house and 6 h for the bedrooms. The last three columns are the calculated CO_2 concentrations at steady-state, 1 h after occupancy and t_{metric}. The whole house air change rates based on Standard 62.2 are about 0.3 h^{-1} in all but the small house/baseline family case, in which it is about 0.5 h^{-1}. The bedroom air change rates cover a range of almost 10 to 1 for the different cases in the large house/baseline family and the small house/small family. In both of those 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. On the other hand, 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 bedrooms cases other than for 62.2/Uniform. For the whole house, the time to steady-state ranges from 3 h to more than 11 h.

The calculated CO_2 concentrations in Table 5 reflect the differences in ventilation and CO_2 generation for the specific occupancies. It is worth noting that the only steady-state bedroom concentrations greater than 1800 mg/m^3 (assuming an outdoor concentration of 700 mg/m^3) occur in the master bedroom for all 62.2/Uniform cases and for the small house/small family 0.5/Uniform case. Also, for cases with short time constants, 2 h or less, the three CO_2 concentrations are not very different from each other. Much larger differences are seen for larger time constants. In all whole house cases, the concentrations at t_{metric} are at least 200 mg/m^3 above outdoors, which is above the uncertainty typically associated with field measurements of indoor CO_2 concentrations. The bedroom concentrations at t_{metric} are typically even higher, except in the 0.5 h^{-1}/CBR/Perfect case, for which the steady-state concentration is less than 200 mg/m^3. The magnitude of these concentrations relative to typical measurement uncertainties supports the use of such calculated concentrations as a metric, although assuming constant occupancy in a whole house for 2 h could be questionable under some circumstances. It is worth noting that the range of CO_2 concentrations at t_{metric} for each occupancy range by at least 4 to 1 in the small house/baseline family case, to as much as almost 9 to 1 in the large house baseline/family case. These differences demonstrate the importance of considering the target ventilation rate in using calculated CO_2 concentrations as a metric. Also, for the same ventilation case, the differences in calculated CO_2 concentrations at t_{metric} for the different occupancies are not as large as those within the same occupancy for the different ventilation cases. However, they are large enough to be reliably measured and support the need to consider house size and occupancy when using calculated concentrations as a metric.

Table 5: Ventilation rates and calculated CO_2 concentrations for the residential cases

	Outdoor air ventilation		**Time to steady-state (h)**	**CO_2 Concentration above outdoors (mg/m^3)**		
Case*	**L/s per person**	**h^{-1}**		**Steady-state**	**1 h**	**t_{metric}**
Large House/Baseline family						
Whole house – 62.2	12.9	0.27	11.1	598	142	250
Whole house – 0.5 h^{-1}	23.8	0.50	6.0	324	127	205
62.2/ MBR/Perfect	12.9	1.13	2.7	461	312	461
62.2/ CBR/Perfect	12.9	0.85	3.5	322	184	320
62.2/MBR/Uniform	3.1	0.27	11.1	1922	456	1543
62.2/CBR/Uniform	4.1	0.27	11.1	1005	238	807
0.5 h^{-1}/MBR/Perfect	23.8	2.08	1.4	250	219	250
0.5 h^{-} CBR/Perfect	23.8	1.56	1.9	174	138	174
0.5 h^{-1}/MBR/Uniform	5.7	0.50	6.0	1041	409	989
0.5 h^{-1}/ CBR/Uniform	7.6	0.50	6.0	544	214	517
10 L/s per person/MBR/Perfect	10.0	0.88	3.4	594	347	591
10 L/s per person/CBR/Perfect	10.0	0.66	4.6	414	199	406
Large House/Large family						
Whole house – 62.2	9.8	0.31	9.8	775	205	356
Whole house – 0.5 h^{-1}	15.9	0.50	6.0	477	188	301
62.2/ MBR/Perfect	9.8	0.85	3.5	609	350	606
62.2/ CBR/Perfect	9.8	0.64	4.7	402	190	393
62.2/MBR/Uniform	3.5	0.31	9.8	1692	448	1425
62.2/ CBR/Uniform	4.7	0.31	9.8	837	221	704
0.5 h^{-1}/MBR/Perfect	15.9	1.39	2.2	375	281	375
0.5 h^{-} CBR/Perfect	15.9	1.04	2.9	247	160	246
0.5 h^{-1}/MBR/Uniform	5.7	0.50	6.0	1041	409	989
0.5 h^{-1}/ CBR/Uniform	7.6	0.50	6.0	514	202	489
10 L/s per person/MBR/Perfect	10.0	0.88	3.4	594	347	591
10 L/s per person/CBR/Perfect	10.0	0.66	4.6	392	189	384
Small House/Baseline family						
Whole house – 62.2	7.3	0.43	7.0	1061	369	610
Whole house – 0.5 h^{-1}	8.5	0.50	6.0	908	357	574
62.2/ MBR/Perfect	7.3	1.07	2.8	819	538	818
62.2/ CBR/Perfect	7.3	0.71	4.2	571	291	563
62.2/MBR/Uniform	2.9	0.43	7.0	2048	713	1891
62.2/ CBR/Uniform	4.4	0.43	7.0	952	331	879
0.5 h^{-1}/MBR/Perfect	8.5	1.25	2.4	701	500	701
0.5 h^{-} CBR/Perfect	8.5	0.83	3.6	489	276	485
0.5 h^{-1}/MBR/Uniform	3.4	0.50	6.0	1753	690	1666
0.5 h^{-1}/ CBR/Uniform	5.1	0.50	6.0	814	320	774
10 L/s per person/MBR/Perfect	10.0	1.48	2.0	594	458	594
10 L/s per person/CBR/Perfect	10.0	0.98	3.1	414	259	413
Small House/Small family						
Whole house – 62.2	11.0	0.32	9.2	700	194	334
Whole house – 0.5 h^{-1}	16.9	0.50	6.0	454	179	287
62.2/ MBR/Perfect	11.0	1.62	1.8	540	433	540
62.2/MBR/Uniform	2.2	0.32	9.2	2700	748	2315
0.5 h^{-1}/MBR/Perfect	16.9	2.50	1.2	351	322	351
0.5 h^{-1}/MBR/Uniform	3.4	0.50	6.0	1753	690	1666
10 L/s per person/MBR/Perfect	10.0	1.45	2.0	594	458	594

* MBR and CBR stand for master bedroom and child bedroom, respectively.

Table 6: Calculated CO_2 concentrations for the residential cases with 25 % ventilation rate reduction

	Outdoor air ventilation		**Time to steady-state (h)**	**CO_2 Concentration above outdoors (mg/m^3)**		
Case*	**L/s per person**	**h^{-1}**		**Steady-state**	**1 h**	**t_{metric}**
Large House/Baseline family						
Whole house – 62.2	10.5	0.22	13.6	**731**	145	261
Whole house – 0.5 h^{-1}	17.8	0.38	8.0	**431**	135	228
62.2/ MBR/Perfect	10.5	0.92	3.3	**564**	340	**562**
62.2/ CBR/Perfect	10.5	0.69	4.3	393	196	387
62.2/MBR/Uniform	2.5	0.22	13.6	**2350**	467	**1728**
62.2/CBR/Uniform	3.4	0.22	13.6	**1228**	244	**903**
0.5 h^{-1}/MBR/Perfect	17.8	1.56	1.9	333	263	333
0.5 h^{-} CBR/Perfect	17.8	1.17	2.6	232	160	232
0.5 h^{-1}/MBR/Uniform	4.3	0.38	8.0	**1387**	434	**1241**
0.5 h^{-1}/ CBR/Uniform	5.7	0.38	8.0	**725**	227	**649**
10 L/s per person/MBR/Perfect	7.5	0.66	4.6	**792**	381	**777**
10 L/s per person/CBR/Perfect	7.5	0.49	6.1	**552**	215	**523**
Large House/Large family						
Whole house – 62.2	8.2	0.26	11.6	**923**	210	372
Whole house – 0.5 h^{-1}	11.9	0.38	8.0	**636**	199	335
62.2/ MBR/Perfect	8.2	0.72	4.2	**725**	371	**716**
62.2/ CBR/Perfect	8.2	0.54	5.6	478	199	459
62.2/MBR/Uniform	2.9	0.26	11.6	**2015**	459	**1587**
62.2/ CBR/Uniform	3.9	0.26	11.6	**996**	227	785
0.5 h^{-1}/MBR/Perfect	11.9	1.04	2.9	**499**	323	**499**
0.5 h^{-} CBR/Perfect	11.9	0.78	3.8	329	178	326
0.5 h^{-1}/MBR/Uniform	4.3	0.38	8.0	**1387**	434	**1241**
0.5 h^{-1}/ CBR/Uniform	5.7	0.38	8.0	**686**	214	**614**
10 L/s per person/MBR/Perfect	7.5	0.66	4.6	**792**	381	**777**
10 L/s per person/CBR/Perfect	7.5	0.49	.1	**522**	203	**495**
Small House/Baseline family						
Whole house – 62.2	6.3	0.37	8.1	**1219**	379	640
Whole house – 0.5 h^{-1}	6.4	0.38	8.0	**1211**	379	639
62.2/ MBR/Perfect	6.3	0.93	3.2	**941**	570	**937**
62.2/ CBR/Perfect	6.3	0.62	4.8	656	303	640
62.2/MBR/Uniform	2.5	0.37	8.1	**2352**	732	**2101**
62.2/ CBR/Uniform	3.8	0.37	8.1	**1093**	340	976
0.5 h^{-1}/MBR/Perfect	6.4	0.94	3.2	**935**	569	**931**
0.5 h^{-} CBR/Perfect	6.4	0.63	4.8	**652**	303	**636**
0.5 h^{-1}/MBR/Uniform	2.5	0.38	8.0	**2337**	731	**2091**
0.5 h^{-1}/ CBR/Uniform	3.8	0.38	8.0	**1086**	340	**971**
10 L/s per person/MBR/Perfect	7.5	1.11	2.7	**792**	530	**791**
10 L/s per person/CBR/Perfect	7.5	0.74	4.1	**552**	288	**545**
Small House/Small family						
Whole house – 62.2	9.1	0.27	11.1	**843**	199	351
Whole house – 0.5 h^{-1}	12.7	0.38	8.0	**606**	189	319
62.2/ MBR/Perfect	9.1	1.35	2.2	**651**	482	**651**
62.2/MBR/Uniform	1.8	0.27	11.1	**3255**	768	**2608**
0.5 h^{-1}/MBR/Perfect	12.7	1.88	1.6	**467**	396	**467**
0.5 h^{-1}/MBR/Uniform	2.5	0.38	8.0	**2337**	731	**2091**
10 L/s per person/MBR/Perfect	7.5	1.11	2.7	**792**	530	**791**

* MBR and CBR stand for master bedroom and child bedroom, respectively.

To the evaluate the usefulness of calculated CO_2 concentrations as ventilation metrics, the calculations presented in Table 5 were redone with the assumed ventilation rates reduced by 25 %. As in the commercial and institutional occupancies discussed in Persily (2018), these additional calculations were performed to assess how much the concentrations change at lower ventilation rates since a useful metric should capture such changes. The CO_2 concentrations for the reduced ventilation rates are shown in Table 6, as well as the outdoor ventilation rates for each case in L/s per person and h^{-1} and the times to reach steady-state. Values that increase by 100 mg/m^3 or more relative to the corresponding values in Table 5 are noted in bold font. The whole-house, reduced-ventilation concentrations at t_{metric} in Table 6 increase very little relative to the corresponding values in Table 5, often by 30 mg/m^3 or less, which is comparable with the measurement accuracy of many field measurements of CO_2 concentrations. This lack of increase is partly due to the long time constants of the whole-house cases, which allow little time for the concentration to increase after only 2 h. The increases in the bedroom concentrations are more significant, typically at least 100 mg/m^3 and often several hundred mg/m^3 higher for the reduced ventilation cases for a t_{metric} of 6 h. These larger increases for the bedroom support the use of a 6 h value of t_{metric} to capture ventilation deficiencies in bedrooms.

In contrast to the commercial and institutional occupancies discussed by (Persily, 2018), these residential cases are less constrained by space size, occupancy and ventilation, making it difficult to generalize these results to develop CO_2 metrics for residential buildings. Instead, the house, occupancy and air distribution approach need to be accounted for in developing a metric or reference point for evaluating the adequacy of the ventilation rate relative to a target value. The online tool discussed in the next section was developed to implement these concepts.

4 ON-LINE CO_2 METRIC CALCULATOR

In order to support application of the proposed CO_2 concentration metric, an online tool (available at https://pages.nist.gov/CONTAM-apps/webapps/CO2Tool/#/) has been developed. This tool 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 then be compared with measured concentrations in a building to evaluate whether the intended or required ventilation rate is actually being achieved. Such a building-specific metric or reference value is far better than using a single value such as 1800 mg/m^3.

Figure 1 shows the first screen encountered when using the tool, where one first selects to analyze a commercial/institutional building or a residential building. Depending on that selection, the user then enters the required inputs. For commercial/institutional buildings, the tool allows one to select from several of the commercial and institutional space types listed in ASHRAE Standard 62.1-2016, and to use the default values in that 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 (2017). However, these assumptions can be modified by selecting User-Defined Model Type, which brings up an alternative input screen.

The residential building inputs are shown in Figure 2. In this case, the user selects whether they are performing a whole building or bedroom analysis. If whole building is selected, the user can select the ventilation requirement based on Standard 62.2-2016 or enter a whole building air change rate in h^{-1}. If instead they chose to perform a bedroom analysis, they need to select the ventilation requirement from Standard 62.2 or enter a L/s per person ventilation rate. In either case, they also need 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. If desired, an Alternate Ventilation per Person input can be input to enable comparison of the results to those obtained with the Primary ventilation rate.

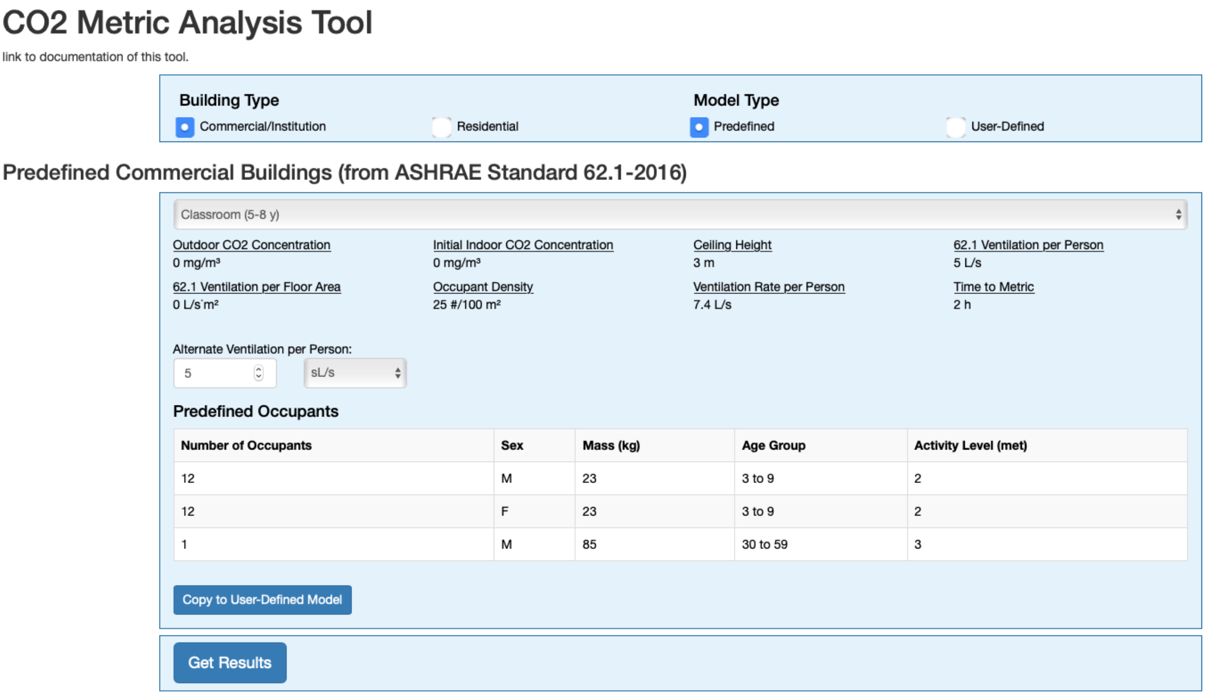

Figure 1: CO_2 Metric Calculator Default Inputs Screen

Once the user has completed the inputs, they click Get Results on the bottom of the Inputs page. This action brings up the Results screen shown in Figure 3, which summarizes the inputs and displays a plot of the indoor CO_2 concentration versus time, along with concentration values at steady-state, t_{metric} and 1 h after occupancy for both the Primary and Alternate ventilation rates.

The tool is 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 calculation assumes 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 whole house, and the calculated value at that time are then used for the comparison. If constant occupancy does not last that long (default value of 2 h), the t_{metric} value in the calculator can be modified.

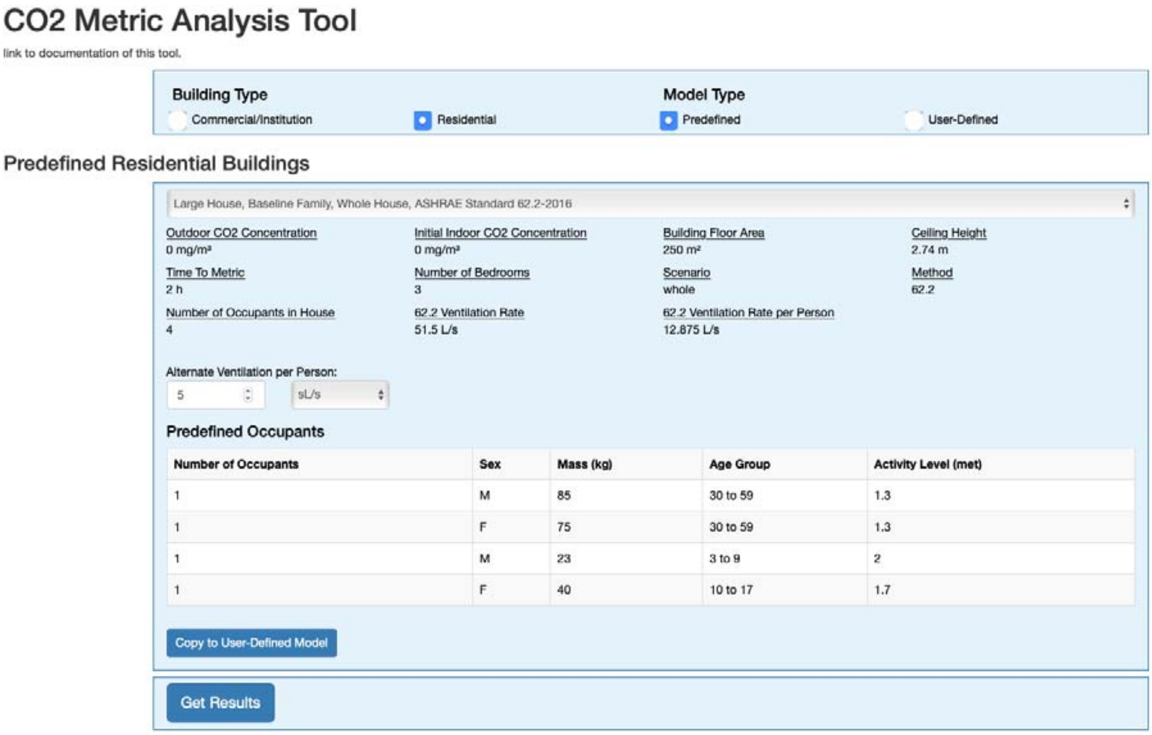

Figure 2: CO_2 Metric Calculator Residential Input Screen

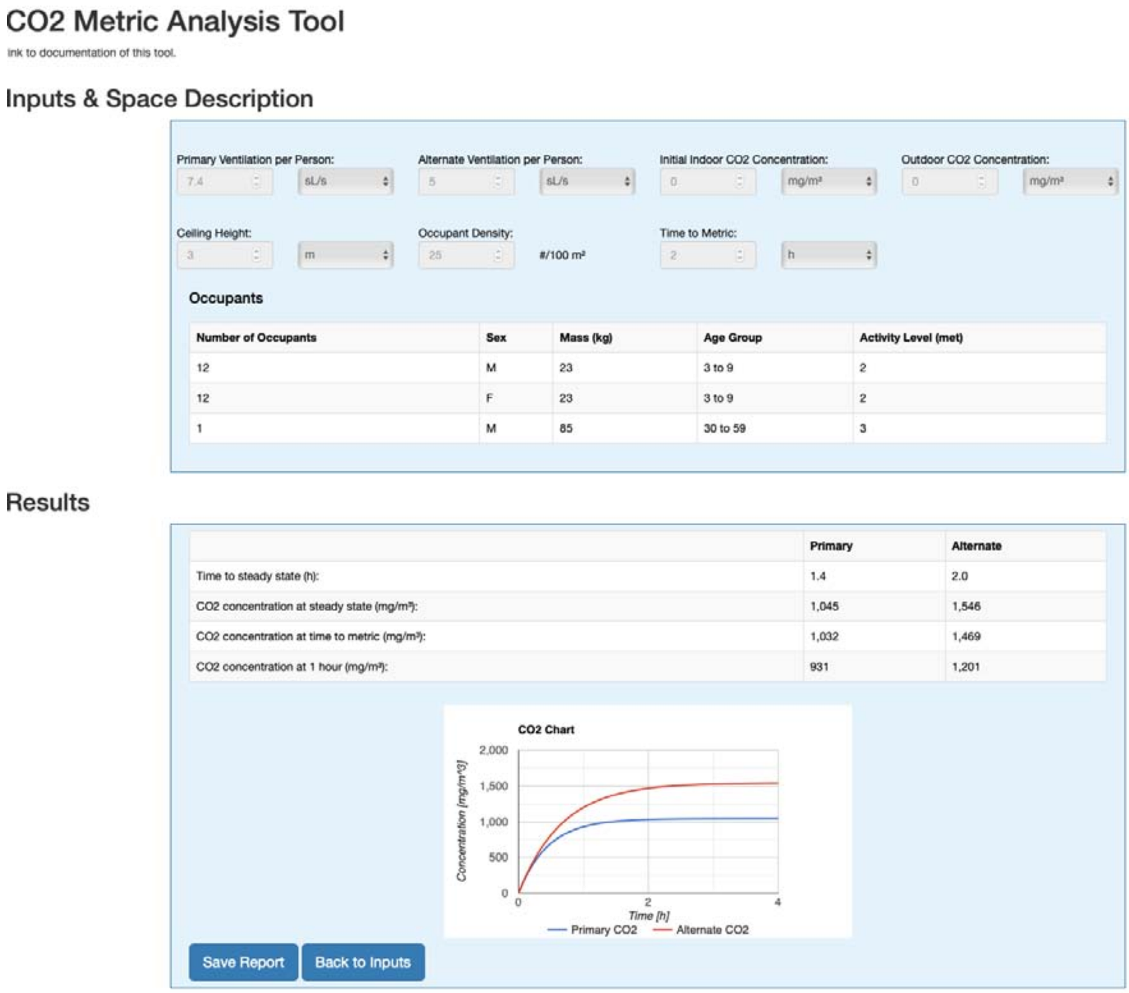

Figure 3: CO_2 Metric Calculator Results Screen

In the case of bedrooms, the calculated CO_2 concentrations can again be compared to measured values in the bedroom. Given the fairly 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 making the concentration comparisons. On making that comparison, a measured value that is higher serves as an indication that the actual ventilation rate is below the assumed or desired ventilation rate. Note that this comparison neglects the impact of interzone transport on the bedroom CO_2 concentration. Also, the calculation assumes that the CO_2 concentration starts at the outdoor level. 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.

5 SUMMARY AND CONCLUSIONS

This paper expands on a previously-described approach to using indoor CO_2 concentration measurements as a metric for ventilation rates per person, which accounts for the ventilation requirements and occupancies of specific spaces. Calculations of CO_2 concentrations at steady state and other times, are presented for selected residential occupancies based on space-specific inputs of ventilation rate, space geometry and occupancy. Application of this CO_2 metric approach to residences requires one to report, at a minimum, the following: house or bedroom geometry (e.g. floor area and ceiling height), occupant characteristics, time at which full occupancy starts, time of CO_2 concentration measurement, and measured indoor and outdoor CO_2 concentrations. These measurements can then be compared with the values calculated with the online tool as an indication of whether the ventilation rate complies with the value in Standard 62.2 or other ventilation requirement of interest. As additional analyses are performed and the concept discussed with practitioners and researchers, it is anticipated that the approach will become more well-defined and more useful.

Note that all of the input values used in these calculations can be revised to examine the impact of other values on the resulting CO_2 concentrations. An online calculator has been developed to allow users to perform these additional calculations. Based on user feedback, the calculator will be revised in the future. One specific addition being considered is to enable Monte Carlo analyses to quantify the impact of uncertainties in the input values on the calculated CO_2 concentrations, as well as to identify the most important input values, using the methodology described in Jones et al. (2015).

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