Revisiting the 1,000 ppm CO_2 Limit

ROBERT E. STUMM P.E.

The 1989 revision of ANSI/ASHRAE Standard 62, *Ventilation for Acceptable Indoor Air Quality*, states that "comfort (odor) criteria are likely to be satisfied if the ventilation rate is set so that 1,000 ppm CO_2 is not exceeded";[1] an accompanying, informative Appendix D describes the mathematical relationship between ventilation rates and steady-state indoor carbon dioxide (CO_2) levels. However, the recommendation regarding CO_2 has changed over the years. Standard 62-1999 replaced the original limit with a guideline stating that indoor CO_2 concentrations should be 700 ppm or less above the ambient outdoor concentration. Standard 62.1-2019 entirely removed both the guideline and Appendix D. Over the years, many practitioners concerned about air quality have mistakenly continued to refer to the 1,000 ppm CO_2 absolute limit of Standard 62-1989 as an indicator of acceptable indoor air quality[2]—but then again, it may be not a mistake after all.

Airborne Pollutants

Many key airborne pollutants affecting human comfort and wellness are by-products of hydrocarbon fuel combustion or biological activity. Indoors, the by-products are predominantly from human respiration, but they can also be from other factors, including bacterial growth and fungi that create microbial volatile compounds (MVOCs), which can cause spaces to smell and impact human health.[3]

Outdoors, the majority of by-products impacting human health are from hydrocarbon combustion, but they can also derive from biological activity of plants, as in the generation of pollen, as well as of bacteria and fungi. The U.S. Environmental Protection Agency (EPA) regulates six common pollutants outdoors: particulates, ozone, nitrogen dioxide, carbon monoxide, lead and sulfur dioxide.[4] However, IAQ can be compromised by a large mixture of pollutants, especially when unprocessed air is brought in from the outdoors.

CO_2 as a Surrogate Air Quality Measure

CO_2 is a stoichiometric by-product of both hydrocarbon fuel combustion and biological metabolism. Therefore, the amount of CO_2 produced is in general in

Robert E. Stumm, P.E., is retired. He served 38 years in the U.S. shipbuilding industry with Newport News Shipbuilding.

proportion to whatever other by-products are produced, depending on the specific reaction. CO_2 is considered not to be a health hazard at low concentrations, but it can be measured easily. Thus, although it is not foolproof or absolute in any sense, as many deviations do exist, measuring CO_2 concentration offers an easy, albeit indirect, way to gage the concentration of the other pollutants.

The use of CO_2 as a surrogate air quality and ventilation measure was proposed in 1858.[5] Over the years, it has come to be regarded by many as a fair indicator of both indoor air quality and the adequacy of the ventilation in a space. Also in 1858, the CO_2 concentration of 1,000 ppm or less was introduced as a rule of thumb for helping to decide when air is "clean." The value was determined from anecdotal observations of when people became uncomfortable in various indoor spaces.[5]

In more recent times, the suggestion has been made that CO_2 monitoring be used to help control the spread of coronavirus.[6] As human exhalation is usually the primary source of CO_2 in an occupied space, an elevated CO_2 level could imply that one may be breathing others' exhalation, possibly laden with infectious particles. Thus, additional ventilation is required. A tuberculosis outbreak at a university in Taipei was stopped when air ventilation was increased and CO_2 levels were brought down to 600 ppm above the outdoor ambient CO_2 level.[7]

These examples show the utility of managing CO_2 concentrations relative to outdoor air levels, as specified in Standard 62-1999's guidance for ventilation rates to achieve CO_2 levels below 700 ppm above outdoor levels for controlling human bioeffluent concentrations in sedentary settings.[2]

One should be to derive an absolute indoor CO_2 level limit for satisfactory air from a relative level by taking the 700 ppm relative value from Standard 62-1999 and adding to it the outdoor CO_2 concentration, which was just under 350 ppm in 1989.[8] Thus:

$$700\text{ ppm} + 350\text{ ppm} = 1{,}050\text{ ppm} \tag{1}$$

This results in an absolute CO_2 limit of about 1,000 ppm, which is the value cited in Standard 62-1989.

Outdoor CO_2 Levels

There is much that is erroneous about the computation presented in *Equation 1*. Most concerning should be the value for outdoor CO_2 concentrations. It is no longer 1989, and outdoor CO_2 levels have been, and are still, rising. As of this writing, the CO_2 level at the Mauna Loa Observatory in Hawaii is 417 ppm.[8] Climate models that assume intensive use of hydrocarbon fuels into the future predict that CO_2 levels will possibly reach near 1,000 ppm by 2100.[9,10] At continued rates of per capita fuel consumption, population growth and deforestation, CO_2 levels of 600 ppm may be seen within the next three decades.[9]

TABLE 1 Nominal daily maximum CO_2 levels (ppm) at select urban sites compared with Mauna Loa values.

SITE	DATA YEAR	MAUNA LOA	URBAN	DIFFERENCE
Phoenix, Ariz.	2000	369	575[12]	206
Baltimore	2006	382	488[13]	106
Evanston, Ill.	2011	392	440[14]	48
Los Angeles	2015	400	622[15]	222

Mauna Loa Data from Reference 8. Data current as of July 2021.

In addition, urban centers are heavy sources of CO_2 emissions, and they exhibit notably higher CO_2 levels than those found on the Hawaiian mountaintop. These centers are often encased by "CO_2 domes" in which CO_2 concentrations are markedly higher than in their adjacent rural areas.[11] Urban CO_2 levels exhibit seasonal cycles and daily variances. A sampling of CO_2 levels at urban sites is presented in *Table 1*.

With constantly rising ambient CO_2 levels and local outdoor CO_2 levels in variance, the merit of an absolute CO_2 level for guiding building ventilation practice is questionable—unless, of course, there is an absolute CO_2 level that really is proportionate to some certain airborne pollutant concentration, whether it be indoors or outdoors.

Aggregation of Indoor and Outdoor Air Pollutants

Many outdoor air pollutants can exacerbate the same human body response mechanisms and stress the same body organs as indoor air pollutants. Combined, their effects may be compounding. It thus makes sense for ventilation practitioners to concern themselves with the aggregation of pollutants from outdoor and indoor air. Numerous indoor air quality studies suggest that while there is no clear CO_2 concentration threshold below which "good" air quality is perceived, some people begin to note diminishing air quality indoors when ventilation rates are brought down to where CO_2 values are around 500 to 600 ppm.[16] One international

TABLE 2 Human body effects of EPA regulated pollutants.

POLLUTANT	SYMPTOMS	TARGET ORGANS
Particulates	Asthma, lung inflammation, decreased lung function, irregular heartbeat	Respiratory tract, cardiovascular (heart)
Ozone	Asthma, breathing difficulties, lung inflammation	Respiratory tract
Nitrogen dioxide	Eye, irritation, respiratory irritation, fatigue	Lungs
Carbon monoxide	Dizziness, headache, nausea, shortness of breath, chest pain	Cardiovascular
Lead	High blood pressure, joint and muscle pain, headache, difficulties with memory or concentration	Skeletal system, nervous system, kidneys, immune system, cardiovascular, reproductive system
Sulfur dioxide	Breathing difficulties, chest tightness	Respiratory tract, eyes

Data primarily derived from https://www.epa.gov/criteria-air-pollutants

Tabulation of symptoms, health effects, and target organs is representative, and not inclusive.

performance-based standard (RESET) specifies a CO_2 limit of 600 ppm for “high-performance” ventilation.[17] The prevalence of sick building syndrome symptoms (eye/throat/nose irritation, breathing difficulty, headache, nausea and dizziness, and mental fatigue) is often associated with poor air quality.[16]

A statistical analysis[18] of data from the EPA’s Building Assessment Survey and Evaluation study, which collected air quality data from 100 office buildings throughout the United States over a five-year period,[19] found a significant correlation between indoor CO_2 levels relative to outdoor CO_2 levels and some sick building syndrome symptoms. The results suggest that increasing ventilation rates, and thus reducing indoor CO_2 levels, will also significantly reduce the prevalence of certain sick building syndrome symptoms, even in buildings with initial CO_2 levels at or below 1,000 ppm.[18]

Table 2 presents a tabulation of nominal health effects from the six outdoor pollutants regulated by the EPA. The effects appear to be fairly similar to the symptoms associated with sick building syndrome.

Correlations between outdoor CO_2 levels and some outdoor pollutant concentrations have been made in a few urban areas,[11,20,21] but while CO_2 serves as a good indicator of the presence of airborne pollutants, the linear relationships are highly dependent on locality and time.[20] Additionally, municipalities monitor the six pollutants defined by the EPA, but do not monitor concurrent CO_2 levels. Also, nationwide average EPA-regulated pollutant levels have been dropping in the United States,[4] while world CO_2 levels have been consistently going up.[8] The ratio between airborne pollutants and CO_2 thus clearly changes over time. Adding CO_2 to the data collection would help researchers to understand better what relationships and trends may exist over time and in different localities. Such knowledge could be valuable in optimizing demand-controlled ventilation systems[22] and any ventilation system where outdoor air is brought in.

One study[21] finds correlation between indoor and outdoor CO_2 levels as well as between corresponding indoor and outdoor particulate concentrations in urban homes. Basically, as outdoor pollution goes up, so does indoor pollution.

Studies focusing on CO_2 impacts on biological organisms and their respective pathogenicities find that higher CO_2 levels generally enhance plant growth. It has been shown that CO_2 stimulates earlier and greater allergenic pollen production.[23] Bacterial and fungal reactions to CO_2 vary depending on whether they make or consume CO_2 in their metabolism. *Alternaria alternata* and *Aspergillus fumigatus* are two asthma-inducing fungi commonly found indoors as well as outdoors.[24,25] Studies have demonstrated that elevating CO_2 concentrations from present outdoor levels to around 500 ppm significantly increases the allergenicity of these two species.[26,27]

It is expected that the rise in CO_2 and the resulting climate change will cause changes in biological activity, which will in turn increase asthma and allergies.[25] However, it is noted that humidity and hygiene are considered to be greater contributing factors to bacterial and fungal activity than CO_2. While many fungi found indoors give off CO_2 along with their characteristic MVOCs, this author found no studies that positively correlate fungal/bacterial activity with building space CO_2 levels. One study investigating the matter was unable to find a significant relationship.[28]

Summarizing the preceding discussion, studies suggest that (1) outdoor pollutants exist in rough proportion to respective outdoor CO_2 levels, (2) indoor pollutants giving rise to certain sick building syndrome symptoms exist in some proportion to indoor CO_2 levels, (3) indoor

CO_2 levels are generally proportionate to outdoor CO_2 levels, and (4) the effects of outdoor pollutants on human wellness appear to be similar to symptoms of sick building syndrome. It all stands to reason because CO_2 and the subject air pollutants are inherently coupled by the combustion and biological processes that produce them.

Suggested here is that some statistical correlation may exist between the concentration of CO_2 and that of the aggregate of other by-product pollutants affecting human comfort and wellness. As there is likely a threshold for the aggregate of subject air pollutants beyond which human physiology no longer tolerates them, it then follows that there might also exist some value for CO_2 concentration above which air quality is likely no longer acceptable—maybe 1,000 ppm?

While variables in CO_2 measurement,[16] and variables causing changes in ratios between CO_2 and other pollutants are many, further study of these hypotheses may still be worth pursuing. However, the debate may be sidestepped should CO_2 itself—until recently thought of as the benign surrogate—turn out to be a principal source of discomfort and illness.

Direct CO_2 Effects

On the International Space Station, the atmosphere is tightly controlled. CO_2 levels are kept notably higher than in most earthbound indoor spaces because CO_2 is difficult to remove; CO_2 removal equipment size becomes overwhelming for spacecraft of limited size. For long missions, the maximum allowable CO_2 concentration was originally 5,000 ppm, and higher concentrations were permitted for shorter periods. However, space station astronauts experienced physical symptoms, most notably headaches, at CO_2 levels two-thirds lower than was expected.[29] CO_2 levels have been brought down a bit, but enduring headaches and other maladies of exposure to the CO_2 levels experienced on spacecraft for prolonged periods of time is now a recognized occupational hazard for space crews.[30]

Studies are emerging suggesting that prolonged exposure to CO_2 may pose health risks at levels presently accepted for comfort and wellness. Studies summarizing the studies also exist.[31,32] While most studies show CO_2 causes few acute overt health symptoms at levels below 5,000 ppm,[31] several studies do state the likelihood of several ailments from chronic CO_2 exposure at levels well below 5,000 ppm, including:[32]

- Chronic low-grade inflammation exciting respiratory and cardiovascular illnesses;
- Appetitive behaviors leading to obesity;
- Bone demineralization;
- Kidney calcification;
- Chronic low-grade metabolic acidosis increasing the risk of kidney and liver disease, type 2 diabetes, loss of skeletal muscle, and osteoporosis;
- Oxidative stress leading to carcinogenic effects and accelerated aging; and
- Mild hypercapnia (excess CO_2 in bloodstream) having symptoms that include flushed skin, drowsiness, headaches, shortness of breath, increased heart rate and being abnormally tired or exhausted.

Of particular interest are several studies providing substantial evidence of acute exposure to CO_2 at levels as low as 1,000 ppm inducing significant reductions in cognition and decision-making abilities.[31,32]

As described by the medical community, breathing under normal conditions is primarily regulated by the CO_2 concentration in the bloodstream via blood acidity (pH) level, which in turn is proportional to the concentration of CO_2 in the air breathed. If breathing air CO_2 concentration goes up, breathing becomes deeper and more rapid. Recent studies show "clear linear physiological changes in circulatory, cardiovascular and autonomic systems, including increased heart rate, and increased sympathetic stimulation at CO_2 exposures in the range of 500 to 5,000 ppm."[33]

Although more study is needed, the effects of lifetime chronic exposure to moderately elevated levels of CO_2 on human health would be difficult to prove. A real-life environment in which to test a statistically sampled population over its lifetime has yet to come about, and hopefully never will. However, a preponderance of existing literature already suggests a sufficient likelihood that CO_2 levels have a direct effect on human wellness. A few studies posit that the risks of elevated CO_2 can be serious.[34,35] In this author's opinion, considering the consequences if one mistakenly assumes that elevated CO_2 levels do not pose a direct risk, the assumption should be made that they do. Liabilities for discounting "sufficient likelihood" can be high.

An absolute indoor CO_2 limit would be useful not only to help guide air quality assessments, but also to guide environmental policies. Considering the recent studies showing CO_2 directly impacting human health, in particular cognition and decision-making, the indoor CO_2 level of 1,000 ppm reappears as a sensible, time-honored upper limit; action should be taken if it is exceeded, and systems should be designed to avoid it.

The Canadian government, for example, recently adopted 1,000 ppm as the recommended maximum continuous exposure limit for CO_2 for residential indoor air quality.[36] The lower level of 600 ppm, as specified in the RESET standard, appears as a possible guideline below which air can be considered satisfactory to most people. Unfortunately, if an indoor air quality absolute limit is set for the concentration of CO_2, a corollary thereto debuts as a most inconvenient realization: it can no longer be assumed that outdoor air will be “fresh.”

The Future for Ventilation

The implication for the HVAC community is enormous. With rising ambient CO_2 levels and additional consideration for urban centers submerged in CO_2 domes, buildings with ventilation systems designed to achieve 700 ppm CO_2 concentrations above the outdoor air may no longer have the indoor air quality originally intended. In future years, the issue will become more aggravated. Specifying a 1,000 ppm absolute limit for CO_2 can hold off creep in indoor air quality loss, but at the cost of ever greater ventilation rates. Should outdoor CO_2 levels actually approach 1,000 ppm, ventilation systems for maintaining indoor air will be overwhelmed. Other technologies to reduce CO_2 will have to be made.

Possibly buildings of the future will be set upon limestone beds that absorb CO_2 out of the building air as it is circulated through them. Gas furnace heating systems may exhaust into tanks filled with lithium hydroxide that can be emptied from time to time, much like a septic tank. Maybe CO_2-sequestering indoor microforests will become fashionable. Maybe ventilation filter media can be laced with CO_2-absorbing fungi[37] to freshen the air. Another option is to let building occupants grapple with CO_2 levels above what is truly satisfactory for sound comfort and wellness, much as space crews must. Building occupants might get a bottle filled with fresh air[38] should they desire a moment of relief.

HVAC practitioners will likely find their work scopes expanding to include managing outdoor air to an even greater extent. It may include helping lower ambient outdoor CO_2 levels, dispersing CO_2 domes or creating “fresh air domes” in urban centers. The prospects sound more appropriate for a science fiction novel. Suffice it to say that HVAC practice is entering a brave new world.

Realistically, this author knows of no technologies that can be practically applied to buildings, especially residential buildings, to reduce indoor CO_2 levels when outdoor CO_2 levels approach the level desired inside. Rather than contending with high outdoor CO_2 levels, it might be better to actively work to help mitigate the anthropogenic activities that are causing the rise in outdoor CO_2 levels with the hope that the unfortunate situation does not come to pass.

Much presented here merely repeats the conclusions of the prior work upon which this article draws. The studies referenced herein cite numerous other studies; together these studies form an aggregate that the reader is encouraged to peruse. The purpose here is to highlight this body of work, to bring attention to the climate models that predict when the subject CO_2 levels will be reached and, with that, hopefully to help establish a sense of urgency regarding rising atmospheric CO_2 levels.

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