BERKLEY SCHOOLS

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Berkley School District

Classroom CO_2 and ACH Analysis

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Submitted by:

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Executive Summary

After receiving some concerns regarding classroom carbon dioxide levels, Berkley School District reached out to Strategic Energy Solutions (SES) to provide engineering feedback regarding acceptable indoor carbon dioxide levels along with any requirements for total air changes per hour (ACH). SES reviewed the carbon dioxide levels provided by Berkley School District for average classrooms located throughout the district. SES also reviewed the total air changes per hour for these same classrooms based on design drawings that were part of the 2016 bond.

The carbon dioxide levels were trended over the course of 2 weeks (10/03/22-10/14/22) every 7 minutes starting at 8:00 AM and ending at 3:30 PM; the time indicated was when the classroom HVAC unit was operating in occupied mode. Based on the district's calendar, Berkley School District was closed on 10/5/2022, and therefore, data for that day was excluded from this report.

During the analysis the following was determined:

	AVERAGE CO2 (PPM)			AVERAGE ACH	
SCHOOL	MIN	MAX	CUMULATIVE AVERAGE	SUPPLY AIR	OUTDOOR AIR
ANGELL ELEMENTARY SCHOOL	438	1100	710	10.4	2.7
BERKLEY BUILDING BLOCKS (AVERY)	413	726	589	7.5	2.0
BURTON ELEMENTARY	448	1111	769	10.9	2.9
PATTENGILL ELEMENTARY	453	1432	893	9.7	2.4
ROGERS ELEMENTARY	468	1277	832	8.8	2.4
ANDERSON MIDDLE SCHOOL	427	1451	869	9.9	2.5
NORUP INTERNATIONAL SCHOOL	425	1152	746	8.1	2.0
BERKLEY HIGH SCHOOL	418	1491	887	10.2	3.6

SES compared the above data against Michigan code requirements and industry standards, guidelines, and position documents. The following was determined:

- There are no code requirements for K-12 schools related to minimum air changes per hour or carbon dioxide concentration. Code requirements focus on cubic feet per minute (CFM) of outdoor air per person and CFM of outdoor air per square foot.
- The average outdoor air carbon dioxide level is 410 parts per million (ppm).
- OSHA requirements limit carbon dioxide exposure to 5000 ppm. The International Space Station and submarine design requirements limit carbon dioxide levels to 4000 ppm.

As equipment ages, damper actuators can loosen from usage. While no immediate action is required, should the district pursue anything further, test and balance (TAB) procedures can be completed for the unit ventilators to ensure supply and outdoor airflow quantities are still being provided to meet code. An updated TAB procedure would ensure the equipment is still operating as designed.

A more detailed analysis of these findings can be found in the report and appendices contained within.

Scope Summary

Strategic Energy Solutions (SES) was tasked with evaluating the carbon dioxide concentration levels and air change per hour for teaching spaces located across Berkely School District's buildings. The following rooms were evaluated:

Angell Elementary School
- Classroom 2
- Classroom 18
- Classroom 20
- Classroom 222

Avery Early Childhood and Administration
- Infant Classroom D101
- Infant Classroom D102

Burton Elementary School
- Classroom 105
- Classroom 107
- Classroom 205
- Classroom 207

Pattengill Elementary School
- Classroom 114
- Classroom 123
- Classroom 128
- Classroom 207

Rogers Elementary School
- Classroom 5
- Classroom 18
- Classroom 19
- Classroom 20

Anderson Middle School
- Classroom 104
- Classroom 107
- Classroom 205
- Classroom 207

Norup International School
- Classroom 130
- Music Room
- Art Room
- Classroom 204

Berkely High School
- Classroom 121
- Classroom 146
- Classroom 205
- Classroom 216
- Classroom 273

Background information has been provided as part of the review completed by SES. The background information addresses what codes/standards are applicable for classroom ventilation. The mechanical system serving each classroom is also described along with its intended operation.

An engineering analysis has been provided specifically addressing the classroom air changes per hour and the carbon dioxide levels present within each space.

Concluding, SES provided a recommendation the district can proceed with should they wish to pursue further action.

Background Information

Codes and Standards

At the time of design/construction, the governing code was the 2012 Michigan Mechanical Code (MMC). The current code, 2015 MMC, was not adopted until April 2017.

The MMC incorporates by reference ASHRAE Standard 62.1 – Ventilation for Acceptable Indoor Air Quality. ASHRAE (American Society of Heating, Refrigeration, and Air-Conditioning Engineers) standards and guidelines are industry recognized recommendations for best practice and building codes will typically derive their code requirements based on ASHRAE publications. ASHRAE publications including standards, guidelines, journals, and position documents are highly regarded in the industry. Application of these documents ensures mechanical engineers meet the standard of care required for HVAC system design.

Existing Systems

Each classroom space throughout the district has a unit ventilator (UV). The UVs were installed as part of the 2016 Bond work. Each UV has a hydronic heating coil, DX cooling coil, supply fan, exhaust fan, outdoor air/return air mixing dampers, and filter. Each unit handles all its own outdoor airflow. The thermostat/carbon dioxide sensor is located on the UV near the return air grille.

The unit ventilators are designed to be constant volume and operate through various occupied and unoccupied sequences of operation. The space's occupancy is determined via a programmed schedule and space occupancy sensor. During occupied times, the outdoor air damper is required to be at minimum position with the ability to increase outdoor air (OA) flow as required to economize (i.e. provide free cooling). During unoccupied times, the OA damper closes, and the unit operates in full recirculation mode. The carbon dioxide sensor is a point used for reference and does not control the operation of the unit.

Engineering Analysis

Air Change Evaluation

Air changes per hour (ACH) is a metric used to evaluate the total number of times the air contained within the room volume is changed over time.

The total supply air into the space, along with the space volume are required to perform the analysis. Existing floor plans from the 2016 Bond were scaled via Bluebeam Revu to estimate room size, the district provided room heights, and basis of design equipment schedules from the 2016 Bond were all used to determine both the supply air change rate and the outdoor air change rate per classroom.

The total supply air change rate is a value that is all encompassing; it includes the sum of both the outdoor air and the return air. The outdoor air change rate is only referencing the amount of air entering via the outdoor air louver located on the unit ventilator.

For example, a room with 10 ACH of supply air and 2 ACH of outdoor air means:

- The total volume of air within the space is circulated through the HVAC system 10 times per hour, or every 6 minutes. This total volume of air includes both return air and outdoor air, and all air passes through filters.
- The total volume of air within the space coming from the outside (i.e. ventilation air) is “replaced” 2 times per hour, or every 30 minutes. Enough outdoor air is brought into the space after 30 minutes to have completely replaced all air within the room.

The current MMC, along with ASHRAE Standard 62.1, do not require a minimum supply or outdoor air change rate for schools. The only requirement established by the MMC is related to CFM/person and CFM/square foot (SF). The MMC requires minimum 10 CFM/person + 0.12 CFM/SF outdoor air flow for classrooms.

There are air change rate requirements at the state level for other building types, like healthcare. For example, a patient room in a hospital requires a minimum 6 supply ACH and 2 outdoor air ACH. Across the district, the average supply ACH is 9.4, and the average outdoor air ACH is 2.6. The ACH for each space evaluated can be found in Appendix A in columns “Supply ACH” and “OA ACH”.

Carbon Dioxide Evaluation

The Berkley School District tracked the carbon dioxide concentration levels across the district over the course of two weeks (10/03/22 – 10/14/22). The readings were taken Monday – Friday every seven minutes during the times of 8:00 AM and 3:30 PM; readings were while the classroom HVAC unit was operating in its occupied mode. The data was then provided to SES for further evaluation. In total, 68 hours of occupied time was reviewed for the spaces evaluated. Appendix A provides a summary of the data for each space in the “Carbon Dioxide Analysis” section of the table. Based on the district’s calendar, the district was closed on 10/5/2022, and therefore, data for that day was excluded from this report.

Please refer to Appendix B for the “ASHRAE Position Document on Indoor Carbon Dioxide” published in 2022 for a full synopsis of what carbon dioxide within a space is and how it impacts occupants. A summary is provided below.

Carbon dioxide is often used as the metric to determine the indoor air quality of a space. Occupants tend to believe the more carbon dioxide in the space, the less they concentrate, the more headaches they suffer from, etc. However, indoor carbon dioxide is not the only factor affecting occupant health, and “elevated carbon dioxide concentrations likely serve[d] as an indicator of inadequate ventilation that increases the concentration of all contaminants with indoor sources.” Meaning, carbon dioxide itself is not the sole indicator of indoor air quality, and that other sources of contaminants affect the air quality. There has yet to be a published and peer reviewed scientific study that specifically controls all other source of contaminants and varies carbon dioxide level to review human response.

Historically, 1000 PPM of carbon dioxide has been used as the upper threshold for controlling carbon dioxide within a space. This value was issued in the 1989 original version of ASHRAE Standard 62.1, however was quickly removed because of its misuse. ASHRAE’s position document indicates there was no clear basis to even provide this threshold. Since then, no ASHRAE 62.1 Standard has included a threshold for maximum carbon dioxide levels within a space. MMC, also, does not provide a limitation to the maximum carbon dioxide level required within a space.

Per ASHRAE's position document, "Carbon dioxide is considered nontoxic at concentrations up to 5000 ppm, which is the U.S. federal standard (Permissible Exposure Level) for workplaces set by the Occupational Safety and Health Administration (OSHA)." OSHA requirements limit a worker's exposure to carbon dioxide to 5000 ppm across 8-hours of a 40-hour work week; a worker cannot be exposed to more than 5000 ppm for more than 20% of their work week. Also indicated in the position document, "guidelines for the International Space Station and U.S. submarines currently suggest that carbon dioxide concentrations be maintained at 4000 to 5000 ppm to reduce the incidence of headaches." Furthermore, ASHRAE's position documents mentions the average outdoor carbon dioxide level is 410 ppm.

Code requirements for indoor air quality (IAQ) are primarily focused on the amount of OA brought into the space. Minimum airflow rates (per person, and per square foot) are provided in Chapter 4 of MMC and Chapter 6 of ASHRAE Standard 62.1. However as noted in ASHRAE's position document, even when following these minimum ventilation requirements, the spaces can expect to see a minimum carbon dioxide concentration of 1000-2500 ppm depending on usage.

Ultimately, there is no current standard or code requirement defining the carbon dioxide concentration spaces cannot exceed, except OSHA's 5000 ppm limitation.

On average, carbon dioxide levels are below 1000 ppm for 90% of the spaces evaluated over the two-week period across the Berkley School District. Although there are spaces where the concentration exceeds 1000 ppm at a max reading during the day, Appendix A also indicates that, for the most part, those spaces rarely will ever exceed 1200 ppm.

SES Recommendations

The district indicated to SES that during the COVID-19 pandemic all MERV 8 filters were replaced with MERV 13 filters. MERV 13 filters offer better filtering of small particles and can aid in reducing the spread of viruses. These filters, however, come with additional pressure drop than the MERV 8 filters and can potentially decrease the total air flow rate of the unit ventilator fan. This directly relates to the total OA coming into the space since the supply fan within the UV is required to pull outdoor air, too.

Over time systems have the potential to adjust from the initial new construction install. In this case, damper actuators may tend to loosen up and fan drives may slip. This will cause a deviation from the originally installed system setting. Because of this, SES recommends the district perform a TAB analysis for the UVs to ensure the supply airflow for each unit still matches that of the design documents. During this process, the contractor should ensure the minimum OA provided to each space matches the indicated airflow as provided in Appendix A in column "MIN REQUIRED OA". This OA is based on the room size along with the current occupancy provided by the district. When completed, this will ensure OA intake meets current code requirements based on current space usage (occupancy count) compared to original design data. Prior to the TAB procedures, new filters should be installed. However, please note:

1. There is no requirement to continue updating facilities to the latest version of the enforced code. Only when substantial renovation or system upgrades are completed should the existing system be required to meet current mechanical code requirements. Furthermore, there is no

code requirement to continually adjust the minimum OA provided for UV's as the number of occupants within a classroom changes year over year or day to day.

2. Even when meeting code minimum ventilation requirements, the carbon dioxide concentration levels are expected to be between 1000 and 2500 ppm [See Carbon Dioxide Analysis section above].
3. If/when adjustments are made to meet current code requirements, further engineering evaluation will be required to ensure the UV heating and cooling coils have the capacity to handle the additional outdoor air.

Appendix A: Tabulated Data

ROOM NUMBER	ROOM NAME	AREA (FT2)	HEIGHT (FT)	VOLUME (FT3)	CO2 ANALYSIS									AIR CHANGE ANALYSIS		MIN REQUIRED OA (CFM) *
					MINIMUM (PPM)	MAXIMUM (PPM)	AVERAGE (PPM)	% TIME >1000 PPM	% TIME >1100 PPM	% TIME >1200 PPM	% TIME >1300 PPM	% TIME >1400 PPM	% TIME >1500 PPM	SUPPLY ACH	OUTDOOR ACH	
ANGELL ELEMENTARY SCHOOL																
2	CLASSROOM	715	9	6435	424	1128	732	0%	1%	0%	0%	0%	0%	11.2	2.8	310
18	CLASSROOM	1052.4	9	9471.6	432	1112	633	0%	0%	0%	0%	0%	0%	9.5	2.5	350
20	CLASSROOM	1078.5	9	9706.5	444	936	640	0%	0%	0%	0%	0%	0%	9.3	2.5	350
222	CLASSROOM	705	8.8	6204	453	1223	833	18%	4%	0%	0%	0%	0%	11.6	2.9	295
BERKLEY BUILDING BLOCKS (AVERY)																
D101	CLASSROOM (INFANT)	906.32	9.8	8881.936	414	650	580	0%	0%	0%	0%	0%	0%	7.4	2.0	285
D102	CLASSROOM (INFANCT)	900.63	9.8	8826.174	412	801	597	0%	0%	0%	0%	0%	0%	7.5	2.0	285
BURTON ELEMENTARY SCHOOL																
105	CLASSROOM	1017.83	9	9160.47	451	1266	868	21%	9%	3%	0%	0%	0%	9.8	2.6	375
107	CLASSROOM	1013.86	8	8110.88	462	1023	692	1%	0%	0%	0%	0%	0%	11.1	3.0	355
205	CLASSROOM	653.06	9	5877.54	460	1091	766	4%	0%	0%	0%	0%	0%	11.2	3.1	290
207	CLASSROOM	639.31	9	5753.79	419	1067	748	1%	0%	0%	0%	0%	0%	11.5	3.1	310
PATTENGILL ELEMENTARY SCHOOL																
114	CLASSROOM	1444.42	9	12999.78	416	1644	1070	63%	50%	32%	16%	6%	2%	6.9	1.8	565
123	CLASSROOM	754.15	9	6787.35	473	1380	842	24%	10%	4%	1%	0%	0%	10.6	2.7	345
128	CLASSROOM	718.12	9	6463.08	488	1554	914	39%	17%	8%	4%	2%	1%	11.1	2.8	330
207	CLASSROOM	822.59	8.8	7238.792	436	1150	746	7%	1%	0%	0%	0%	0%	9.9	2.5	280
ROGERS ELEMENTARY SCHOOL																
5	CLASSROOM	970	10	9700	495	1450	862	25%	5%	1%	1%	0%	0%	9.3	2.5	360
18	CLASSROOM	1241.28	10	12412.8	454	1123	771	1%	0%	0%	0%	0%	0%	7.3	1.9	370
19	CLASSROOM	704	10	7040	466	1371	912	42%	17%	3%	2%	0%	0%	9.4	2.6	315
20	CLASSROOM	704	10	7040	455	1165	784	3%	1%	0%	0%	0%	0%	9.4	2.6	325
ANDERSON MIDDLE SCHOOL																
104	CLASSROOM	714	8.5	6069	422	1457	880	32%	14%	7%	2%	1%	0%	11.9	3.0	340
125	CLASSROOM	1112.4	8.5	9455.4	417	1508	758	30%	23%	14%	8%	2%	0%	7.6	1.9	425
203	CLASSROOM	896.2	8	7169.6	438	1521	948	46%	28%	14%	7%	2%	0%	10.0	2.5	400
208	CLASSROOM	897	8	7176	430	1318	891	35%	16%	4%	1%	0%	0%	10.0	2.5	360
NORUP INTERNATIONAL SCHOOL																
130	CLASSROOM	1006	8.7	8752.2	430	904	665	0%	0%	0%	0%	0%	0%	8.2	2.1	325
	MUSIC	1389.24	9.2	12781.008	421	1352	777	19%	8%	3%	0%	0%	0%	5.6	1.4	385
	ART	1147.68	9.2	10558.656	411	1142	763	3%	1%	0%	0%	0%	0%	6.8	1.7	480
204	CLASSROOM	712.41	8.5	6055.485	437	1209	781	9%	1%	0%	0%	0%	0%	11.9	3.0	360
BERKELY HIGH SCHOOL																
121	CLASSROOM	901.4	9	8112.6	412	1651	833	33%	25%	17%	7%	2%	2%	7.4	2.6	460
146	CLASSROOM	832.06	8	6656.48	413	1186	688	7%	2%	0%	0%	0%	0%	11.3	4.1	320
205	CLASSROOM	649.09	9	5841.81	409	1488	957	53%	34%	20%	5%	2%	0%	10.3	3.6	430
216	CLASSROOM	713.4	9	6420.6	411	1287	903	49%	23%	6%	0%	0%	0%	11.7	4.2	430
273	CLASSROOM	652.4	9	5871.6	444	1842	1057	59%	46%	35%	23%	13%	7%	10.2	3.6	430

* MIN REQUIRED OA (CFM) IS CALCULATION FROM 2015 MMC REQUIREMENTS WITH OCCUPANCIES PROVIDED BY THE BERKLEY SCHOOL DISTRICT.

ASHRAE Position Document on Indoor Carbon Dioxide

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COMMITTEE ROSTER

The ASHRAE Position Document on Indoor Carbon Dioxide was developed by the Society's Indoor Carbon Dioxide Position Document Committee with Andrew Persily as its chair.

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The authors declare they have no conflict of interest related to the subject of this position document.

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HISTORY OF REVISION/REAFFIRMATION/WITHDRAWAL DATES

The following summarizes this document's revision, reaffirmation, and withdrawal dates:

2/2/2022—BOD approves Position Document titled *ASHRAE Position Document on Indoor Carbon Dioxide*

Note: ASHRAE's Technology Council and the cognizant committee recommend revision, reaffirmation, or withdrawal every 30 months.

Note: ASHRAE position documents are approved by the Board of Directors and express the views of the Society on a specific issue. The purpose of these documents is to provide objective, authoritative background information to persons interested in issues within ASHRAE's expertise, particularly in areas where such information will be helpful in drafting sound public policy. A related purpose is also to serve as an educational tool clarifying ASHRAE's position for its members and professionals, in general, advancing the arts and sciences of HVAC&R.

CONTENTS

ASHRAE Position Document on Indoor Carbon Dioxide

ABSTRACT

Indoor carbon dioxide (CO_2) has played a key role in discussions of ventilation and indoor air quality (IAQ) for centuries. Those discussions have evolved to focus on the use of indoor CO_2 as an IAQ metric, estimation of ventilation rates using CO_2 as a tracer gas, control of outdoor air ventilation based on CO_2 concentrations, and impacts of CO_2 on building occupants. More recently, the measurement of indoor CO_2 has been discussed in the context of airborne infectious disease transmission. However, many applications of indoor CO_2 do not reflect a sound technical understanding of the relationship between indoor CO_2 concentrations, ventilation, and IAQ. Some applications have been technically flawed, leading to misinterpretations of the significance of indoor CO_2. This position document discusses the role of indoor CO_2 in the context of building ventilation and IAQ based on ASHRAE's long involvement with those topics as well as the interests of its members and stakeholders. The positions stated within address the use of CO_2 as a metric of IAQ and ventilation, the impacts of CO_2 on building occupants, the measurement of CO_2 concentrations, the use of CO_2 to evaluate and control outdoor air ventilation, and the relationship of indoor CO_2 to airborne infectious disease transmission. This document recommends research into the impacts of CO_2 on occupant health, comfort, and performance and on the application of indoor CO_2 concentrations in building operation, as well as the development of guidance on the measurement and practical application of CO_2 concentrations.

EXECUTIVE SUMMARY

While indoor CO_2 concentrations have long been considered in the context of building ventilation and IAQ, the meaning of indoor CO_2 as an indicator of IAQ and ventilation is commonly misinterpreted within the HVAC industry and the research community and among the public. Despite many efforts to address this confusion in standards and guidance documents, technical publications, conference presentations, and workshops, significant misunderstandings remain. Given ASHRAE's involvement in ventilation and IAQ research and standards, this position document has been developed to clarify the role of indoor CO_2 and how it can be used to understand and manage building performance. It addresses the history of CO_2 in relation to ventilation and IAQ, what is known about health and cognitive impacts of CO_2 exposure on building occupants, existing standards and guidelines on indoor CO_2 concentrations, limitations in the use of CO_2 as an indicator of ventilation and IAQ, how CO_2 can be used to evaluate and control outdoor air ventilation, increases and variations in outdoor CO_2 concentrations, indoor air cleaning to remove CO_2, and the use of CO_2 as an indicator of the risk of airborne disease transmission indoors. It focuses on non-industrial indoor environments intended for human occupancy, including residences, offices, schools, and transportation environments.

ASHRAE takes the following positions:

- Indoor CO_2 concentrations do not provide an overall indication of IAQ, but they can be a useful tool in IAQ assessments if users understand the limitations in these applications.
- Existing evidence for direct impacts of CO_2 on health, well-being, learning outcomes, and work performance at commonly observed indoor concentrations is inconsistent, and therefore does not currently justify changes to ventilation and IAQ standards, regulations, or guidelines.
- The use of indoor CO_2 measurements to assess and control the risk of airborne disease transmission must account for the definition of acceptable risk, the type of space and its occupancy, and differences in CO_2 and infectious aerosol emissions and their subsequent fate and transport.
- Differences between indoor and outdoor CO_2 concentrations can be used to evaluate ventilation rates and air distribution using established tracer gas measurement methods, but accurate results require the validity of several assumptions and accurate input values.
- Sensor accuracy, location, and calibration are all critical for drawing meaningful inferences from measured indoor CO_2 concentrations.
- Air-cleaning technologies that remove only CO_2 will not necessarily improve overall IAQ and can interfere with systems using CO_2 for ventilation control or IAQ monitoring.

ASHRAE recommends research on the following topics:

- Indoor CO_2 exposure as a modifier of human responses to other environmental factors such as thermal comfort and other airborne contaminants
- The development of IAQ metrics that cover the wide range of indoor contaminants and sources
- Health and performance impacts of indoor CO_2 in concentration ranges typical of non-industrial indoor environments in both laboratory and field settings covering a diverse range of subjects, including variations in age, gender, and health status

- Physiological impacts of elevated CO_2 concentrations, such as changes in blood chemistry and respiration, including those associated with increasing outdoor CO_2 concentrations
- The relationship between indoor CO_2 concentrations and the risks of airborne infectious disease transmission
- Indoor CO_2 concentration measurement, including sensor performance and sensor locations for different applications and the performance and application of low-cost CO_2 sensors
- The use of occupant-generated CO_2 as a tracer gas to estimate building ventilation rates, including approaches that capture transient effects and account for multiple-space ventilation systems and different air distribution approaches
- Strategies for demand-controlled ventilation (DCV) using CO_2 and other indicators of occupancy that overcome limitations of current approaches and control contaminants that are not linked to occupancy
- Indoor CO_2 concentrations, ventilation rates, and occupancy in different building types in different countries to establish benchmark data and better understand the impacts of new building and system designs, tighter construction, advanced operation and control strategies, and other changes in the building stock

ASHRAE also recommends the following activities:

- Development of guidance and standards on indoor CO_2 concentration measurement and sensor selection, especially for DCV applications
- Development of educational programs, conference sessions and workshops, and guidance documents to help practitioners and researchers understand the application of indoor CO_2 concentrations as an indicator of ventilation and IAQ
- Development of guidance on HVAC equipment and controls using CO_2 monitoring
- Development of guidance on the use of CO_2 as a tracer gas for measuring building ventilation rates and air distribution

1. THE ISSUE

Indoor CO_2 has been considered in the context of ventilation and IAQ for centuries. These discussions have focused on two areas: how CO_2 concentrations relate to occupant perception of human bioeffluents and other aspects of IAQ, and the use of CO_2 to evaluate outdoor air ventilation rates. While these topics have been studied for decades, misinterpretation of CO_2 concentration as an indicator of IAQ and ventilation still occurs in the HVAC industry, IAQ research community, and the public. Despite many efforts to address this confusion in standards and guidance documents, technical publications, conference presentations and workshops, significant misunderstanding remains.

In addition to the need to clarify the relationship of indoor CO_2 concentration to IAQ and ventilation, another motivation for this position document is the need to address recent research results on the impacts of CO_2 on human performance at commonly observed indoor concentrations. Given trends of increasing outdoor CO_2 concentrations, additional concerns have been expressed regarding these potential health and performance impacts. Moreover, a variety of organizations and government bodies have issued standards and regulations for indoor CO_2 concentrations in non-industrial workplaces. Also, concerns have long existed regarding the accuracy of indoor CO_2 concentration measurements, which are increasingly common due to the availability and more widespread application of less expensive sensors. Indoor CO_2 monitoring has also been promoted as a ventilation indicator in the context of managing the risks of airborne disease transmission. Finally, most of these applications of indoor CO_2 measurements require values for the rate at which building occupants generate CO_2 and other inputs, and the uncertainty of these values has not been well characterized.

2. BACKGROUND

This section expands on the topics in the The Issue section in support of the positions and recommendations in this document. Specifically, this section covers the history of the role of indoor CO_2 concentrations in the context of ventilation and IAQ, health and cognitive impacts of exposure to CO_2, existing standards and regulations for indoor CO_2 concentrations, CO_2 as an indicator of IAQ and ventilation, use of CO_2 as a tracer gas for estimating ventilation rates, increases in outdoor CO_2 concentrations, air cleaning directed at CO_2 removal, and CO_2 as an indicator of the risk of airborne disease transmission. More detail on these topics, including extensive references for the statements herein, is contained in the appendix to this position document.

2.1 History of CO_2 in Relation to Building Ventilation and IAQ

Carbon dioxide has been discussed in the context of building ventilation since the seventeenth and eighteenth centuries, when CO_2 rather than a lack of oxygen was considered to be a cause of physiological effects attributed to bad air. In the nineteenth century, Pettenkofer stated that it was not CO_2 but the presence of organic material from human skin and lungs that caused the negative effects attributed to poor ventilation, proposing that CO_2 not be considered as a cause of discomfort but rather as a surrogate for vitiated air. In the early twentieth century, studies by Billings, Hermans, Flugge, Hill, and others showed that warmth combined with smells in a crowded room were a source of discomfort in poorly ventilated rooms. The work of Lemberg and later Yaglou showed that occupant perception of body odor produced by humans could be used as a criterion for ventilation. Perceived odor intensity was used as a criterion for ventilation rate requirements of about 7.5 to 10 L/s (15 to 20 cfm) per person, and again CO_2 was not considered to be a pollutant but rather an indicator of body odor. Studies in the latter part of the twentieth century by Fanger, Cain, and Iwashita confirmed the results of Yaglou and Lemberg. This research on body odor perception was used to develop the ventilation requirements in ASHRAE and European Committee for Standardization (CEN) standards. The 1989 edition of ASHRAE's ventilation standard, Standard 62 (subsequently Standard 62.1), had a CO_2 limit of 1000 ppm_v, but this was removed from subsequent editions due to its common misinterpretation.

2.2 Health and Cognitive Effects of CO_2 Exposure

Indoor concentrations of CO_2 greater than 1000 ppm_v have been associated with increases in self-reported, nonspecific symptoms commonly referred to as *sick building syndrome (SBS) symptoms*. However, these observations were not controlled for other contaminants or environmental parameters; therefore, elevated CO_2 concentrations likely served as indicators of inadequate ventilation that increased the concentrations of all contaminants with indoor sources. More recently, several groups have explored the cognitive effects of short-term exposure (2 to 8 h) to pure CO_2 at concentrations between 600 and 5000 ppm_v. Some of these studies demonstrated concentration-dependent impairment, an indicator of a causal effect, but other studies did not show any effects on cognition. These inconsistencies require further investigation, including study of the mechanisms involved. This research is a priority due to the ubiquity of indoor concentrations of CO_2 in excess of 1000 ppm_v.

2.3 Existing Standards and Regulations for Indoor CO_2 Concentrations

Many countries have proposed mandatory or suggested guideline values for indoor CO_2 in non-industrial spaces. It should be noted that the rationales supporting these guideline values are not generally provided along with these guideline values. These indoor CO_2 limits tend to be on the order of 1000 ppm_v but range as high as about 1500 ppm_v. They are generally intended for the management of generic IAQ concerns and SBS symptoms. CO_2 guideline values in the context of airborne infectious disease transmission are discussed in the later section on CO_2 as an indicator of airborne infection risk transmission.

For workplaces, the United States Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH) have established a time-weighted average limit value of 5000 ppm_v for airborne exposure in any 8-hour work shift during a 40-hour workweek and 30,000 ppm_v as a short-term exposure limit, i.e., a 15-minute time-weighted average that should not be exceeded at any time during a workday. ASHRAE Standard 62.1 has not contained a limit value for indoor CO_2 since the 1989 edition of the standard. Misunderstanding of previous editions of the standard continue to lead many to incorrectly attribute a 1000 ppm_v limit to ASHRAE.

2.4 CO_2 as an Indicator of IAQ and Ventilation

As noted previously, indoor CO_2 has been prominent in discussions of ventilation and IAQ for centuries. While CO_2 concentrations are related to the perception of human bioeffluents and the level of acceptance of their odors, they are not a good overall metric of IAQ, as many important contaminant sources do not depend on the number of occupants in a space. For example, contaminants emitted by building materials and those that enter from outdoors are not correlated with CO_2 concentrations. Nevertheless, if outdoor air ventilation rates are reduced in an occupied building, concentrations of CO_2 will increase along with the concentrations of other contaminants generated indoors.

An indoor CO_2 concentration below 1000 ppm_v has long been considered an indicator of acceptable IAQ, but this concentration is at best an indicator of outdoor air ventilation rate per person. This value of 1000 ppm_v has been used for decades without an understanding of its basis, which is its link to the perception of human body odor by building occupants. This misunderstanding of the significance of 1000 ppm_v has resulted in many confusing and erroneous conclusions about IAQ and ventilation in buildings. The use of CO_2 as an indicator of outdoor air ventilation must reflect the fact that outdoor air ventilation requirements depend on space type, occupant density, and occupant characteristics (e.g., age, body mass, and activity levels). Therefore, a single CO_2 concentration does not apply to all space types and occupancies for the purposes of assessing the ventilation rate. Also, CO_2 concentrations can vary significantly within a building or space based on the details of how ventilation and air distribution are implemented.

Indoor CO_2 concentrations have long been used to control outdoor air intake rates, using demand-controlled ventilation (DCV). This control strategy reduces the energy use associated with overventilation during periods of low occupancy and helps to ensure that spaces are adequately ventilated based on their actual occupancy. DCV is in fact required by some energy efficiency standards such as ASHRAE/IES Standard 90.1, and CO_2 monitoring is one means of implementing DCV. Note that this control strategy can be more complex to implement in multiple-space ventilation systems when complying with the ventilation requirements in ASHRAE Standard 62.1 and the designer still must address contaminants not associated with occupancy levels.

2.5 Use of Occupant-Generated CO_2 as a Tracer Gas

The use of indoor CO_2 concentration as an indicator of the adequacy of outdoor air ventilation rates is based on the application of CO_2 as a tracer gas. Tracer gas dilution methods for measuring outdoor air change rates have been used for decades and are well documented in existing ASTM and ISO standards. Application of CO_2 with these methods simply takes advantage of a convenient tracer gas source, the building occupants. Tracer gas methods also exist to quantify air distribution and ventilation efficiency in spaces, and CO_2 can be used for these measurements as well.

There are two common tracer gas methods for estimating outdoor air ventilation rates using CO_2: decay and steady state, both of which are best suited to single zones. Both methods are based on the following assumptions: the tracer gas concentration is uniform in the space being monitored, the outdoor CO_2 concentration is constant during the test (or monitored in real time), and the rate at which occupants generate CO_2 is known and constant for the steady-state method. People emit CO_2 at a rate based on their sex, age, body mass, and level of activity, and therefore information on the occupants is required to estimate these rates. Because these are single-zone methods, they do not account for airflow or CO_2 transport between the zone of interest and other building zones. The measurement errors associated with using a single-zone approach in a space or building that is not a single zone at a uniform concentration are difficult to quantify, and these errors are often neglected in the application of these methods.

2.6 Increases in Outdoor CO_2 Concentrations

Outdoor CO_2 concentrations are relevant to consideration of indoor CO_2 for two reasons. First, when using DCV based on the absolute indoor CO_2 concentration, and not the indoor-outdoor difference, the outdoor air intake rate varies not only with occupancy but also with the outdoor CO_2 concentration. Second, if exposure to CO_2 is established to have health and cognitive impacts, then increases in outdoor concentrations will increase the prevalence of these impacts.

Global average CO_2 concentrations are determined by a complex interaction of sources, sinks, and driving forces. On a geological timescale, they have varied widely, but for hundreds of thousands of years, up until the early twentieth century, they were below 300 ppm_v, first exceeding 300 ppm_v in 1912. Since that time, the average outdoor CO_2 concentration has increased, reaching 420 ppm_v in 2021. Superimposed on the trend of increasing outdoor CO_2 concentration are daily and seasonal variations, as well as larger variations in urban areas. These variations in outdoor CO_2 make it important to measure outdoor concentrations when monitoring indoor CO_2.

2.7 Air Cleaning Directed at CO_2 Removal Alone

While CO_2 may be a useful indicator of ventilation and IAQ under limited circumstances, indoor CO_2 concentrations are not necessarily well correlated with other important indoor air pollutants such as viruses, mold, formaldehyde, carbon monoxide, asbestos, and airborne particles. Using air-cleaning technologies to reduce CO_2 for commonly observed indoor concentrations can result in an unjustified expectation that other indoor pollutants are not a concern. It is critical not to presume that air cleaning directed at CO_2 removal or conversion alone will remove other important indoor air contaminants. Also, when using CO_2-based DCV, the ventilation system will not operate as intended if using CO_2 removal.

2.8 CO_2 as an Indicator of Airborne Infection Risk Transmission

During the COVID-19 pandemic, recommendations have been made to use indoor CO_2 measurement as an indicator of the risk of airborne infection transmission. ASHRAE does not recommend a specific CO_2 concentration as a metric of infection risk, but other organizations have issued recommended or mandated CO_2 concentration limits. Many of these are based on CO_2 as an indicator of the outdoor ventilation rate per person. The ventilation rates on which many of these CO_2 concentrations are based can be derived from ventilation standards that are intended to provide acceptable IAQ but do not target the control of airborne disease transmission, except in healthcare settings. Recommendations or requirements for ventilation rates and CO_2 concentrations to limit infectious disease transmission have been suggested but are highly uncertain given the many factors that impact infection risk, including differences between pathogens.

All else being equal, higher CO_2 concentrations correspond to lower outdoor air ventilation rates and the potential for an increased risk of airborne transmission. While CO_2 concentrations can be a useful qualitative indicator, they do not capture the impacts of the reduced occupancy that is common in many buildings or the impacts of particle filtration and air cleaning on infection risk. Other factors impact exposure and transmission risk, such as the amount of virus in the air (which does not necessarily scale with CO_2), respiratory activity, and type of pathogen. Note also that if CO_2-based DCV is being used, lower occupancy will reduce the outdoor air ventilation rate and presumably increase the risk of transmission, which is why several organizations have recommended disabling DCV systems.

Rather than using indoor CO_2 concentration as an indicator of desired ventilation rates, several analyses of airborne infection risk have used CO_2 as an indicator of the “rebreathed fraction” of indoor air (the fraction of inhaled air that was exhaled by someone else in the space). If the incidence of an airborne disease in the population and the infectious dose of the pathogen are known, these methods can be used to estimate the percentage of new infections for a particular scenario. These methods rely on multiple assumptions about the distribution of indoor CO_2 and infectious aerosol, the relative significance of different infection modes, and dose response relationships that are subject to large uncertainties. Consequently, they may not be highly accurate predictors of risk.

APPENDIX

This appendix contains a detailed and thoroughly referenced expansion of the discussion in the Background section of this position document for readers who desire an in-depth understanding of that material. As does the Background section, this appendix expands on the topics identified in the The Issue section in support of the positions and recommendations in this document: the history of the role of indoor CO_2 concentrations in the context of building ventilation and IAQ, health and cognitive impacts of exposure to CO_2, existing standards and regulations for indoor CO_2 concentrations, CO_2 as an indicator of IAQ and ventilation, use of CO_2 as a tracer gas for estimating ventilation rates, increases in outdoor CO_2 concentrations, air cleaning directed at CO_2 removal alone, and CO_2 as an indicator of the risk of airborne disease transmission.

A.1 History of CO_2 in Relation to Building Ventilation and IAQ

The overview of early CO_2 research discussed in this paragraph is provided by Wargocki (2021). Carbon dioxide has been discussed in the context of building ventilation since the seventeenth century when Mayow proposed igneo-aerial particles produced by candles to cause the demise of animals. In the eighteenth century, Lavoisier attributed the effects of these particles to CO_2. At that time, CO_2 rather than a lack of oxygen was considered to be a cause of physiological effects attributed to bad air and an indicator of whether the air was stale or fresh. In the nineteenth century, Max Josef von Pettenkofer stated that it was not CO_2 but the presence of organic material from human skin and lungs that caused the negative effects attributed to poor ventilation. He and Saeltzer proposed that CO_2 not be considered as a cause of discomfort but rather as a surrogate for vitiated air and an indicator of deleterious airborne substances of unknown origin. Pettenkofer proposed 1000 ppm_v of CO_2 as a marker of inadequate ventilation indoors and 700 ppm_v for bedrooms. In the early twentieth century, studies by Billings, Hermans, Flugge, Hill and others showed that warmth combined with smells in a crowded room were a source of discomfort in poorly ventilated rooms. Experiments with CO_2 increasing to 3% or 4% and oxygen falling to 17% did not show negative effects except for deepened breath and the need for cooling. The work of Lemberg and later Yaglou showed that response to body odor produced by humans could be used as a criterion for ventilation. Perceived odor intensity was used as a criterion for ventilation rate requirements of about 7.5 to 10 L/s (15 to 20 cfm) per person (Persily 2015). CO_2 was, again, not considered a pollutant but rather a marker of body odor perception, since humans emit both CO_2 and bioeffluents at rates related to their metabolism. Studies in the latter part of the twentieth century by Fanger, Cain, and Iwashita, in which acceptability of perceived air quality was used as the criterion for ventilation requirements, confirmed the results of Yaglou and Lemberg. This research on body odor perception was used to develop the ventilation requirements in ASHRAE and European Committee for Standardization (CEN) standards. The 1989 edition of ASHRAE's ventilation standard, Standard 62 (subsequently Standard 62.1), had a CO_2 limit of 1000 ppm_v, but this was removed from subsequent editions due to its common misinterpretation.

A.2 Health and Cognitive Effects of CO_2 Exposure

Carbon dioxide is considered nontoxic at concentrations up to 5000 ppm_v, which is the U.S. federal standard (Permissible Exposure Level) for workplaces set by the Occupational Safety and Health Administration (OSHA) as noted in the later section on existing standards and regulations. Guidelines for the International Space Station and U.S. submarines currently suggest that CO_2 concentrations be maintained at 4000 to 5000 ppm_v to reduce the incidence of headaches (James and Zalesak 2013; Scully et al. 2019). Indoor concentrations greater than 1000 ppm_v have been associated with increases in self-reported, nonspecific symptoms commonly referred to as *sick building syndrome (SBS) symptoms*, as well as decreased performance of office work and schoolwork, as discussed in the following paragraph. These observations were not controlled for other contaminants or environmental parameters; therefore, elevated CO_2 concentrations likely served as indicators of inadequate ventilation that increases the concentration of all contaminants with indoor sources (Persily 2015; Lowther et al. 2021).

Several groups have explored the effects of acute exposure (duration from 2 to 8 h) to pure CO_2 at concentrations between 600 and 5000 ppm_v, as summarized by Fisk et al. (2019), Du et al. (2020), and Lowther et al. (2021). Five studies reported an association between CO_2 and decreased cognitive performance at concentrations in the range of 1000 ppm_v (Satish et al. 2012; Allen et al. 2016, 2018; Kajtar and Herczeg 2012; Lee et al. 2022), and one was equivocal (Scully et al. 2019). While three of these studies demonstrated concentration-dependent impairment, an indicator of a causal effect, other studies did not show any cognitive effects (Zhang et al. 2016a, 2016b). These inconsistencies require further investigation, including study of the mechanisms involved. Further human subject research is a priority due to the ubiquity of indoor concentrations in excess of 1000 ppm_v as well as recent animal work that provides direction for investigation of mechanisms for declines in cognitive function.

Although CO_2 lacks direct chemical reactivity, recent studies with mice show inflammatory changes in the blood at 2000 to 4000 ppm_v and leakage of fluid from blood vessels into brain tissue at 2000 ppm_v (Thom et al. 2017a). Further confirmation of these results was found in in-vitro experiments with human neutrophils (a type of white blood cell) at the same concentrations (Thom et al., 2017b). These findings support the phenomenon of brain toxicity from pure CO_2 and are mechanistically consistent with reports of cognitive changes observed in the human experiments at commonly observed indoor concentrations. Further research to resolve questions regarding the neurotoxicity of CO_2 should be a priority (Jacobson et al. 2019).

A.3 Existing Standards and Regulations for Indoor CO_2 Concentrations

Many countries have proposed mandatory or suggested guideline values for indoor CO_2 in non-industrial spaces. It should be noted that the rationales supporting these guideline values are not necessarily provided in the reference documents and that CO_2 guideline values proposed in the context of the COVID-19 pandemic are not included in this discussion. Pandemic-motivated values are discussed in the later section on airborne infection risk transmission.

Several countries have published indoor CO_2 limits, in some cases for all occupied buildings and in other cases making a distinction between residential and nonresidential buildings. These limits tend to be on the order of 1000 ppm_v but range as high as about 1500 ppm_v. They are generally intended for the management of generic IAQ concerns and SBS symptoms, with CO_2 being used as an indicator of ventilation. Of particular note is the 1000 ppm_v limit in Japan that was issued in 1970; thousands of buildings are tested every year to determine if they comply with the Building Sanitation Maintenance Law.

For workplaces, the United States Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH) have established a time-weighted average limit value of 5000 ppm_v for airborne exposure in any 8-hour work shift during a 40-hour workweek and 30,000 ppm_v as a short-term exposure limit, i.e., a 15-minutes time-weighted average that should not be exceeded at any time during a workday (NIOSH 1976; OSHA 2017).

Despite many statements to the contrary, ANSI/ASHRAE Standard 62.1 (ASHRAE 2019b) does not provide a limit value for indoor CO_2. Misunderstanding of information in previous editions of the standard continue to lead many to incorrectly attribute a 1000 ppm_v limit to ASHRAE. CEN 16798-1 (2019) provides four categories of indoor environmental quality that include CO_2 concentrations above outdoors, noting that these values serve as indicators of outdoor air ventilation rates per person: Category I, 550 ppm_v; Category II, 800 ppm_v; and Category III and IV, 1350 ppm_v. These categories correspond to the expectations of occupants, with normal expectations corresponding to Category II.

Carbon dioxide is also addressed in green building certification programs. Two recent reviews of the major green building certifications developed worldwide and the indicators they use to assess indoor environment quality showed that CO_2 is one of the top IAQ metrics in these certifications (Wei et al. 2015, 2020). However, the reference values used to assess CO_2 concentrations are not uniform, varying from 530 to 1500 ppm_v (Wei et al. 2015).

A.4 CO_2 as an Indicator of IAQ and Ventilation

As previously noted in the history section, indoor CO_2 has been prominent in discussions of ventilation and IAQ for centuries. While CO_2 concentrations are related to the perception of human bioeffluents and the level of acceptance of their odors, they are not a good overall metric of IAQ, as many important contaminant sources do not depend on the number of occupants in a space. For example, contaminants emitted by building materials and those that enter from outdoors are not correlated with CO_2 concentrations. Nevertheless, all else being equal, if outdoor air ventilation rates are reduced in an occupied building, concentrations of CO_2 will increase along with the concentrations of other contaminants generated indoors. This fact likely explains observed associations of increased CO_2 concentrations with higher SBS symptom rates, absenteeism, and other effects (Apte et al. 2000; Shendell et al. 2004; Gaihre et al. 2014; Fisk 2017).

An indoor CO_2 concentration below 1000 ppm_v has long been considered an indicator of acceptable IAQ, but this concentration is at best an indicator of outdoor air ventilation rate per person. That relationship is based on the use of CO_2 as a tracer gas as described in the next section and is associated with an outdoor air ventilation rate of about 8 L/s (16 cfm) per person. This value of 1000 ppm_v has been used for decades without an understanding of its basis, which is its link to the perception of human body odor by building occupants. This misunderstanding of the significance of 1000 ppm_v has resulted in many confusing and erroneous conclusions about IAQ and ventilation in buildings. Use of CO_2 as an indicator of outdoor air ventilation must reflect the fact that outdoor air ventilation requirements are a function of space type and occupant characteristics (e.g., age and body mass), activity levels, and density. Therefore, a single CO_2 concentration does not apply to all space types and occupancies for the purposes of assessing the ventilation rate. Also, CO_2 concentrations can vary significantly within a building or space based on the details of how ventilation and air distribution are implemented.

Indoor CO_2 concentrations have long been used to control outdoor air intake rates, using a process referred to as *demand-controlled ventilation* (DCV) (Emmerich and Persily 1997). This control strategy reduces the energy use associated with overventilation during periods of low occupancy and helps to ensure that spaces are adequately ventilated based on their actual occupancy. DCV is in fact required by some energy efficiency standards such as ASHRAE/IES Standard 90.1 (ASHRAE 2019a), and CO_2 monitoring is one means of implementing DCV. Note that this control strategy can be more complex to implement in multiple-space ventilation systems when complying with the ventilation requirements in ASHRAE Standard 62.1 (ASHRAE 2019b) and the designer still must address contaminants not associated with occupancy levels. Recent research on DCV has led to control sequences for multiple-space systems (Lin and Lau 2015), which must also address the number and locations of sensors in different building zones and variations in CO_2 generation among zones and over time.

A.5 Use of Occupant-Generated CO_2 as a Tracer Gas

The use of indoor CO_2 concentration as an indicator of the adequacy of outdoor air ventilation rates is based on the application of CO_2 as a tracer gas. Tracer gas dilution methods for measuring outdoor air change rates have been used for decades and are well documented in existing standards (ASTM 2011; ISO 2017). Application of CO_2 to these methods simply takes advantage of a convenient tracer gas source, i.e., the building occupants. Tracer gas methods also exist to quantify air distribution and ventilation efficiency in spaces, and CO_2 can be used for these measurements as well. However, most applications of CO_2 as a tracer gas assume the space in question is a single zone at a uniform tracer gas concentration.

As noted in ASTM D6245 (2018), there are two tracer gas methods for estimating outdoor air ventilation rates using CO_2: decay and steady state, both of which are best suited to single zones. Both methods are based on the following assumptions: the tracer gas concentration is uniform in the space being monitored, the outdoor CO_2 concentration is constant during the test (or monitored in real time), and the rate at which occupants generate CO_2 is known and constant for the steady-state method. People emit CO_2 at a rate based on their sex, age, body mass, and level of activity as described in ASTM D6245, and therefore information on the occupants is required to estimate these rates. When reporting the results of these tracer gas measurements, it is essential also to report the uncertainty of the results. ASTM D6245 discusses how to estimate these uncertainties. Because these are single-zone methods, they do not account for airflow and CO_2 transport between the zone of interest and other building zones. The measurement errors associated with using a single-zone approach in a space or building that is not a single zone at a uniform concentration is difficult to quantify, and these errors are often neglected in the application of these methods.

Peak CO_2 concentrations are commonly used to estimate ventilation rates per person using the constant injection tracer gas dilution method. For this approach to yield a valid result, the indoor concentration must be at steady state and the ventilation rate must be constant. Using a CO_2 concentration measured before achieving steady state will overestimate the ventilation rate. In a study of the uncertainty associated with CO_2 tracer gas measurements in an occupied space (Kabirikopaei and Lau 2020), the steady-state approach resulted in the lowest uncertainty and CO_2 sensor accuracy was the dominant factor in determining the overall uncertainty.

A.6 Increases in Outdoor CO_2 Concentrations

Outdoor CO_2 concentrations are relevant to consideration of indoor CO_2 for two reasons. First, when using DCV based on the absolute indoor CO_2 concentration, and not the indoor-outdoor difference, the outdoor air intake rate varies not only with occupancy but also with the outdoor air concentration. Second, if exposure to CO_2 is established to have health and cognitive impacts, then increases in outdoor concentrations will increase the prevalence of these impacts.

Global average CO_2 concentrations are determined by a complex interaction of sources, sinks, and driving forces. On a geological timescale, they have varied widely, but for hundreds of thousands of years, up until the early twentieth century, they were below 300 ppm_v, first exceeding 300 ppm_v in 1912 (EPA 2021). Over the ensuing half century, the average outdoor CO_2 concentration grew slowly, reaching 317 ppm_v in 1960 as measured at the Mauna Loa observatory in Hawaii. Since that time, atmospheric CO_2 concentrations have risen more rapidly, passing 400 ppm_v in 2013 and reaching 420 ppm_v in 2021. The annual growth rate has increased from less than 1 ppm_v per year in 1959 to roughly 2.5 ppm_v per year (NOAA 2021).

Superimposed on the trend of increasing outdoor CO_2 concentration are daily, seasonal, and annual variations. Daily variations are generally small, but a study of concentration over terrestrial ecosystems found an average seasonal peak-to-trough amplitude of 14.8 ppm_v, roughly three times the variation observed at the Mauna Loa observatory (Liu et al. 2015). Seasonal variations are attributable to cycles of biomass and photosynthetic activity of plants, with CO_2 being higher when plants are less active (Cleveland et al. 1983). Urban areas may experience much larger excursions of CO_2 above the global average due to lack of vegetation and the effects of internal combustion engine vehicles, as well as large vertical variations (Lietzke and Vogt 2013). Transient local concentrations may be hundreds of ppm_v above average in some locations, approaching or exceeding 600 ppm_v (Balling et al. 2001). Local concentrations can also be below the average depending on season, time of day, and local vegetation (Liu et al. 2015). These variations in outdoor CO_2 make it important to measure outdoor concentrations when monitoring indoor CO_2.

A.7 Air Cleaning Directed at CO_2 Removal Alone

While CO_2 can be useful as an indicator of ventilation and IAQ under limited circumstances, indoor CO_2 concentrations are not necessarily well correlated with other important indoor air pollutants such as viruses, mold, formaldehyde, carbon monoxide, asbestos, and airborne particles. Using air-cleaning technologies to reduce CO_2 for commonly observed indoor concentrations can result in an unjustified expectation that other indoor pollutants are not a concern.

It is important to distinguish between different air-cleaning technologies and how they impact different types of pollutants. The removal or conversion of CO_2 in the air can be achieved only by chemical reaction processes using sorption-type air cleaners (Hu et al. 2017). The removal of other important indoor contaminants requires other approaches, for example, airborne particle removal by mechanical filters. It is critical not to presume that air cleaning directed at CO_2 removal or conversion alone will remove other indoor air contaminants that might be of more concern. Also, when using CO_2-based DCV, the ventilation system will not operate as intended if using CO_2 removal devices, since these ventilation controls assume that the measured indoor CO_2 concentration is proportional to human occupancy.

A.8 CO_2 as an Indicator of Airborne Infection Risk Transmission

During the COVID-19 pandemic, recommendations have been made to use indoor CO_2 measurements as an indicator of the risk of airborne infection transmission. ASHRAE does not recommend a specific CO_2 concentration as a metric of infection risk, but other organizations have recommended (Centers for Disease Control and Prevention [CDC 2021] in the United

States; Federation of European Heating, Ventilation and Air Conditioning Associations [REHVA 2021] in Europe; and Environmental Modelling Group and Scientific Pandemic Insights Group on Behaviours [EMG/SPI-B 2021] in the United Kingdom) or mandated (Belgian Federal Government [BFG 2021]) CO_2 concentration limits. Many of these are based on CO_2 as an indicator of the outdoor ventilation rate per person, which implicitly involves the use of CO_2 as a tracer gas along with a target ventilation rate. The ventilation rates on which these CO_2 concentrations are based can be derived from ventilation standards, which are not based on the control of airborne disease transmission except in healthcare settings, or from a ventilation rate specifically intended to control transmission. Note that the ventilation requirements in ASHRAE Standard 62.1 (2019b) are a function of space use and occupancy and therefore the corresponding indoor CO_2 concentration varies by space type. For example, the steady-state CO_2 concentrations corresponding to the ventilation requirements in Standard 62.1 range from about 1000 ppm_v in office spaces and classrooms with younger students to between 1500 and 2000 ppm_v in restaurants, lecture classrooms, and retail spaces to above 2500 ppm_v in conference rooms and auditoriums. Recommendations or requirements for ventilation rates and CO_2 concentrations to limit infectious disease transmission have been suggested but are highly uncertain given the many factors that impact infection risk, including differences between pathogens. It is important to bear in mind that ventilation is only one control strategy that should be implemented as part of a layered approach to risk management.

All else being equal, higher CO_2 concentrations correspond to lower outdoor air ventilation rates and potentially an increased risk of airborne transmission. While CO_2 concentrations can be a useful qualitative indicator, they do not capture the impacts of the reduced occupancy that is common in many buildings or the impacts of particle filtration and air cleaning on infection risk. Other factors impact exposure and transmission risk, such as the amount of virus in the air (which does not necessarily scale with CO_2), respiratory activity, and type of pathogen. Note also that if CO_2-based DCV is being used, lower occupancy will reduce the outdoor air ventilation rate and presumably increase the risk of transmission, which is why several organizations have recommended disabling DCV systems or lowering their set points. These two strategies will have different impacts on outdoor air ventilation rates, with the former maintaining design minimum outdoor air intake and the latter potentially increasing outdoor air ventilation.

Rather than using indoor CO_2 concentration as an indicator of desired ventilation rates, several analyses of airborne infection risk have used CO_2 as an indicator of the “rebreathed fraction” of indoor air (the fraction of inhaled air that was exhaled by someone else in the space). If the incidence of an airborne disease in the population and the infectious dose of the pathogen are known, these methods can be used to estimate the percentage of new infections for a particular scenario (Rudnick and Milton 2003; Peng and Jimenez 2021). These methods rely on multiple assumptions about the distribution of indoor CO_2 and infectious aerosol, the relative significance of different infection modes, and dose response relationships that are subject to large uncertainties. Consequently, they may not be highly accurate predictors of absolute risk.

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