Measure CO_2 to Improve VENTILATION/IAQ

A CO_2-logging primer for facility managers and building engineers of offices, schools, healthcare facilities and residential communities.

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Images courtesy of Onset.

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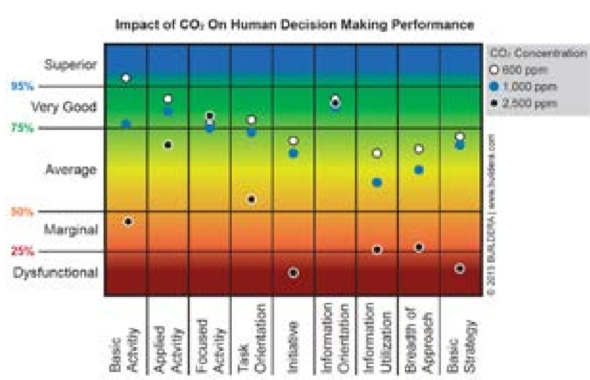
Scientific and medical research correlates poor indoor-air quality (IAQ) and elevated carbon dioxide (CO_2) levels to occupant discomfort and productivity loss in offices, schools, healthcare facilities and dwellings. CO_2 is a trace pollutant that impairs cognitive and respiratory function. Sustained concentrations exceeding 600–700 ppm over outside levels are associated with inadequate ventilation and, thus, serve as a convenient proxy for overall indoor-air health.

The U.S. EPA identified IAQ as one of the top five most urgent environmental risks to public health. Facility managers and building engineers are often responsible for ensuring optimal ventilation in work and living spaces, yet many are unfamiliar with the scientific rationale or methods to achieve such control. Wireless data loggers that measure CO_2, together with temperature and humidity, provide critical real-time awareness—essential to enforcing high environmental standards for occupants.



Moderate to elevated levels of indoor CO_2 result in lower scores on six of nine scales of human decision-making performance.

With long-term CO_2 monitoring, building operators can gain insights to support better decisions regarding ventilation control and HVAC upgrades—projects that can lead to significant energy savings and improved overall IAQ. Comprehensive, location-specific CO_2 data in building environments also helps to focus HVAC improvements on the most effective and cost-efficient solutions.

Fortunately, battery-powered CO_2 data loggers easily measure indoor concentrations. These compact hand-held devices—roughly the same size and shape as a wall-mounted home thermostat—may reside anywhere throughout a building where CO_2 data is needed. Measurements typically range from 0–5,000 ppm. Today's newer options enable users to access data from mobile devices and quickly download data directly to a laptop, or from the cloud.

This primer explains risks of elevated CO_2 with a global perspective, and how data logging can be a cost-effective indicator of degraded IAQ and sick-building syndrome (SBS). Practical measurement and logger-selection tips help facility managers and building engineers make informed deployments, including proper sensor calibration and placement in service.

High indoor CO_2 concentrations

ASHRAE defines acceptable IAQ as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction."

A key marker of IAQ is carbon dioxide. At low densities, CO_2 is odorless and tasteless. However, its differential indoor concentration is a surrogate for certain air-quality metrics, particularly occupant perception of odorous bioeffluents (body odor). Not only does inadequate building ventilation promote excess moisture and mold, but elevated CO_2 increases complaints of stale air while impairing occupant productivity and decision-making.

In a groundbreaking controlled study, according to the Lawrence Berkeley National Laboratory, "On nine scales of decision-making performance, test subjects showed significant reductions on six of the scales at CO_2 levels of 1,000 ppm and large reductions on seven of the scales at 2,500 ppm. The most dramatic declines in performance, in which subjects were rated as 'dysfunctional,' were for taking initiative and thinking strategically."

This research challenges the conventional wisdom that CO_2 concentrations of 5,000 ppm are acceptable occupational limits in the work environment. Imagine the impact on office workers, instructors, students, and medical professionals when critical cognitive and decision-making functions degrade. Although this study did not test learning ability versus CO_2 concentration, it clearly demonstrated impaired cognitive and decision-making abilities, which could impact student reasoning and test scores. This is a wake-up call for educators globally, and warrants further research.

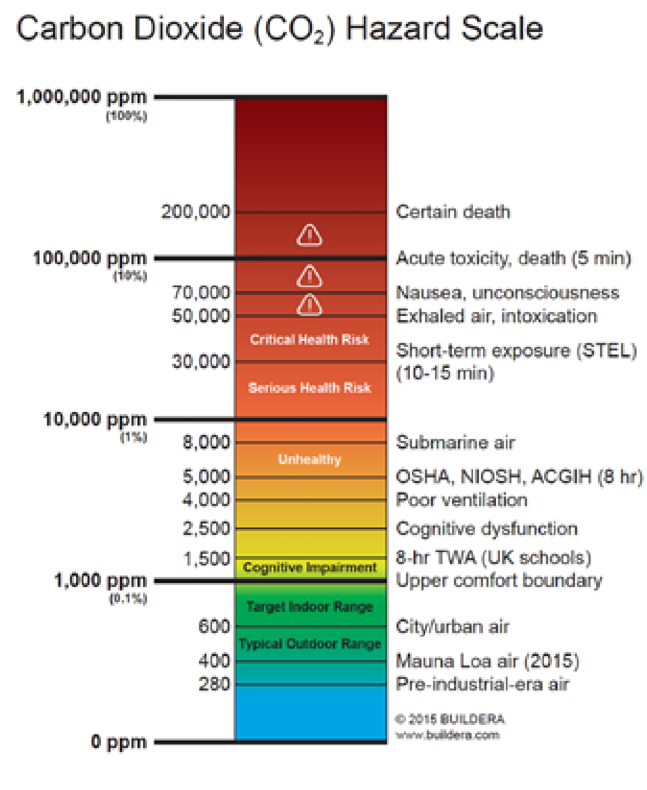
Energy conservation vs. IAQ

Recent and emerging global building standards dictate tight building envelopes that purposely restrict outside-air infiltration in an effort to conserve energy and reduce carbon footprint. Ironically, these well-intentioned conservation measures compete with the need to reduce indoor-air pollutants, including volatile organic compounds (VOCs), tobacco smoke (where existing), carbon monoxide (CO), and CO_2 buildup from anthropogenic sources. Moreover, existing ventilation standards are typically minimum recommendations and may not result in optimal air quality or cognitive function, particularly during peak occupancy.

Newer, modern structures rely increasingly on adaptive demand-controlled ventilation (DCV) that modulates air exchange according to real-time measurement of CO_2 concentration—a proxy for occupant load. When properly deployed and calibrated, auxiliary CO_2 loggers can be useful throughout such DCV facilities to ensure that the ventilation system is working as intended, and to identify potential duct blockages or control-system issues.

Unfortunately, most existing offices, schools, and smaller healthcare facilities do not have this ventilation technology. They rely instead on fixed mechanical systems and natural ventilation, blind to dynamic occupancy levels and other environmental factors. At certain times of the year, when inside-outside temperature differentials are large, windows may be shut to conserve energy, promoting high CO_2 concentration and trapping unhealthful indoor pollutants.

As a result, marginal or poor IAQ is commonplace in conference rooms, auditoriums, school classrooms, healthcare facilities and residential dwellings. Studies from around the world consistently document elevated indoor CO_2 concentrations ranging from under 1,000 ppm to extremes over 6,000 ppm—far exceeding the threshold of cognitive dysfunction previously noted.



Carbon-dioxide health hazard versus concentration.

While fossil-fuel combustion and plant photosynthesis largely drive atmospheric CO_2 concentration, indoor CO_2 concentrations vary widely due to factors such as number of occupants, ventilation rate, air volume, unvented combustion, and organic decay from food and garbage. Without proper ventilation, SBS spreads.

Table 1 compares acceptable CO_2-concentration thresholds established by ASHRAE and other global governments and standards bodies. In most cases, these figures do not factor in the most recent research correlating even modest CO_2 levels with cognitive function. Conversely, these figures define levels at which human health may be impacted without regard to impairment of cognitive abilities or perception of poor IAQ. Figures specifically exclude sensitive individuals who would benefit from even lower concentration levels. Furthermore, studies show strong correlation of even 100 ppm over outside air to be positively correlated to increased likelihood of sore/dry throats, wheezing, and other respiratory issues.

When assessing indoor levels, it is important not only to measure absolute CO_2 ratios, but also compare them to outdoor levels. Ventilation effectiveness relates to the difference between indoor and outdoor levels, whereas health considerations and cognitive function correlate both to overall ventilation, as well as the absolute CO_2 levels present in a structure.

CO_2 Exposure Limits for Selected Countries			
Country	Agency/Standard	Maximum Level	Notes
America (USA)	ASHRAE 62.1-2013 Appendix C	700 ppm above outside levels	This is a measure of occupant discomfort, not an absolute health guideline. The ASHRAE 1,000 ppm guideline has since been redacted.
	Occupational Safety and Health Administration (OSHA)	5,000 ppm (PEL-TWA) 30,000 ppm (STEL) (CAL/OSHA)	TWA=Time-weighted over five 8-hour work day average for industrial environments
	CDC/NIOSH	5,000 ppm (REL-TWA) 30,000 ppm (STEL) [15 min]	Non-narcotic central nervous system effects (eye flickering, psychomotor excitation, myoclonic twitching, headache, dizziness, dyspnea, sweating, restlessness)
	ACGIH	5,000 ppm 30,000 ppm [15 min]	
Australia	Safe Work Australia; Workplace Exposure Standards for Airborne Contaminants (2011)	5,000 ppm (TWA) 30,000 ppm (STEL)	12,500 ppm TWA allowable in coal mines with 30,000 STEL
Canada	Federal-Provincial Advisory Committee on Environmental and Occupational Health	3,500 ppm (ALTER)	Exposure guidelines for residential indoor-air quality
Germany	Deutsche Forschungsgemeinschaft (DFG)	5,000 ppm (MAK)	8-hour work day average
	DIN 1946-6 DIN 1946-2	1,000 ppm (recommended) 1,500 ppm (upper limit)	Recommended Outside Air: 30m³/h per person; Minimum 20m³/h per person
Japan	Japan Society for Occupational Health (2004)	1,500 ppm	
New Zealand	Ministry of Business, Innovation and Employment	5,000 ppm (TWA) 30,000 ppm (STEL)	Workplace Exposure Standards and Biological Exposure Indices 7th Edition (2013)
Sweden	Occupational Exposure Limit Values, AFS 2011:18	5,000 ppm (LLV) 10,000 ppm (STV)	Sweden sets a Short-Term Value (STV) 3x below most nations
UK	Health and Safety Commission (HSE) – UK	5,000 ppm (LTEL) 15,000 ppm (STEL) [15 min]	Industrial environments per EH40/2005 Workplace Exposure Limits
	UK Building Bulletin 101	1,500 ppm	School average levels for full day not to exceed (UK)

›› Table 1 **CO_2 occupational exposure limits for select countries.**

Relating CO_2 concentration to ventilation rates

Table 2 estimates internal carbon dioxide levels for a given ventilation rate per person. Figures are based on sedentary metabolic rates and are considered minimum acceptable values. ASHRAE 62.2-2013 Ventilation and *Acceptable Indoor Air Quality in Low-Rise Residential Buildings*—the latest edition of the standard at the time of writing—does not establish CO_2 limits in low-rise residential buildings. It does state, however, that minimum ventilation rates shall be:

Qtot = 0.03Afloor + 7.5(Nbr + 1)

Where:

→*Qtot* = total required ventilation rate, cfm;

→*Afloor* = floor area of residence, sq ft; and

→*Nbr* = number of bedrooms (not to be less than 1).

Thus, a 2,500-sq-ft residence with four bedrooms would require at least 113 cfm of whole-building ventilation. Specific areas such as bathrooms and kitchens have a minimum additional demand-controlled ventilation of 100 cfm (50 L/s) and 50 cfm (25 L/s), respectively. Ventilation rates for multifamily buildings are slightly higher, and include a provision of 0.06 cfm per sq ft (30 L/s per 100 m^2) of floor area for common areas within the conditioned space.

However, these minimum levels may not be sufficient to keep CO_2 levels to acceptable thresholds, particularly in high-occupancy facilities. Thus, the need to deploy data loggers carries more importance as facility managers and engineers pay attention to CO_2 risks in their buildings.

Carbon Dioxide	Outside Air Per Person	CO_2 Differential (inside-outside)
800 ppm	20 cfm or less	400 ppm
1,000 ppm	15 cfm or less	600 ppm
1,400 ppm	10 cfm or less	1,000 ppm
2,400 ppm	5 cfm or less	2,000 ppm

Table 2 **Adapted from Washington State University Extension Energy Program, these figures are approximate based on a constant number of sedentary adult occupants, a constant ventilation rate, and an updated outdoor air CO_2 concentration of 400 ppm (was 380 originally).**

CO_2 data logger choice

Choosing the right logger can be daunting without first understanding key differentiators between available devices. Although many loggers today offer comparable measurement range and sensor accuracy, usability factors, including connectivity options, alarming, battery life and long-term calibration costs, vary more widely. The following are several attributes to consider when looking at data loggers:

Bluetooth capability—Smart wireless technology provides efficient data collection, easy management with data sharing and overall user-friendly operation. Some CO_2 data loggers now incorporate Bluetooth Low Energy (BLE) technology that retrieves data and logger status faster using a mobile phone. BLE CO_2 data logger can record and transmit wirelessly to mobile devices on demand, essentially streamlining IAQ studies and decreasing the time and costs associated with monitoring programs. BLE solutions are particularly advantageous when deploying multiple data loggers inside buildings, or in hard-to-reach locations where physically downloading data from the logger would otherwise prove difficult. Ventilation-system monitoring is one example where loggers may reside out-of-reach (to avoid tampering), or inside a return-air duct.

Alarm notifications—CO_2 data loggers that feature programmable alarm notifications issue audible alerts and display visual warnings during a qualified trigger event, such as a CO_2 concentration that exceeds a healthy threshold. Options that provide both keep building managers alert to problems as they occur, aiding efficient corrective action.

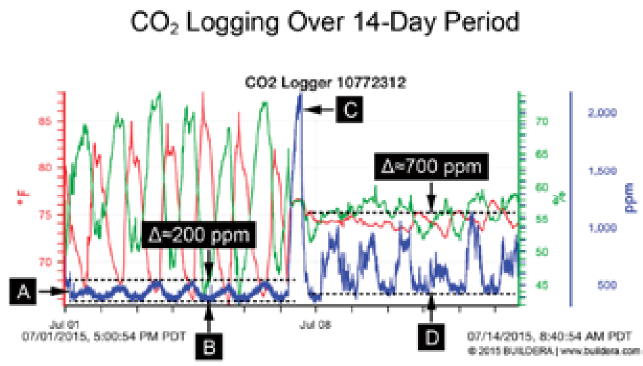
Battery life—Long battery life is an important factor because it provides flexibility, increased spatial coverage, and the ability to set up monitoring in locations where no AC power exists, such as in—or near—HVAC return-air ducts.

Integrated USB—USB ports improve flexibility of data access and analysis giving users the ability to connect a CO_2 data logger directly to a computer to run graphing/analysis software, and help enable quick plotting, comparison, and data extraction. A USB port can additionally support a wider range of application scenarios.

Calibration—When assessing calibration and operating costs, aim for products that offer both manual and automatic calibration methods, as well as elevation/altitude compensation. The sensor subsystem inside most CO_2 loggers requires periodic calibration to a known reference and careful placement to avoid erroneous results. Some also include automatic temperature and dynamic pressure compensation, but are typically less common on mid-range products. Many commercial loggers use maintenance-free non-dispersive infrared (NDIR) sensing technology. This consists of a gas chamber, IR source transmitter, optical filter, and IR detector. The detection wavelength is tuned to measure the concentration of CO_2 molecules to a reasonable degree of precision. Depending on the sensor design, the transmitter and detector can drift over time, causing long-term errors and under-reporting of actual CO_2 concentrations. While optimal calibration methods require calibrated gas concentrations and sealed test chambers, this is not cost effective or practical for maintenance personnel, particularly where a large number of devices may be operating. Manual and automated calibration algorithms improve accuracy for typical CO_2 logging applications, while keeping operating and maintenance costs to a minimum.

Calibration options and differential measurements

In the manual calibration mode, the user calibrates the logger outdoors, using exterior CO_2 concentration as a calibration baseline. As of the time of writing, most loggers adopt 400 ppm as the outdoor reference concentration, which is based on normalized data from global atmospheric observatories. However,



iPhone plot from a Bluetooth logger showing temperature, humidity, and CO_2 concentration between July 1-14, 2015 in the San Francisco Bay Area of California. A. The initial baseline correction to 400 ppm on July 1, 2015 after first manual outdoor calibration. B. Sinusoidal variation in CO_2 represents outdoor diurnal concentration variation with approximately 200-ppm peak-to-peak variation between late afternoon (min) and early morning (max), attributed to CO_2 absorption from photosynthesis. C. Step-increase to unhealthy 2,178-ppm peak is indoor measurement of room within a multi-family dwelling with four occupants, windows closed. D. Shows improvement in worst-case peak-to-peak CO_2 concentration of approximately 700 ppm for same dwelling upon opening a window to provide natural ventilation. Sampling interval = 1 minute.

Summary of CO_2 Logger Mounting Recommendations [45-47]
• 48-72 inches (122-183 cm) above floor for IAQ measurements near return-air duct if possible
• 12-18 inches (30-45 cm) from floor for compressed CO_2 storage applications
• ≥36 inches (91 cm) from any corner
• ≥ 24 inches (61 cm) from any open doorway
Do not mount in these locations:
• Interior side of exterior walls
• Near fixed or operable windows
• In areas with poor circulation, such as behind doors or alcoves
• Near combustion equipment
• Areas exposed to direct breathing, such as near water coolers or coffee machines

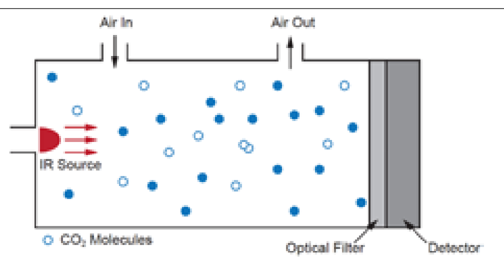
Table 3 Recommended CO2 logger mounting tips.

diurnal and monthly variations of 50 to over 200 ppm in urban CO_2 concentration can cause potential calibration errors depending on the time of day the initial calibration occurs.

The automatic baseline calibration (ABC) method assumes that, during a given 7.5 to 8-day stretch, there are periods where few or no building occupants are present. Thus, the internal levels will return to equilibrium with outdoor concentrations approximating 400 ppm. Upon detecting minimum levels, the logger computes a new baseline under the assumption that the minimum value (without occupants) is 400 ppm. This iterative method works well in many offices or school classrooms where occupancy approaches zero overnight, or on weekends and holidays. Pre-programmed air purges during periods of non-occupancy also help to reduce residual CO_2 to ensure that interior levels approximate outdoor levels. However, automatic calibration is not suitable in a hospital, hotel or other public space subjected to continuous presence of personnel and visitors. A quality logger allows the user to select which calibration modes are most appropriate for the situation.

As gas pressure declines exponentially versus elevation, fewer CO_2 molecules enter the fixed NDIR-sensor chamber at higher altitudes, despite the relatively constant 400 ppm CO_2-concentration ratio in the troposphere. Failure to set the correct elevation could result in CO_2-concentration errors of 1%-50% or more, depending on the elevation. Note that altitude compensation provides a more coarse correction and does not compensate for dynamic fluctuations in ambient pressure that change rapidly, such as during storms or high winds.

To reduce the impact of calibration errors, deploying a differential measurement setup with two or more CO_2 loggers can help. Differential measurements are also the best indicator of ventilation performance and additive CO_2 from internal sources. In this configuration, one logger remains outdoors in a suitably protected area with free airflow (ideally protected from direct solar radiation), while the remaining loggers reside indoors. By subtracting time-stamped outdoor readings from inside readings, common-mode calibration errors largely cancel. This assumes that the initial manual calibrations were performed concurrently in the same outdoor location. During the initial calibration process—but prior to final placement—allow all loggers to stabilize outdoors for at least 30–60 minutes. Next, initialize the manual calibration procedure on each logger. All loggers should read approximately 400 ppm in the same outdoor location. The loggers are then ready for final installation in their target locations.



This image shows how an NDIR Sensor operates (adapted from CO2Meter.com).

Mounting recommendations

Carbon dioxide is more than 60% denser than air, and tends to settle at first near the bottom of the floor. This could lead to distorted readings if the logger is placed too low on a wall. Over time, however, diffusion will occur and the total volume of air should contain similar concentrations of CO_2. Table 3 summarizes recommended mounting practices depending on the measurement objective.

For typical IAQ measurements mount the logger in the breathing zone, approximately 48–72 in. (122–183 cm) vertically above the floor surface—several feet away from occupants where exhalation could alter the localized CO_2 concentration. Stay at least 36 in. (91 cm) away from any corner, 24 in. (61 cm) from an open doorway, and well away from operable windows, outside doors, and vents.

Some manufacturers recommend mounting the loggers inside the return-air duct in the rooms of interest, assuming such a duct exists. This can be more practical in commercial buildings versus residential units, as the latter typically have no more than one centralized air return.

Conclusion

CO_2 concentration is a key indicator of IAQ and ventilation effectiveness in offices, schools, healthcare facilities, dwellings and any enclosed space subject to variable occupancy. Elevated CO_2, more than 600–700 ppm above outdoor levels, warrants special focus on ventilation function and emission sources. Although many existing global standards stipulate maximum daily average exposure limits up to 5,000 ppm, research shows that cognitive impairment and perception of poor air quality commence at 1,000 ppm (absolute), or 600–700 ppm (differential) over outside levels. Keeping CO_2 levels in check typically helps to reduce other pollutants due to engineering focus on improved ventilation.

Facility managers and building engineers have a responsibility to ensure compliance with all laws, as well as commitment to recommended best practices, which frequently go well beyond minimum requirements set forth in building codes and ventilation standards. CO_2 data loggers provide one cost-effective method to assess indoor CO_2 concentration levels to help increase IAQ and eliminate SBS.

Greg Lowitz is the Founder and CEO of Buildera. He created the company to develop and market innovative products and services in the fields of civil engineering, construction, energy, environmental, geotechnical, HVAC, mechanical, and forensic structural engineering. He leads the technical vision and product strategy with a hands-on approach. Buildera also conducts field product testing and analysis for leading manufacturers on a range of construction tools and scientific test and measurement equipment. For more information, visit www.buildera.com or www.onsetcomp.com.