Chris Schaefer Expert Witness Report

Introduction

This report discusses the hazards of the types of so-called "masks" that are typically mandated by governments to be worn to purportedly prevent the spread of COVID-19. These "masks" are the medical, non-medical, and procedural masks. Some government mandates only permit the wearing of medical and procedural masks.

The Nature of "Masks"

Masks designed to cover the mouth and nose of the wearer are required to have engineered breathing openings for air to flow in during inhalation and to be purged during exhalation. Examples of masks include respirator masks, scuba masks, hockey goalie masks, and Halloween costume masks.

The medical, nonmedical/cloth, and procedural "masks" that have been government mandated to be used to purportedly prevent the transmission of COVID-19 do not have engineered breathing openings for air to flow in and exhaled air to be purged out. Therefore, they are not respirator masks, or even masks at all. It is erroneous to call these devices "masks", as they are simply breathing barriers that interfere with normal healthy inflow of atmospheric oxygen and outflow of toxic carbon dioxide.

Wearing any of these barriers creates a lower oxygen and higher carbon dioxide breathing environment that is hazardous to the wearer, regardless of contaminant filtration efficiency. Simply put, all closed barriers or covers worn over the mouth and nose are hazardous to the wearer, regardless of whether there is an atmospheric contaminant.

These barriers, by design, cause the wearer to rebreathe their own exhaled air, which is hazardous.[1] Proper respirators have an engineered breathing system that eliminates the risk of capture and re-inhalation of exhaled air. They are designed with two inhalation valves, covered by filters, through which atmospheric air enters with inhalation, and an exhalation valve in between that causes exhaled air to exit.

"Masks" and Increased Carbon Dioxide

Carbon dioxide is a toxic gas that is produced from cellular respiration. Ordinary outdoor atmospheric air contains 400 ppm (parts per million) of carbon dioxide depending upon the environment that a person is located in.[2]

[1] http://thebetteroxygenmask.com/harmful-effects-of-rebreathing-carbon-dioxide-co2/
[2] https://climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide/

The MultiRAE Lite air testing monitor, which I am competent to operate, measures both oxygen and carbon dioxide levels in air. Using a calibrated MultiRAE Lite, I observed that the carbon dioxide concentration detected from inside a wearer's non-medical, procedural and medical "masks" was in excess of 1000 ppm within 30 seconds of measuring.[3] The Health Canada standard, as of 2021, sets the maximum indoor exposure limit regarding carbon dioxide at 1,000 ppm.

As a result of the testing which I have performed, the measured results indicate that all persons wearing a non-medical/cloth, procedural, or medical "masks" immediately exceed the Health Canada limit for carbon dioxide exposure within less than 30 seconds.

"Masks" and Decreased Oxygen

In addition to being a toxic gas, carbon dioxide is also an asphyxiant, and displaces oxygen and creates an oxygen deficient atmosphere between a wearer's "mask" and their face.

Using the MultiRAE Lite, I have observed that upon commencement of wearing a nonmedical/cloth, medical or procedural cover, oxygen levels inside the "mask" immediately drop. Readings showed oxygen levels often below 19.5%. The *Occupational Health and Safety Code*, Alberta Reg. 87/2009 describes oxygen levels below 19.5% as "hazardous", an "emergency", and a "respiratory danger".[4] According to the Occupational Health and Safety Administration (OSHA), below 19.5% oxygen is immediately dangerous to life and health (IDLH).[5]

The measured results of the testing I have performed show that while wearing a medical, non-medical/cloth mask, or procedural "mask", the oxygen level available to the wearer rapidly drops and stays below the acceptably safe oxygen level most of the time.

Conclusion

1. A proper mask is a specially engineered device for ***safe*** breathing.

2. A respirator mask is designed to prevent contaminants from being inhaled with also permitting ***safe*** breathing.

3. The government mandated procedural, nonmedical/cloth, and medical "masks" are not true masks or respirators.

4. Testing demonstrates that theses "masks" create for the wearer hazardously high levels of carbon dioxide and dangerously low levels of oxygen.

[3] https://www.canada.ca/en/health-canada/services/publications/healthy-living/residential-indoor-air-quality-guidelines-carbon-dioxide.html
[4] See sections 52(1)(a), 55(3)(b), 244(1)(b), 252(a)(i), 253(a), 254(1)(a)(ii).
[5] https://www.osha.gov/laws-regs/standardinterpretations/2007-04-02-0

5. Testing showed hazardously high levels of carbon dioxide and dangerously low levels of oxygen inhaled by wearers of mandated procedural, nonmedical/cloth, and medical “masks in as little as 30 seconds of wearing.

Chris Schaefer

SafeCom Training Services Inc.

August 11, 2021

Harmful Effects of Rebreathing Carbon Dioxide (CO2)

July 11, 2016 OxyMask™ News

Carbon dioxide (CO_2) is a gas the body naturally produces as waste. We breathe in oxygen (O_2) to fuel organs and tissues and the end product is CO_2. The balance between these two gases is required for a healthy body. However, when we rebreathe CO_2 it can have harmful and sometimes dangerous effects on the body. When CO_2 levels are elevated in the body it is known as hypercapnia. Hypercapnia can occur for a number of reasons, one of which is rebreathing our own exhaled CO_2. Rebreathing CO_2 can lead to increased blood pressure, headaches, muscle twitches, rapid heart rate, chest pain, confusion, and fatigue. In extreme cases, if left untreated, hypercapnia can lead to organ damage and even have long standing effects on the brain.

NEWS | October 9, 2019

The Atmosphere: Getting a Handle on Carbon Dioxide

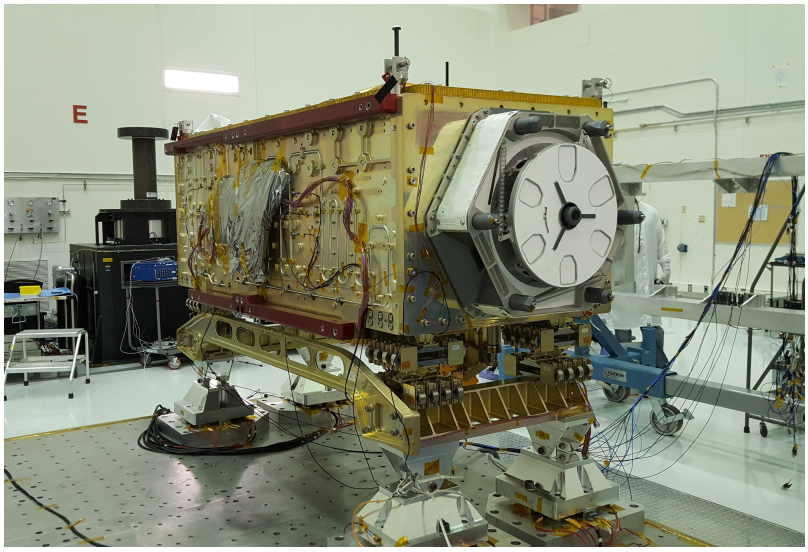
Sizing Up Humanity's Impacts on Earth's Changing Atmosphere: A Five-Part Series

By Alan Buis,
NASA's Jet Propulsion Laboratory

Part Two

Earth's atmosphere is resilient to many of the changes humans have imposed on it. But, says atmospheric scientist David Crisp of NASA's Jet Propulsion Laboratory in Pasadena, California, that doesn't necessarily mean that our society is.

"The resilience of Earth's atmosphere has been proven throughout our planet's climate history," said Crisp, science team lead for NASA's Orbiting Carbon Observatory-2 (OCO-2) satellite and its successor instrument, OCO-3, which launched to the International Space Station on May 4. "Humans have increased the abundance of carbon dioxide by 45 percent since the beginning of the Industrial Age. That's making big changes in our environment, but at the same time, it's not going to lead to a runaway greenhouse effect or something like that. So, our atmosphere will survive, but, as suggested by UCLA professor and Pulitzer-Prize-winning author Jared Diamond, even the most advanced societies can be more fragile than the atmosphere is."



NASA’s OCO-3 instrument sits on the large vibration table (known as the "shaker") in the Environmental Test Lab at NASA’s Jet Propulsion Laboratory. Thermal blankets were later added to the instrument at NASA’s Kennedy Space Center, where a Space-X Dragon capsule carrying OCO-3 launched on a Falcon 9 rocket to the space station on May 4, 2019. Credit: NASA/JPL-Caltech

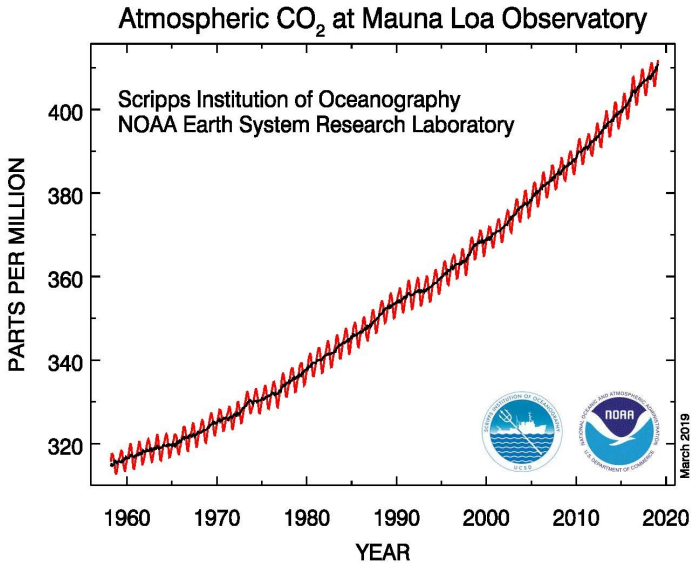
Changes to our atmosphere associated with reactive gases (gases that undergo chemical reactions) like ozone and ozone-forming chemicals like nitrous oxides, are relatively short-lived. Carbon dioxide is a different animal, however. Once it’s added to the atmosphere, it hangs around, for a *long* time: between 300 to 1,000 years. Thus, as humans change the atmosphere by emitting carbon dioxide, those changes will endure on the timescale of many human lives.

Earth’s atmosphere is associated with many types of cycles, such as the carbon cycle and the water cycle. Crisp says that while our atmosphere is very stable, those cycles aren’t.

“Humanity’s ability to thrive depends on these other planetary cycles and processes working the way they now do,” he said. “Thanks to detailed observations of our planet from space, we’ve seen some changes over the last 30 years that are quite alarming: changes in precipitation patterns, in where and how plants grow, in sea and land ice, in entire ecosystems like tropical rain forests. These changes should attract our attention.

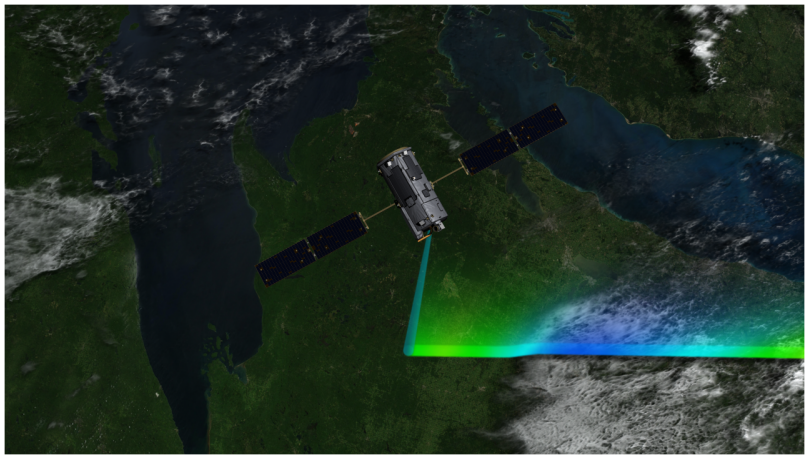
“One could say that because the atmosphere is so thin, the activity of 7.7 billion humans can actually make significant changes to the entire system,” he added. “The composition of Earth’s atmosphere has most certainly been altered. Half of the increase in atmospheric carbon dioxide concentrations in the last 300 years has occurred since 1980, and one quarter of it since 2000. Methane concentrations have increased 2.5 times since the start of the Industrial Age, with almost all of that occurring since 1980. So changes are coming faster, and they’re becoming more significant.”

The concentration of carbon dioxide in Earth’s atmosphere is currently at nearly 412 parts per million (ppm) and rising. This represents a 47 percent increase since the beginning of the Industrial Age, when the concentration was near 280 ppm, and an 11 percent increase since 2000, when it was near 370 ppm. Crisp points out that scientists know the increases in carbon dioxide are caused primarily by human activities because carbon produced by burning fossil fuels has a different ratio of heavy-to-light carbon atoms, so it leaves a distinct “fingerprint” that instruments can measure. A relative decline in the amount of heavy carbon-13 isotopes in the atmosphere points to fossil fuel sources. Burning fossil fuels also depletes oxygen and lowers the ratio of oxygen to nitrogen in the atmosphere.



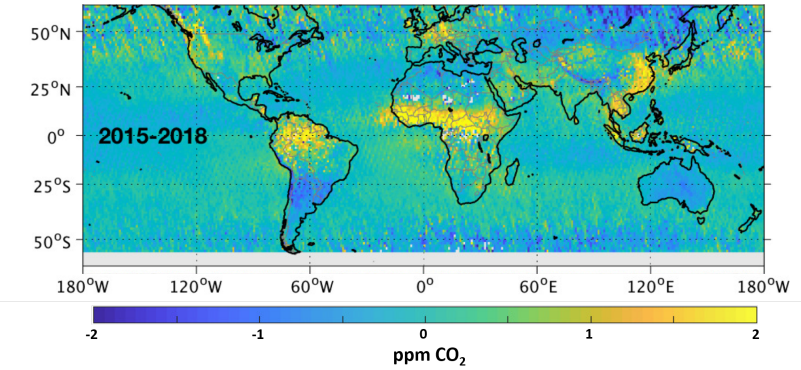
A chart showing the steadily increasing concentrations of carbon dioxide in the atmosphere (in parts per million) observed at NOAA's Mauna Loa Observatory in Hawaii over the course of 60 years. Measurements of the greenhouse gas began in 1959. Credit: NOAA

OCO-2, launched in July 2014, gathers global measurements of atmospheric carbon dioxide with the resolution, precision and coverage needed to understand how this important greenhouse gas — the principal human-produced driver of climate change — moves through the Earth system at regional scales, and how it changes over time. From its vantage point in space, OCO-2 makes roughly 100,000 measurements of atmospheric carbon dioxide every day.



Artist's rendering of NASA's Orbiting Carbon Observatory (OCO)-2 in orbit above the U.S. upper Great Plains. Credit: NASA-JPL/Caltech

Crisp says OCO-2 has already provided new insights into the processes emitting carbon dioxide to the atmosphere and those that are absorbing it.

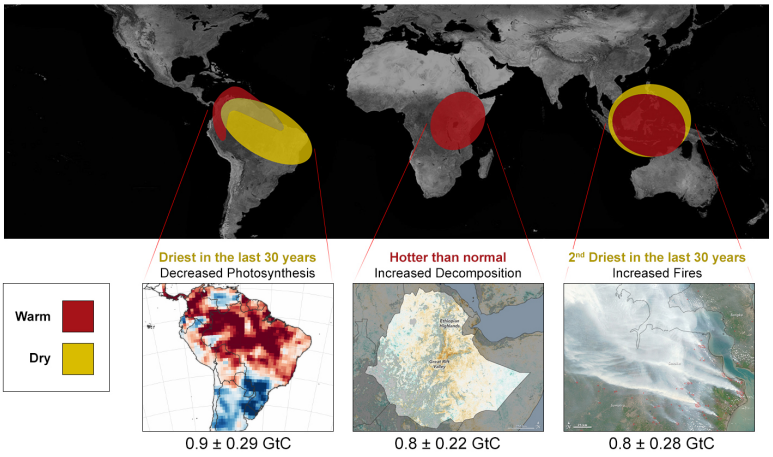


Map of the most persistent carbon dioxide “anomalies” seen by OCO-2 (i.e. where the carbon dioxide is always systematically higher or lower than in the surrounding areas). Positive anomalies are most likely sources of carbon dioxide, while negative anomalies are most likely to be sinks, or reservoirs, of carbon dioxide. Credit: NASA/JPL-Caltech

“For as long as we can remember, we’ve talked about Earth’s tropical rainforests as the ‘lungs’ of our planet,” he said. “Most scientists considered them to be the principal absorber and storage place of carbon dioxide in the Earth system, with Earth’s northern boreal forests playing a secondary role. But that’s not what’s being borne out by our data. We’re seeing that Earth’s tropical regions are a net *source* of carbon dioxide to the atmosphere, at least since 2009. This changes our understanding of things.”

Measurements of atmospheric carbon dioxide in the tropics are consistently higher than anything around them, and scientists don’t know why, Crisp said. OCO-2 and the Japan Aerospace Exploration Agency’s Greenhouse gases Observing SATellite (GOSAT) are tracking plant growth in the tropics by observing solar-induced fluorescence (SIF) from chlorophyll in plants. SIF is an indicator of the rate at which plants convert light from the Sun and carbon dioxide from the atmosphere into chemical energy.

“We’re finding that plant respiration is outstripping their ability to absorb carbon dioxide,” he said. “This is happening throughout the tropics, and almost all of the time. When we first launched OCO-2, our first two years of on-orbit operations occurred during a strong El Niño event, which had a strong impact on global carbon dioxide emissions. Now we have more than five years of data, and we see that the tropics are always a source (of carbon dioxide), in every season. In fact, the only time we see significant absorption of carbon dioxide in the tropics is in Africa during June, July and August. So that’s half the story.



The last El Niño in 2015-16 impacted the amount of carbon dioxide that Earth's tropical regions released into the atmosphere, , leading to Earth's recent record spike in atmospheric carbon dioxide. The effects of the El Nino were different in each region. Credit: NASA-JPL/Caltech

“The other half is also quite interesting,” he added. “We’re seeing northern mid- and high-latitude rainforests becoming better and better absorbers for carbon dioxide over time. One possible explanation for this is that the growing season is getting longer. Things that didn’t used to grow well at high latitudes are growing better and things that were growing well there before are growing longer. We’re seeing that in our data set. We see that South America’s high southern latitudes — the so-called cone of South America — are also strong absorbers for carbon. We don’t know if it was always this way and our previous understandings were incomplete or wrong, or if climate change has

increased the intensity of the growing season. So we've established a new baseline, and it appears to be somewhat of a paradigm shift. Our space-based measurements are beginning to change our understanding of how the carbon cycle works and are providing new tools to allow us to monitor changes in the future in response to climate change."

Crisp says OCO-2, OCO-3 and other new satellites are giving us new tools to understand how, where and how much carbon dioxide human activities are emitting into the atmosphere and how those emissions are interacting with Earth's natural cycles. "We're getting a sharper picture of those processes," he said.

Impacts from agricultural activities also seem to be changing, he says. During summer in the U.S. upper Midwest, scientists are seeing an intense absorption of carbon dioxide associated with agricultural activities. The same thing is being observed in Eastern and Southern Asia. The strong absorption of carbon dioxide across China is erasing all but a thin strip of fossil fuel emissions along the coast, with Central China now functioning as a net absorber of carbon dioxide during the growing season. Thanks to the development of big, sophisticated computer models combined with wind and other measurements, we're able to quantify these changes for the first time.

In response to the rapid changes observed in carbon dioxide concentrations and their potential impact on our climate, 33 of the world's space agencies, including participants from the United States, Europe, Japan and China, are now working together to develop a global greenhouse gas monitoring system that could be implemented as soon as the late 2020s, Crisp added. The system would include a series of spacecraft making coordinated measurements to monitor these changes. Key components of the system would include the OCO-

2 and OCO-3 missions, Japan's GOSAT and GOSAT-2, and Europe's Copernicus missions. The system would be complemented by ground-based and aerial research.

Crisp said he and his fellow team members are eagerly poring over the first science data from OCO-3. The new instrument, installed on the exterior of the space station, will extend and enhance the OCO-2 data set by collecting the first dawn-to-dusk observations of variations in carbon dioxide from space over tropical and mid-latitude regions, giving scientists a better view of emission and absorption processes. This is made possible by the space station's unique orbit, which carries OCO-3 over locations on the ground at slightly different times each orbit.

NASA's OCO-3 mission launched to the International Space Station on May 4, 2019. This follow-on to OCO-2 brings new techniques and new technologies to carbon dioxide observations of Earth from space. Credit: NASA-JPL/Caltech

The Copernicus CO2 Mission, scheduled for launch around 2025, will be the first operational carbon dioxide monitoring satellite constellation. Crisp, who's a member of its Mission Advisory Group, said the constellation will include multiple satellites with wide viewing swaths that will be able to map Earth's entire surface at weekly intervals. While its basic measurement technique evolved from the GOSAT and OCO-2 missions, there's a key difference: the earlier satellites are sampling systems focused on improving understanding of Earth's

natural carbon cycle, while Copernicus will be an imaging system focused on monitoring human-produced emissions. In fact, it will have the ability to estimate the emissions of every large power plant in every city around the world.

Crisp says as time goes on the objective is to build an operational system that will monitor all aspects of Earth's environment. Pioneering satellites like OCO-2, OCO-3, GOSAT and GOSAT-2 are adding greenhouse gas measurements to the data on temperature, water vapor, cloud cover, air quality and other atmospheric properties that have been collected for decades.

"We know our atmosphere is changing and that these changes may affect our civilization," he said. "We now have the tools to monitor our atmosphere very carefully so that we can give policymakers the best information available. If you've invested in a carbon reduction strategy, such as converting from coal to natural gas or transitioning from fossil fuels to renewables, wouldn't you like to know that it worked? You can only manage what you can measure."

RESIDENTIAL INDOOR AIR QUALITY GUIDELINES

CARBON DIOXIDE

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Health Canada is the federal department responsible for helping the people of Canada maintain and improve their health. Health Canada is committed to improving the lives of all of Canada's people and to making this country's population among the healthiest in the world as measured by longevity, lifestyle and effective use of the public health care system.

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PREAMBLE

Health Canada assesses the health risks posed by specific indoor pollutants in residential environments and provides recommendations on how to reduce those risks. Residential Indoor Air Quality Guidelines (RIAQG) summarize the known health effects, pollutant sources, and exposure levels in Canadian homes and characterize the risks to health, based on the best scientific data available. Recommended exposure limits (also referred to as guideline values) for short- and/or long-term exposure to the pollutant are developed, representing indoor air concentrations below which health effects are unlikely to occur. The recommended exposure limits take into account the reference concentrations (RfC) for the pollutant and the feasibility of achieving such levels through control of indoor sources. The RIAQG also include recommendations for controlling sources or other actions to reduce exposure to the pollutant.

For some pollutants, a recommended exposure limit may not be developed, although the available scientific evidence justifies reducing Canadians' exposure to the pollutant. In this case, a guidance document that focuses on actions to control sources and reduce exposure is developed.

The RIAQG and guidance documents serve as a scientific basis for activities to evaluate and reduce the risk from indoor air pollutants including, but not limited to:

- assessments by public health officials of health risks from indoor air pollutants in residential or similar environments;
- performance standards that may be applied to pollutant-emitting materials, products, and devices, so that their normal use does not lead to air concentrations of pollutants exceeding the recommended exposure limits; and
- communication products informing Canadians of actions they can take to reduce their exposure to indoor air pollutants and to help protect their health.

The RIAQG and guidance documents replace a series of exposure limit values for indoor air pollutants from a report entitled *Exposure Guidelines for Residential Indoor Air Quality* (Health Canada 1987). In addition to updates for the substances included in the 1987 report, guidelines or guidance documents will be developed for other substances that are identified as having the potential to affect human health in the indoor environment.

The focus of this document is carbon dioxide (CO_2). In the 1987 Health Canada publication *Exposure Guidelines for Residential Indoor Air Quality*, an acceptable long-term exposure range (ALTER) of ≤ 3500 ppm was set for CO_2 in residential indoor air. This value was derived from the lowest concentration at which direct physiological adverse health effects (i.e., increased blood acidity) had been observed in humans after several weeks of continuous exposure, based on the health and toxicological literature available at that time. Since the publication of these guidelines, new information has become available regarding potential health effects of exposure to elevated CO_2 levels (particularly epidemiological and controlled human exposure studies) and indoor air exposure in Canada.

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RESIDENTIAL INDOOR AIR QUALITY GUIDELINES FOR CARBON DIOXIDE (CO_2)

Exposure Limit	Concentration		Critical effect(s)
	mg/m^3	ppm	
Long-term (24 h)	1800	1000	As CO_2 increases, there may be an increased risk of: • mucous membrane or respiratory symptoms (e.g., eye irritation, sore or dry throat, stuffy, congested or runny nose, sneezing, coughing, and rhinitis) • decreased test performance (e.g., decision-making, task performance, standardized test scores) • neurophysiological symptoms (such as headache, tiredness, fatigue, dizziness or difficulty concentrating)

The recommended long-term exposure limit for CO_2 is 1000 ppm (based on a 24-hour average). The guidelines are based on effects observed in epidemiological studies in schools or offices and controlled exposure studies.

BACKGROUND

Carbon dioxide is an odourless, colourless, and non-flammable gas; the main source of CO_2 indoors is from the respiration of occupants. Indoor CO_2 concentrations are often used as a surrogate for ventilation rate and as an indicator of general indoor air quality.

The Residential Indoor Air Quality Guidelines (RIAQG) are intended to provide a recommended long-term indoor air exposure limit for CO_2 which would indicate adequate ventilation as well as minimize risks to human health from CO_2 and other indoor air pollutants.

The guideline document also shows that levels in some Canadian homes may exceed the recommended exposure limit, and recommends various risk mitigation measures to improve general indoor air quality and reduce exposure to CO_2.

SOURCES AND EXPOSURE

Natural sources of atmospheric CO_2 include animal and plant respiration, organic matter decomposition, outgassing from water surfaces, forest fires, and volcanic eruptions. Anthropogenic sources of CO_2 emissions include the combustion of fossil fuels, building heating and cooling, land-use changes such as deforestation, and some industrial processes. Indoors, CO_2 is mainly produced through the respiration of occupants, but it can also originate from other sources, such as unvented or poorly vented fuel-burning appliances and cigarette smoke.

As ventilation is the primary means of removal of CO_2 from indoor environments, poorly ventilated homes or homes with unvented or poorly vented fuel-burning appliances may have elevated CO_2 concentrations, especially if several occupants are present. Indoor CO_2 concentrations are often used as a surrogate for ventilation rate and as an indicator for other occupant-derived pollutant (bioeffluent) concentrations and odours. Many building standards and guidelines for CO_2 were established based on target CO_2 concentrations that would indicate adequate ventilation for occupant comfort with respect to bioeffluents (odours) and not on direct health effects of CO_2.

HEALTH EFFECTS

Studies in humans in school or office settings have found associations between CO_2 exposure and mucous membrane or respiratory symptoms, rhinitis, neurophysiological symptoms, a lack of concentration, headaches, dizziness, heavy-headedness, tiredness, and decreased performance on tests or tasks. Studies in laboratory animals were generally at high concentrations of CO_2; however, the results from studies investigating the neurological effects of CO_2 exposure or its effects on the developing brain support the observations from human studies.

Indigenous peoples may be considered more vulnerable to the health effects of CO_2, as close to one-fifth of the Indigenous population lived in crowded housing (on and off reserve) in 2016, which is higher than the non-Indigenous population, and the portion of First Nations people with registered or treaty Indian status living in a crowded dwelling was higher on reserve (over one third). Individuals living in low income housing are also considered to be more vulnerable to the health effects of air pollution in general, as they are more likely to live in homes with poor conditions.

Infants and children are also considered a vulnerable population, as they may be exposed to elevated indoor CO_2 levels in environments outside of their home, such as schools and daycare centres. In addition, because of their size, children inhale more air in relation to their body weight than adults. Infants and children may also be more susceptible than adults to the health effects of air contaminants due to differences in their ability to metabolize, detoxify, and excrete contaminants, and because they undergo rapid growth and development.

Individuals with pre-existing health conditions (such as allergies and asthma) were found to be more susceptible to the mucous membrane and respiratory effects of CO_2 than those without these conditions. Patients suffering from panic disorder were found to be more susceptible to the anxiogenic effects of CO_2 compared to healthy subjects. Due to the physiological and metabolic actions of CO_2 in the body, it is expected that individuals with cardiovascular conditions may also be more susceptible to the health effects of elevated CO_2 exposure.

RISK MANAGEMENT RECOMMENDATIONS

Measured data confirms there are Canadian homes, schools, and daycare centres in which the recommended exposure limit for CO_2 is exceeded. Therefore, there may be an increased risk of respiratory symptoms, decreased test performance, headaches, dizziness and tiredness.

As CO_2 levels are strongly correlated with occupant density and ventilation, achieving a CO_2 level in the home that is below the recommended exposure limit should be feasible with uncrowded housing and adequate ventilation. These strategies include the following:

- increasing natural ventilation by opening windows (taking into consideration ambient air quality);
- ensuring fuel-burning appliances are in good working order and properly vented;
- setting the mechanical ventilation system to a higher setting or letting it run longer;
- running the kitchen range hood exhaust fan when cooking;
- using the furnace fan or, if necessary, a separate fan or air supply to make sure air is distributed throughout the home;
- avoiding the use of unvented fuel-burning appliances (e.g., space heaters) indoors;
- not smoking indoors; and
- avoiding crowded living situations, if possible.

In terms of implementation of CO_2 reduction strategies, specifically increased ventilation, ambient air quality must be considered. During periods of poor ambient air quality, such as those experienced during forest fire events, reducing air intake and thus infiltration of ambient air pollutants may be more beneficial from a health risk perspective, compared to reducing indoor CO_2 levels to below the recommended exposure limit. The information contained within this document may be used to inform the development of additional scenario-specific CO_2 exposure limits.

1 PHYSICAL AND CHEMICAL CHARACTERISTICS

Carbon dioxide is a colourless, odourless, and non-flammable gas. At normal atmospheric temperatures and pressures, CO_2 is a gas heavier than air, with a density of approximately one and a half times that of air. Carbon dioxide is relatively stable and inactive; however, it will react with water to form carbonic acid (H_2CO_3) (refer to section 4.1). Due to its small molecular size, CO_2 diffuses readily through biological membranes and dissolves readily in aqueous solutions, including body fluids (Harper, Rodwell and Mayes 1979). Some of its physical and chemical properties are summarized in Table 1 (PubChem).

Table 1. Physical and chemical properties of CO_2

Property	Value	Chemical structure
Molecular formula	CO_2	
Molecular weight	44.01 g/mol	
CAS registry number	124-38-9	
Density	1.976 g/L at 0 °C and 760 mm Hg	
Water solubility	Miscible in water (2000 mg/L) as well as in hydrocarbons and most organic liquids	
Boiling point	-78.464 °C at 101.3 kPa (sublimes)	
Common synonyms	Carbonic acid gas, dry ice	
Conversion factors	1 ppm = 1.8 mg/m^3 1 mg/m^3 = 0.56 ppm 0.1% = 1000 ppm	

2 SOURCES IN THE AIR

2.1 OUTDOOR SOURCES

Natural sources of atmospheric CO_2 include animal and plant respiration, organic matter decomposition, outgassing from water surfaces, forest fires, and volcanic eruptions. Carbon dioxide is constantly being removed from the air by its direct absorption into water and by vegetation through photosynthesis (ECCC 2015).

Anthropogenic sources of CO_2 emissions include the combustion of fossil fuels, building heating and cooling, land-use changes including deforestation, and some industrial processes (ECCC 2015). The combustion of fossil fuels (e.g., power generation, transportation, and industry) is the main anthropogenic source of CO_2 emissions in Canada. The *National Inventory Report 1990–2016: Greenhouse Gas Sources and Sinks in Canada* indicates that Canada's emissions of CO_2 were about 559 megatonnes in 2016, and that CO_2 emissions are the largest contributor to total greenhouse gas emissions (accounting for 79% of total emissions in 2016). Over the 2005–2016 period, national total greenhouse gas emissions have decreased by 3.8% in Canada (ECCC 2018).

2.2 INDOOR SOURCES

The primary indoor source of CO_2 is exhaled air from the occupants of the indoor space (Kiray et al. 2014). An average person will produce approximately 15 L/hr of CO_2 at rest and approximately 45 L/hr of CO_2 during moderate activity (Sundell 1982). The relative contribution of the occupants' respiration to indoor CO_2 levels depends on the number of people in the building, their level of physical activity, the volume of air per person, and the length of time spent in the building (Bureau of Chemical Hazards 1985). Thus, indoor settings with greater occupant density (e.g., schools, office buildings, and daycare centres) are considered to be more likely to experience elevated CO_2 levels, particularly if ventilation is inadequate.

Health Canada exposure data collected from homes in Ottawa, Edmonton, Halifax, Montreal, Quebec, and the Annapolis Valley (Health Canada 2016, 2013, 2012; Health Canada and INSPQ 2015; Wheeler et al. 2011) showed that an increase in CO_2 levels correlated with an increase in the number of occupants, although this trend was not always statistically significant (Health Canada 2018b). In studies in Quebec (winter) and Halifax (winter), marginally higher levels of CO_2 were also observed in households with pets (Health Canada and INSPQ 2015; Health Canada 2012). Other sources of CO_2 in indoor air include unvented or poorly vented fuel-burning appliances (e.g., gas stoves, space heaters, water heaters, and furnaces) and cigarette smoking.

Properly vented (and maintained) water heaters and furnaces are not expected to release significant amounts of CO_2 into the indoor environment. However, fuel-burning appliances may vent gases directly into the house if the air pressure indoors is less than that outdoors (e.g., in tightly sealed buildings or with the use of exhaust fans from other appliances pumping air outside, such as a dryer) (IEC Beak Consultants Ltd. 1983). Furthermore, poorly located vents may result in the re-entry of emissions (e.g., through windows, doors, and small cracks in the outside walls).

The use of a gas stove or a fuel-burning space heater can have a significant impact on indoor CO_2 levels. Peak CO_2 concentrations of up to 3000 ppm were measured in homes with a gas stove (Singer et al. 2017; Traynor 1984; Traynor et al. 1983). Similarly, the mean levels of CO_2 were higher in the kitchens of homes during cooking with a gas stove as compared to an electric appliance (906 ppm vs. 744 ppm, respectively) (Willers et al. 2006). Marginal increases in the geometric mean concentrations of CO_2 were observed with the daily use of a stove or oven (Health Canada 2018b) for homes in Edmonton (winter) or Halifax (summer), but no similar association was observed in other Health Canada studies (Wheeler et al. 2011; Health Canada 2013, 2012).

Carbon dioxide levels of up to 4500 ppm have been measured in homes during the use of kerosene space heaters (Hanoune and Carteret 2015; Richie and Oatman 1983; Traynor et al. 1983). Hanoune and Carteret (2015) investigated the indoor air quality of seven homes using kerosene space heaters and reported that all events of indoor CO_2 levels > 1000 ppm observed could be attributed to combustion sources (i.e., kerosene heaters, gas stove cooking, or smoking). They indicated that the use of kerosene heaters was at the origin of all CO_2 levels > 2500 ppm. They also found CO_2 concentrations correlated with the duration of use of the space heaters. Whitmyre and Pandian (2018) conducted a probabilistic analysis to estimate the impact of vent-free gas heating appliances on indoor air pollutant concentrations in energy-efficient homes in the United States. Predicted CO_2 concentrations (i.e., 50–100th percentile values estimated using the American Gas Association Research Division vent-free gas appliance model) ranged from 398 to 2147 ppm.

Cigarette smoking is also considered a source of CO_2 in indoor air. The contribution of CO_2 from two cigarettes smoked in a one-hour period (in a 40 m^3 room with a ventilation rate of 0.5 air changes per hour [ACH]) was estimated to range from 9 to 27 ppm (Bureau of Chemical Hazards 1985). Halios et al. (2005) investigated the concentration of indoor pollutants, including CO_2, generated by smoking in a controlled environment and reported that smoking (i.e., 10 cigarettes smoked in a six-hour period) increased indoor CO_2 concentrations by up to 4-fold compared to the baseline level, reaching approximately 1900 ppm CO_2. However, the study design does not make it possible to determine what proportion of the CO_2 increase is attributable to smoking alone, as opposed to other sources such as the respiration of occupants.

2.2.1 Ventilation

Ventilation describes the movement of air into or out of houses and is one of the key strategies to maintaining good indoor air quality. Ventilation can be characterized by an air exchange rate (AER) expressed in ACH, where low AERs (and low ACH) indicate low ventilation.

Residential ventilation may occur naturally or mechanically. Natural ventilation is caused by pressure differences between the inside and the outside of the house, allowing movement of air through the building envelope (e.g., exterior walls, foundations, roof, windows, and doors). Mechanical ventilation is created through the use of fans, ducting, and designed openings in the building envelope (e.g., exhaust fans, clothes dryer exhausts, range hoods, and heat or energy recovery ventilators) (Health Canada 2018c).

Due to an increased focus on reducing energy costs for heating and air conditioning, buildings in Canada have generally become more airtight. This change has led to decreasing AER in residences (Allen et al. 2016). Air exchange rates also depend on other factors such as the presence of a mechanical ventilation system, use of exhaust fans, geographic location, season, and weather conditions as well as the extent to which windows and doors are opened. As ventilation is the primary means of removal of CO_2 from indoor environments, poorly ventilated homes or homes with unvented or poorly vented fuel-burning appliances may have elevated CO_2 concentrations, especially if several occupants are present (Health Canada 2018c).

Indoor CO_2 concentrations are often used as a surrogate for ventilation rate and as an indicator for other occupant-derived pollutant (bioeffluent) concentrations and odours. It is in this context that many building standards and guidelines for CO_2 were established (i.e., they are not based on the intrinsic health effects of CO_2). For example, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard on ventilation for acceptable indoor air quality recommends maintaining indoor CO_2 levels at no greater than 700 ppm above ambient levels to indicate adequate ventilation for occupant comfort with respect to bioeffluents. As the outdoor CO_2 level is assumed to range between 300 and 500 ppm, the indoor air concentration of CO_2 should be maintained below 1000 ppm (ASHRAE 2016). Similarly, other countries including France, Norway, Germany, Portugal, Korea, and Japan have established standards or guidelines for CO_2 of 600 to 1000 ppm, based on general air quality rather than direct health effects. More details on international guidelines for CO_2 can be found in Appendix C.

3 CONCENTRATIONS IN INDOOR AND OUTDOOR AIR

Canadian indoor and outdoor exposure concentrations of CO_2 are presented in Table 2.

3.1 OUTDOOR CONCENTRATIONS

In a Health Canada study, the median and 95th percentiles of average hourly CO_2 concentrations measured outside of 4 schools located in Ottawa were 419 and 532 ppm, respectively (MacNeill et al. 2016) (see Table 2). In the published literature, normal ambient outdoor ground-level CO_2 concentrations in the range of 328 to 442 ppm have been reported in the United States, Europe, Australia, and Japan (Muscatiello et al. 2015; Haverinen-Shaughnessy, Moschandreas and Shaughnessy 2011; Simoni et al. 2010; Ziska et al. 2001).

3.2 INDOOR CONCENTRATIONS

Results from the Canadian Human Activity Pattern Survey 2 indicate that Canadians spend approximately 90% of their time indoors (Matz et al. 2014), most of which (70%) is indoors at home, with less time (19%) spent at other indoor locations such as schools, public buildings, offices, factories, stores, and restaurants. Therefore, the concentration of CO_2 in the indoor environment is an important consideration for the health of Canadians.

The level of CO_2 in indoor air is a function of the following three main factors: the outdoor CO_2 concentration; indoor sources of CO_2; and the rate of removal or dilution of indoor CO_2 with outdoor air by ventilation.

The concentrations of CO_2 in Canadian homes, schools, and daycare centres reported in Heath Canada studies and the published literature are summarized in Table 2.

The median hourly average CO_2 concentrations measured in Canadian residences located in Ottawa, Edmonton, Halifax, Montreal, Quebec, and the Annapolis Valley ranged from 418 to 729 ppm (Mallach et al. 2017; Health Canada 2016, 2013, 2012; Health Canada and INSPQ 2015; Wheeler et al. 2011). Measured 95th percentiles for hourly average CO_2 concentrations ranged from 477 to 1483 ppm. Where residential measurements were taken in different seasons (i.e., Edmonton and Halifax), the winter indoor median average hourly CO_2 concentrations were approximately 80 to 160 ppm higher than those measured in summer. As these Health Canada studies collected data from over 200 households in six cities across Canada in both summer and winter, they are considered to be the most recent and most representative data available for quantifying long-term levels of indoor exposure to CO_2 in Canadian single-family homes.

Based on existing data, CO_2 levels measured during winter in on-reserve First Nations homes located in Ontario and Manitoba and in Inuit communities in Nunavut were higher than those measured during winter in other Canadian residences, with median and 95th percentile hourly average CO_2 concentrations ranging from 1058 to 1139 ppm, and from 2121 to 2436 ppm, respectively (Health Canada 2018a, 2007a; Weichenthal et al. 2012). Mean and maximum CO_2 levels of 1358 ppm and 2327 ppm, respectively, were reported in another study measuring CO_2 concentrations in 49 homes located in the Qikiqtaaluk (Baffin) Region in Nunavut (Kovesi et al. 2007).

Limited Health Canada data are available on CO_2 concentrations in schools and daycare centres. A study conducted by Health Canada measured indoor and outdoor CO_2 concentrations in four Ottawa elementary schools during school hours (MacNeill et al. 2016). The median and 95th percentiles of measured hourly average CO_2 concentrations in the schools were 491 and 1171 ppm, respectively. Another Health Canada study measuring CO_2 concentrations during operational hours in 21 daycare centres located in Montreal found that the mean CO_2 concentration was 1333 ppm (standard deviation of 391) (St-Jean et al. 2012). The presence of a mechanical ventilation system and a large surface of play area per child were each significantly associated with lower CO_2 levels; together they accounted for 44% of the variance in indoor CO_2 concentrations.

The available Health Canada data on CO_2 concentrations in schools and daycare centres are not expected to be representative of all of Canada. Therefore, data in the published literature on CO_2 levels in Canadian schools and daycare centres were also considered. In the greater Montreal area, minimum, mean, and maximum CO_2 levels of 861, 1505, and 2442 ppm, respectively, were measured during the winter of 1989 in 91 daycare centres, with 70% of these centres exceeding CO_2 concentrations of 1000 ppm and 13% exceeding 2500 ppm (Daneault, Beausoleil and Messing 1992). Dionne and Soto (1990) also reported CO_2 concentrations exceeding 1000 ppm in four daycare centres located in the Montreal area.

In order to better characterize exposure of Canadians to CO_2 in schools and daycare centres, data from other countries were also considered. The CO_2 concentrations reported in schools and daycare centres in Canada are within the ranges reported internationally in the public literature (Mendell et al. 2016; Dorizas, Assimakopoulos and Santamouris 2015; Muscatiello et al. 2015; da Conceição Ferreira and Cardoso 2014; Gaihre et al. 2014; Fromme, Bischof et al. 2013; Fromme, Lahrz et al. 2013, Norbäck, Nordström and Zhao 2013; Clausen et al. 2012, Myhrvold, Olsen and Lauridsen 1996), although it is recognized that climate, ventilation, and building characteristics could vary substantially.

No indoor CO_2 exposure concentrations were found in Health Canada studies or in the published literature for emergency situations such as emergency shelters, which involve the non-routine use of municipal infrastructure. However, since the primary source of indoor CO_2 is exhaled air from the occupants, and emergency shelters are likely to have high occupant density, it is anticipated that these environments may be more likely to experience elevated CO_2 levels. This is particularly true if the ventilation is inadequate or if the outdoor air supply needs to be reduced or eliminated (i.e., to prevent outdoor air pollutants from entering the shelter, such as during a wildfire). In addition, an elevated outdoor air CO_2 concentration could result in an increased indoor CO_2 concentration from ventilation or infiltration in homes or emergency shelters.

Table 2. Concentrations of CO_2 in indoor and outdoor air in Canada

Location	Season	Average hourly concentration (ppm)								Reference
		No. homes/ schools/ daycare centres	No. of samples	Mean	Minimum	Median	75th percentile	95th percentile	Maximum	
INDOOR—RESIDENTIAL										
Edmonton, Alberta	Summer Winter	48 32	7992 5339	612 750	321 396	537 696	715 848	1085 1258	2160 2608	Health Canada (2013)
Montreal, Quebec	Winter	44	7301	813	407	729	948	1483	2000	Health Canada and INSPQ (2015)
Ottawa, Ontario	Winter	44	7396	688	407	658	760	995	2000	
Quebec, Quebec	Winter	46	7111	772	362	705	931	1338	2000	
Halifax, Nova Scotia	Summer Winter	50 50	8253 8179	695 758	294 397	623 705	775 868	1211 1201	2691 2409	Health Canada (2012)
Ottawa, Ontario	Fall	2	48	421	388	418	440	477	485	Health Canada (2016)
Ottawa, Ontario	Winter	29	7900	679	372	667	771	930	2042	Mallach et al. (2017)
Annapolis Valley, Nova Scotia	Winter	32	2339	809	447	658	848	1282	10 000	Wheeler et al. (2011)
Swan Lake, Manitoba	Winter	20	8541	1248	393	1114	1546	2436	3828	Weichenthal et al. (2012)
Nunavut	Winter	18	1995	1225	395	1139	1451	2121	3739	Health Canada (2007a)
Sioux Lookout, Ontario	Winter	46	5792	1138	–	1058	1355	2140	4479	Health Canada (2018a)
Qikiqtaaluk Region, Nunavut	Winter	49	49	1358 (SD: 531)	–	–	–	–	2327 (SD: 1068)	Kovesi et al. (2007)
INDOOR—SCHOOLS OR DAYCARE CENTRES										
Ottawa, Ontario	Fall	4	4736	583	338	491	610	1171	2750	MacNeill et al. (2016)
Montreal, Quebec	Winter	21	–	1333 (SD: 391)	723	–	–	–	2252	St-Jean et al. (2012)
Montreal, Quebec	Winter/ Spring	91	1672	1505	861	–	–	–	2442	Daneault, Beausoleil and Messing (1992)
OUTDOOR										
Ottawa, Ontario (outside of schools)	Fall	4	5313	523	294	419	453	532	5047	MacNeill et al. (2016)

4 METABOLISM AND PHARMACOKINETICS

4.1 RESPIRATION

Carbon dioxide enters the body from the atmosphere through the lungs via external respiration. It is also formed in cells as an end-product of aerobic metabolism (i.e., internal or cellular respiration) (Guyton 1982). Following its production in the body, CO_2 diffuses from tissue cells into the surrounding capillaries and is carried by the blood bound to hemoglobin or dissolved as CO_2, carbonic acid or bicarbonate (HCO_3^-) ion, or as minor amounts of carbamino compounds (Guais et al. 2011).

Dissolved CO_2 in the blood undergoes hydration in erythrocytes to form $H2CO_3$, which then dissociates into hydrogen ions (H^+) and HCO_3^- (Guais et al. 2011). This mechanism is represented by the following chemical reaction:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

This reaction can interfere with the body's acid-base balance, as shown by the Henderson-Hasselbalch equation (Guais et al. 2011):

$$pH = pK + \log (HCO^-/CO_2)$$

Under normal conditions, the partial pressure of CO_2 in pulmonary capillary blood of approximately 6.75% (or 45 mm Hg) is greater than that in alveolar air (6% or 40 mm Hg). Thus, the gas is able to pass freely through the alveolar membrane into exhaled air by passive diffusion as there is a partial pressure gradient between blood and air in the alveoli (Guais et al. 2011).

4.2 CHEMICAL CONTROL OF RESPIRATION

Multiple sites in the brainstem (central chemoreceptors) and in the carotid and aortic bodies (peripheral chemoreceptors) are CO_2/H^+-chemosensitive (i.e., highly sensitive to changes in the concentration of either blood CO_2 or H^+ (Jiang et al. 2005; Lahiri and Forster 2003). Excess CO_2 or H^+ in the blood stimulates the respiratory centre in the brainstem, resulting in increased respiration and elimination of CO_2 via exhalation. Increased respiration also removes H^+ from the blood because of the decreased blood H_2CO_3 (Guyton 1982). An increase of the partial pressure of CO_2 in arterial blood (Pa_{CO_2}) as small as 0.015% (1 mm Hg) results in increased respiration (Jiang et al. 2005).

4.3 RESPONSES TO ELEVATED CO_2 LEVELS IN THE BLOOD

As the CO_2 concentration in air increases, the CO_2 concentration gradient between blood and alveolar air decreases. Since less CO_2 can diffuse into pulmonary alveoli from the blood during each breath, blood CO_2 concentrations increase with increased exposure duration. Hypercapnia (or hypercarbia) defines the condition where there is too much CO_2 in the blood (i.e., Pa_{CO_2} > 6.75% or > 45 mm Hg) (Guais et al. 2011).

The physiological responses of the body to an elevation of CO_2 levels in blood depend on the duration of exposure to and the concentration of CO_2.

Respiratory regulation

The elevation of CO_2 levels in blood has a very strong short-term effect on respiratory control. Within seconds after Pa_{CO_2} increases (Pa_{CO_2} [increase]/pH [decrease]), central and peripheral chemoreceptors become stimulated and induce an increase in breathing depth (tidal volume) and breathing rate. This effect reaches its peak within about one minute and then declines over the following days (Guyton 1982).

Renal/cellular regulation

When the body is unable to expel excess CO_2, the excess is converted to H^+ and HCO_3^-, thus raising the body's concentration of H^+ and decreasing the body's pH, which may result in acute or chronic acidosis (i.e., pH < 7.35). In addition to the respiratory regulation discussed above, the excess H^+ can be neutralized by cellular buffering (occurring within minutes to hours) or renal compensation (occurring over three to five days) (Guais et al. 2011). Renal regulation of the blood pH is very active during chronic exposure to CO_2 concentrations greater than 30 000 ppm in air, but occurs more slowly and is less effective during chronic exposure to CO_2 concentrations below 30 000 ppm (Guais et al. 2011).

Bone buffering

As mentioned above, renal regulation of CO_2-mediated acidosis is less effective when CO_2 concentrations are below 30 000 ppm for a long period of time. At this level, bone buffering has been postulated to be the primary compensatory mechanism (Bureau of Chemical Hazards 1985). Drummer et al. (1998) investigated the effects of prolonged exposure to elevated CO_2 concentrations on calcium metabolism in human subjects, and observed decreases in serum calcium concentrations and biomarkers of bone formation as well as mild bone resorption (as indicated by the excretion rate of deoxypyridinoline) at 12 000 ppm CO_2.

5 HEALTH EFFECTS

This section provides a brief summary of the health effects of inhaled CO_2 in humans (see section 5.1) as well as relevant toxicological studies in experimental animals (see section 5.2). It focuses primarily on studies that examined the effects of relevant CO_2 exposure concentrations (i.e., expected indoors under normal circumstances as seen in section 3.2). Studies examining the effects of CO_2 at higher concentrations were also considered as they may be relevant to atypical exposure scenarios such as emergency shelters. Relevant information is drawn from a previous review of the health effects of inhalation exposure to CO_2 conducted by Health Canada when developing the 1987 *Exposure Guidelines for Residential Indoor Air Quality* (Bureau of Chemical Hazards 1985). Relevant publications identified from a search of the literature published between 1986 and 2017 where inhalation was the route of exposure were also considered.

5.1 EFFECTS IN HUMANS

A summary of relevant studies on health effects in humans following prolonged or repeated exposure to CO_2 is presented in Table B1 (controlled exposure studies) and Table B2 (epidemiological studies) in Appendix B.

5.1.1 Effects on blood chemistry

A decrease in blood pH (acidosis) was observed in subjects continuously exposed to elevated CO_2 concentrations (i.e., 7000 to 15 000 ppm for a minimum of 20 days) in studies conducted in a submarine environment (Schaefer 1982; Messier et al. 1979; Schaefer et al. 1963). The ALTER for CO_2 in residential indoor air of ≤ 3500 ppm was derived by Health Canada (1987) from the lowest concentration at which this effect had been observed in humans (i.e., 7000 ppm) after the application of an uncertainty factor of 2 for database uncertainties.

5.1.2 Respiratory effects

A number of epidemiological studies have investigated the relationship between respiratory effects and CO_2 concentrations in indoor settings such as schools and office environments. Most of these studies used self-reporting symptom surveys to measure the adverse effects, with only two using clinical tests in addition to those surveys (Norbärk et al. 2011; Simoni et al. 2010). Half of the studies did not control for exposures to other pollutants, while others controlled for exposures to certain pollutants (e.g., particulate matter [PM], volatile organic compounds [VOCs], ozone, nitrogen dioxide) (Dorizas, Assimakopoulos and Santamouris 2015; Lu et al. 2015; Tsai, Lin and Chan 2012; Kim et al. 2011; Simoni et al. 2010).

Associations between CO_2 concentration and respiratory and mucous membrane symptoms have been reported (Dorizas, Assimakopoulos and Santamouris 2015; Lu et al. 2015; Carreiro-Martins et al. 2014; Tsai, Lin and Chan 2012; Norbärk et al. 2011; Simoni et al. 2010; Erdmann and Apte 2004; Apte, Fisk and Daisey 2000; Myhrvold, Olsen and Lauridsen 1996). Effects such as eye irritation, sore or dry throat, stuffy, congested or runny nose, sneezing, and coughing were more likely to be reported by individuals exposed to CO_2 concentrations > 800 ppm than by those exposed to lower CO_2 levels (Tsai, Lin and Chan 2012; Norbärk et al. 2011). Carbon dioxide concentrations > 1000 ppm were associated with a higher risk of experiencing rhinitis (sneezing or a runny or blocked nose) (Simoni et al. 2010). Some authors have reported that a 100 ppm increase in CO_2 concentration or in differential CO_2 (i.e., the difference between indoor and outdoor CO_2 concentrations) can increase the odds of experiencing various respiratory or mucous membrane symptoms (e.g., dry eyes, sore throat, nose/sinus symptoms, tight chest, sneezing, coughing, wheezing, and rhinitis) (Lu et al. 2015; Kim et al. 2011; Simoni et al. 2010; Erdmann and Apte 2004; Apte, Fisk and Daisey 2000).

Building-related symptoms include ocular, respiratory (e.g., nose or throat irritation, rhinitis, cough), and general (e.g., fatigue and headache) symptoms that are temporally related to time spent in a building, particularly offices (Burge 2004; Erdmann and Apte 2004). Carbon dioxide concentrations are generally considered a surrogate for other occupant-derived pollutant (bioeffluent) concentrations and ventilation rates in these studies. Individuals with certain health conditions (such as allergies and asthma) were found to be more likely to report experiencing building-related symptoms (sometimes referred to as sick building syndrome) than those without these conditions (Erdmann and Apte 2004).

Acute inhalation exposure to CO_2 levels between 50 000 and 80 000 ppm decreases specific airway conductance (Tashkin and Simmons 1972) and was reported to cause respiratory symptoms (Maresh et al. 1997). Acute inhalation exposure to higher concentrations of CO_2 produces nasal irritation (> 350 000 ppm) (Wise, Wysocki and Radil 2003) and can cause asphyxia (700 000 ppm) due to displacement of oxygen (Hill 2000).

Infants of mothers who smoked or misused substances during pregnancy were found to have a dampened ventilatory response and a lower increase in central respiratory drive in response to hypercapnia (i.e., induced by exposure to 20 000 and 40 000 ppm CO_2) in the immediate newborn period compared with control subjects (Ali et al. 2014).

5.1.3 Neurological effects

A number of studies investigated the neurophysiological effects or effects on performance (e.g., decision-making, proofreading) in adults exposed to varying CO_2 concentrations under controlled conditions. In these studies (discussed below), pure CO_2 was injected into the room or chamber or the ventilation was adjusted to achieve specific occupant-generated CO_2 concentrations.

Satish et al. (2012) studied decision-making performance under elevated CO_2 concentrations (generated via injection of pure CO_2) in an office-like chamber for 2.5 hours. A computer-based program called the Strategic Management Simulation (SMS) test was used to measure nine scales of decision-making performance. Effects on decision-making performance were observed for CO_2 exposure at 1000 ppm compared to 600 ppm. Under similar conditions, Kajtar and Herczeg (2012) investigated the effects of CO_2 concentration on some physiological parameters, subject comfort, and task performance via two series of experiments in a laboratory setting (70-minute exposure). Effects on subject comfort (based on subjective evaluation of air quality as well as tiredness and concentration), task performance, and level of mental effort required to complete a task were observed at CO_2 concentrations of 3000 ppm compared to 600 ppm. It is important to note that both of these studies were conducted with a small number of subjects (i.e., 10–22 individuals).

Other studies investigated the effects of variation in ventilation on perceived air quality, sick building syndrome symptoms, and task performance. Wargocki et al. (2000) reported improved task performance (i.e., text typing) with increasing ventilation (and corresponding decrease in CO_2 concentration). In the experiment, CO_2 levels under the various ventilation conditions ranged from 195 to 1266 ppm above outdoor levels, while other parameters, including total volatile organic compounds (TVOC), remained constant (275-minute exposure).

In some controlled exposure experiments, variations in ventilation affected TVOC levels and bioeffluents (i.e., compounds generated by the human body, including VOCs such as acetone and acetaldehyde) (Tsushima, Wargocki and Tanabe 2018; Tang et al. 2016) as well as CO_2. Allen et al. (2016) simulated indoor environmental quality conditions in "green" (low VOC) and "conventional" (elevated VOC) office buildings with varying ventilation rates and CO_2 levels (CO_2 concentrations ranged from 550 to 1400 ppm; 8-hour exposure). The impacts on performance on nine cognitive function tests were evaluated using the SMS test. Ventilation rate and CO_2 concentration were found to be independently associated with cognitive test performance. After adjustment for participants, it was estimated that a 400 ppm increase in CO_2 was associated with a 21% decrease in a typical participant's test score and a 20 cubic feet per minute increase in ventilation rate was associated with an 18% increase in these scores. Volatile organic compound levels were also independently associated with performance on the cognitive tests.

Other authors have studied the effects of ventilation on perceived air quality, sick building syndrome symptoms, and cognitive performance and reported neurophysiological symptoms (e.g., headaches and sleepiness) or decreased performance under lower ventilation conditions for 4 hours (Maula et al. 2017; Vehviläinen et al. 2016; Maddalena et al. 2015). However, based on the study designs or uncontrolled conditions (e.g., variation in TVOCs, other bioeffluents, PM or relative humidity), it cannot be determined whether the effects observed resulted from the variation in CO_2 or in any other parameters.

Zhang et al. (2017) explored the effects of exposure to CO_2 with or without bioeffluents on symptoms reporting and task performance (255-minute exposures). Exposures to bioeffluents with CO_2 at 3000 ppm reduced perceived air quality and increased the intensity of reported headache, fatigue, sleepiness, and difficulty in thinking clearly (compared to 500 ppm CO_2). Exposure to 3000 ppm CO_2 with bioeffluents also decreased speed of addition, increased response time in redirection, and decreased the number of correct linkages in a Tsai-Partington test for cue-utilization capacity. No statistically significant effects on perceived air quality, acute health symptoms or cognitive performance were seen during exposures of up to 3000 ppm CO_2 without bioeffluents. Based on those findings, the authors suggested that CO_2 alone did not affect task performance or symptoms to the same extent as bioeffluents.

Several epidemiological studies investigated the relationship between neurophysiological symptoms or academic/work performance and CO_2 concentrations in schools and office environments. It is important to note that as the majority of these studies did not control for exposures to other pollutants (whose levels tend to be highly correlated with those for CO_2), it is difficult to determine the direct effects of CO_2 alone.

Associations between increased CO_2 concentrations and increased prevalence of self-reported neurophysiological symptoms (such as headache, tiredness, fatigue, dizziness or difficulty concentrating) or increased risk of experiencing these symptoms have been reported (Dorizas, Assimakopoulos and Santamouris 2015; Lu et al. 2015; Muscatiello et al. 2015; da Conceição Ferreira and Cardoso 2014; Norbäck, Nordström and Zhao 2013; Myhrvold, Olsen and Lauridsen 1996). In addition, da Conceição Ferreira and Cardoso (2014) found an association between lack of concentration and CO_2 levels of > 984 ppm (maximum reference level according to Portuguese law), compared to levels < 984 ppm, while Myhrvold, Olsen and Lauridsen (1996) reported an association between increased prevalence of headache, dizziness, heavy headedness, tiredness, and difficulty concentrating and CO_2 levels > 1500 ppm, compared to < 1500 ppm. Other studies reported increased odds of experiencing neurophysiological symptoms for every 100 ppm rise in indoor CO_2 levels (Lu et al. 2015; Muscatiello et al. 2015).

Increased CO_2 concentrations have also been associated with decreased performance in school and office settings (e.g., lower standardized test results, power of attention or task performance speed) (Dorizas, Assimakopoulos and Santamouris 2015; Coley, Greeves and Saxby 2007; Wargocki and Wyon 2007a, 2007b; Myhrvold, Olsen and Lauridsen 1996). Several studies also reported associations between decreased ventilation rates in monitored classrooms or offices (estimated in most studies from CO_2 measurements) and poorer academic or work performance (Mendell et al. 2016; Petersen et al. 2016; Haverinen-Shaughnessy and Shaughnessy 2015; Bako-biro et al. 2012; Haverinen-Shaughnessy, Moschandreas and Shaughnessy 2011; Wargocki and Wyon 2007a, 2007b; Shaughnessy et al. 2006; Federspiel et al. 2004).

Neurological effects, such as reported headache, fatigue, visual impairment, and difficulty concentrating as well as temporarily increased cerebral blood flow velocity (which gradually decreased) have been reported in studies investigating the effects of prolonged exposure to high

concentrations of CO_2 (i.e., 1 to 30 days at CO_2 concentration between 6000 and 45 000 ppm) (Carr 2006; Manzey and Lorenz 1998; Sliwka et al. 1998; Radziszewski, Giacomoni and Guillerm 1988; Sinclair, Clark and Welch 1969). Acute inhalation exposure to high concentrations of CO_2 (i.e., 17 000 to 80 000 ppm) has been shown to decrease depth perception (Sun, Sun and Yang 1996) and the ability to detect motion (Yang, Sun and Sun 1997). Symptoms such as tingling in the extremities, dizziness, and blurred or distorted vision have also been reported (Maresh et al. 1997).

Cerebrovascular reactivity (increased blood flow velocity) to hypercapnia has been observed in all blood vessels studied except the superior mesenteric artery (Miyaji et al. 2015; Sato et al. 2012). Dynamic cerebral autoregulation (i.e., maintenance of blood flow during changes in blood pressure) is also reduced (Ogoh et al. 2014). Increased anxiety and panic-like response have also been reported (Nillni et al. 2012; Pappens et al. 2012; Bailey et al. 2005), those suffering from panic or separation anxiety disorder being more likely to react and/or react more severely to CO_2 exposure than those that do not (Atli, Bayin and Alkin 2012; Roberson-Nay et al. 2010; Pine et al. 2000; Beck, Ohtake and Shipherd 1999; Antony, Brown and Barlow 1997; Woods et al. 1988). At very high concentrations (> 150 000 ppm), CO_2 is known to cause loss of consciousness and convulsions (Bove and Davis 2004). Inhalation of 350 000 ppm CO_2 (one or two breaths) was found to activate the hypothalamus-pituitary-adrenal axis in the subjects and cause significant cardiovascular (increase of blood pressure) and psychological (anxiogenic) effects (Argyropoulos et al. 2002), and panic attacks in some individuals (Muhtz et al. 2010).

5.1.4 Cardiovascular effects

Vehviläinen et al. (2016) investigated the physiological and functional effects of indoor CO_2 concentrations in four healthy male subjects in a meeting room located in an office building under ventilated and non-ventilated conditions, for 4 hours. Increases in blood CO_2 concentration, changes in heart rate variability, and increased peripheral blood circulation were measured in participants in the non-ventilated room (CO_2 concentrations of 2756 ± 1100 ppm). The observed changes were associated with concomitant increases in concentrations of CO_2, VOCs, and PM as well as with increased temperature and relative humidity. As the data analysis did not control for confounders (i.e., other pollutants), it cannot be determined whether the effects observed resulted from the increase in CO_2 or in the other parameters, or from a combination of factors.

Zhang, Wargocki and Lian (2017) explored the effects of CO_2 and bioeffluents on physiological parameters. Four-hour exposures to CO_2 at 3000 ppm without bioeffluents (obtained by adding pure CO_2 to the outdoor air supply) resulted in higher end-tidal CO_2 and heart rate compared to the reference CO_2 condition (500 ppm; obtained from outdoor air supply only). Exposures to 1000 and 3000 ppm CO_2 with bioeffluents (obtained by restricting ventilation) significantly increased diastolic blood pressure and reduced nasal peak flow compared to their pre-exposure levels, and increased heart rate compared to exposure to 500 ppm CO_2. Based on the study results, the authors suggested that CO_2 alone did not affect symptoms to the same extent as bioeffluents did.

Cardiovascular effects of prolonged inhalation exposure to elevated CO_2 concentrations (7000 or 12 000 ppm for 23 days) in humans include reduced diffusing capacity for carbon monoxide (CO) and a fall in cardiac output (Sexton et al. 1998), increased ventilation (air exchange between the environment and the lungs) (Elliot et al. 1998; Hoffmann et al. 1998), and temporarily increased heart and respiratory rates (Gundel, Drescher and Weihrauch 1998).

Symptoms such as increased blood pressure and heart rate, heart palpitations, and chest pressure have been reported following acute inhalation exposure to CO_2 (50 000 to 80 000 ppm) (Bailey et al. 2005; Maresh et al. 1997). Cooper et al. (1970) investigated the effects of inhalation of 50 000 ppm CO_2 on stroke patients with and without hypertension, and reported a rise in systemic and pulmonary arterial blood pressure and in cardiac work in subjects exposed to CO_2. At very high concentrations (300 000 ppm), CO_2 is associated with clinically significant cardiac arrhythmia and significant but transient cardiopulmonary morbidity (Halpern et al. 2004; McArdle 1959).

5.1.5 Carcinogenic effects

No studies on the carcinogenic potential of inhaled CO_2 in humans were identified in the literature.

5.2 TOXICOLOGICAL STUDIES

5.2.1 Respiratory effects

Acute inhalation exposure to CO_2 (127 000–150 000 ppm for 1–6 hours) in rodents has been observed to cause an increase in lamellar bodies in alveolar lining cells, congestion, edema, and haemorrhage in lung tissue (Schaefer, Avery and Bensch 1964) as well as an inflammatory response in the lungs (Schwartz et al. 2010). Acute exposure at higher levels has been found to depress respiration, and cause posthypercapneic hypotension as a result of decreased cardiac output (at 500 000 ppm CO_2) and complete respiratory and circulatory cessation (at 800 000–1 000 000 ppm CO_2) (Ikeda et al. 1989).

With respect to longer term exposure (at CO_2 levels ranging from 10 000 to 30 000 ppm), respiratory effects included minor lung changes (Schaefer et al. 1979) and abnormalities (such as incomplete expansion of part of the lung and hyaline membrane formation) (Niemoleler and Schaefer 1962). Statistically significant effects on the olfactory sensitivity to pheromone and the nasal structure (e.g., changes in the cell number and thickness of the vomeronasal or olfactory epithelium, a reduction in the mitotic activity of the basal epithelium cells, and an increase of mature olfactory neurons) were also observed in female mice exposed to 30 000 ppm CO_2 for four weeks (for 5 h/day or 12 h/day for 5 days/week) (Hacquemand et al. 2010; Buron et al. 2009). The changes observed in the epithelium thickness suggested the effect was dependent on exposure duration.

5.2.2 Neurological effects

Toxicological studies investigating the neurological effects of CO_2 exposure or its effects on the developing brain, albeit at very elevated exposure concentrations, support a line of evidence for effects reported in the epidemiological literature, in which those exposed to elevated CO_2 levels

indicated increased sleepiness and decreased neurocognitive performance. Possible modes of action could involve inhibitory effects of CO_2 on the gamma-aminobutyric acid ($GABA_A$) receptor (Sanna et al. 1992) and sodium ion (Na^+) channel (Gu et al. 2007, see section 5.2.3) activity, both of which reduce neuronal activity.

Acute inhalation exposure to high levels of CO_2 (i.e., 75 000 to 350 000 ppm) was found to reduce the function of the $GABA_A$-ionophore receptor complex in various brain areas of rats (Sanna et al. 1992) and increase plasma levels of free norepinephrine metabolite (MHPG), growth hormone, prolactin, and cortisol in monkeys (Krystal et al. 1989). In addition, the findings of a study conducted by Itoh, Yoshioka and Kennotsu (1999) suggest that hypercapnia (induced in anaesthetized and artificially ventilated Wistar rats exposed to 130 000 ppm CO_2 in inspired air) may suppress hippocampal synaptic transmission and its long-term potentiation.

Additional studies on the effects of CO_2 on the developing brain are described in section 5.2.3.

5.2.3 Reproductive/developmental effects

Few studies have examined the reproductive and developmental effects of CO_2 at relevant exposure concentrations. A series of experiments were conducted to investigate the neurological, reproductive, and developmental effects of inhalation exposure to CO_2 concentrations ranging from 1000 to 25 000 ppm in rats—that is, a range-finding study (Hardt, James, Gut and Gargas 2011), a 28-day exposure study which included post-exposure mating (Hardt, James, Gut, Mcinturf, et al. 2011), and a 98-day, two-generation study modeled after the 1998 United States Environmental Protection Agency test guidelines for Reproduction and Fertility Effects (Hardt et al. 2015). The study results showed no reproductive or developmental effects and no adverse changes to estrous cycles or reproductive hormones. Neurotoxicity endpoints were also examined; there were no effects in motor activity or maze tests, and although there were some differences in pup distress vocalization and maternal retrieval in the 28-day study, the results were not consistent or dose-related.

Studies published prior to 1987 demonstrated that short-term exposure to very elevated concentrations of CO_2 (i.e., 50 000 to 350 000 ppm) may result in reproductive (degenerative changes in testes, tubular disturbances, effects on spermatogenesis) and developmental (cardiac and skeletal malformations, increased tissue and cellular maturation in the lungs) effects in experimental animals (Nagai et al. 1987; VanDemark, Schanbacher and Gomes 1972; Schaefer et al. 1971; Grote 1965; Haring 1960). Developmental effects such as neovascularisation of the retina (Holmes et al. 1998, 1997; Holmes, Leske and Zhang 1997; Holmes, Duffner and Kappil 1994) and changes in the characteristics of the alveoli and gene regulation for lung development (Ryu et al. 2010; Das et al. 2009; Li et al. 2006) have also been reported in other neonatal rodent studies exploring the effects of exposure to high levels of CO_2 (i.e., 60 000 to 100 000 ppm CO_2).

Kiray et al. (2014) studied the effects of lower CO_2 exposure on brain development (i.e., on the hippocampus, prefrontal cortex, and amygdala). They exposed rats to air containing 500 (control), 1000 or 3000 ppm CO_2 in utero during the entire pregnancy and up to postnatal day 38 (adolescence). They reported statistically significant changes in hormonal and enzymatic activity,

increased apoptosis in hippocampus as well as increased anxious behaviour and impaired memory and learning in pups. The study findings suggest a dose-dependent effect of CO_2 on memory and learning. However, due to errors noted and limited information on the study protocol, the reliability of these findings are questionable.

Tachibana et al. (2013) exposed rat pups (7-day-old) to 130 000 ppm CO_2 (for 2–4 hours), and studied hippocampal function at 10 weeks of age via learning ability (Morris water maze test) and long-term potentiation induction and paired-pulse responses in the hippocampus. Impaired induction of long-term potentiation in the synapses of the cornu ammonis 1 area was observed and paired-pulse responses of population spikes increased significantly in CO_2-exposed rats, which suggest decreased recurrent inhibition in the hippocampus. The authors indicated that these long-lasting modifications in hippocampal synaptic plasticity may contribute to the learning impairments associated with perinatal hypoxic hypercapnia and acidosis. Spatial reference learning ability was also observed to be delayed, but the memory was retained after learning took place.

Gu, Xue and Haddad (2004) and Gu et al. (2007) found that exposure to elevated CO_2 concentrations (75 000–120 000 ppm) can have an effect on the excitability of neurons in neonatal mice (as indicated by statistically significant changes to neuron properties); this effect was dependent on the duration and the level of CO_2 exposure. Their investigation indicated that the difference in excitability observed at 120 000 ppm CO_2 was related to a reduction of types I and III Na^+ channel expression. Das et al. (2009) observed that exposure to 80 000 ppm CO_2 resulted in a statistically significant increase in TUNEL-positive hippocampal cells, an indicator of apoptosis, necrosis or generalized deoxyribonucleic acid (DNA) injury compared to control conditions as well as a statistically significant increase in the expression of specific apoptotic mediators.

5.2.4 Cardiovascular effects

Thom et al. (2017) showed that mice exposed for two hours to 2000 or 4000 ppm CO_2 had elevated neutrophil and platelet activation and diffuse vascular injury compared to controls.

5.2.5 Carcinogenicity and genotoxicity

No relevant studies on the carcinogenic potential of inhaled CO_2 in experimental animals were identified in the literature. The few published in vivo animal studies examining a possible carcinogenic effect of CO_2 were not considered relevant to this assessment as they used extremely high concentrations (450 000–1 000 000 ppm), and protocols involved exposure by intraperitoneal insufflation or in vitro tissue exposure followed by transplantation (ANSES 2013, Guais et al. 2011).

In vitro, some studies have shown that high CO_2 concentrations (80 000–120 000 ppm) can promote division or proliferation in lung cells; and in bacteria, at concentrations as low as 40 to 1000 ppm, CO_2 increased DNA damage and mutations caused by reactive oxygen species (ANSES 2013; Guais et al. 2011).

5.3 SUMMARY OF HEALTH EFFECTS

Epidemiological studies looking at CO_2 concentrations and health effects in school or office environments showed that mucous membrane or respiratory symptoms (e.g., eye irritation, sore or dry throat, stuffy, congested or runny nose, sneezing, and coughing) were more likely to be reported by individuals exposed to CO_2 concentrations > 800 ppm than by those exposed to lower CO_2 levels (Tsai, Lin and Chan 2012; Norbärk et al. 2011). Carbon dioxide concentrations > 1000 ppm were associated with a higher risk of experiencing rhinitis (sneezing or a runny or blocked nose) (Simoni et al. 2010). Dose-response associations between increases in CO_2 levels and the odds of experiencing various respiratory or mucous membrane symptoms (e.g., dry eyes, sore throat, nose/sinus symptoms, tight chest, sneezing, coughing, wheezing, and rhinitis) were also reported (Lu et al. 2015; Kim et al. 2011; Simoni et al. 2010; Erdmann and Apte 2004; Apte, Fisk and Daisey 2000).

The epidemiological data from school or office environments also showed associations between increased prevalence of self-reported neurophysiological symptoms (such as headache, tiredness, fatigue, dizziness or difficulty concentrating) or increased risk of experiencing these symptoms and elevated CO_2 concentrations (Dorizas, Assimakopoulos and Santamouris 2015; Lu et al. 2015; Muscatiello et al. 2015; da Conceição Ferreira and Cardoso 2014; Norbäck, Nordström and Zhao 2013; Myhrvold, Olsen and Lauridsen 1996). Specifically, CO_2 levels of > 984 ppm were associated with a lack of concentration (da Conceição Ferreira and Cardoso 2014; Myhrvold, Olsen and Lauridsen 1996), while CO_2 levels > 1500 ppm were associated with increased prevalence of headaches, dizziness, heavy headedness, and tiredness, compared to levels < 1000 ppm (Myhrvold, Olsen and Lauridsen 1996). Other studies reported increased odds of experiencing neurophysiological symptoms for every 100 ppm increase in CO_2 levels (Lu et al. 2015; Muscatiello et al. 2015). Individuals with certain health conditions (such as allergies and asthma) were found to be more likely to report experiencing neurophysiological symptoms than those without these conditions (Erdmann and Apte 2004).

Associations (not always but often statistically significant) between increased CO_2 concentration (or decreased ventilation rate per person where that was the metric) and decreased performance in school or office settings (e.g., decision-making, task performance, standardized test scores) were also observed (Mendell et al. 2016; Petersen et al. 2016; Dorizas, Assimakopoulos and Santamouris 2015; Haverinen-Shaughnessy and Shaughnessy 2015; Toftum et al. 2015; Bako-Biro et al. 2012; Twardella et al. 2012; Coley, Greeves and Saxby 2007; Wargocki and Wyon 2007a, 2007b; Shaughnessy et al. 2006; Federspiel et al. 2004; Myhrvold, Olsen and Lauridsen 1996).

Controlled exposure studies on the effects of varying CO_2 concentrations suggest that bioeffluents may have contributed to symptom reporting and task performance (Zhang et al. 2017; Allen et al. 2016), but this was not quantified. Allen et al. (2016) found ventilation rate, VOCs, and CO_2 concentration to be independently associated with cognitive test performance and reported that a 400 ppm increase in CO_2 was associated with a 21% decrease in a typical participant's test score.

Furthermore, effects on decision-making or task performance were observed for exposures to CO_2 ≥ 1000 ppm relative to 600 ppm in studies conducted under controlled conditions (i.e., pure CO_2 injected into a laboratory or chamber) (Satish et al. 2012).

Reported health effects associated with increasing CO_2 concentrations in human studies are presented in Table 3 below. Note that only studies which reported health effects at measured CO_2 concentrations, or an association between health effects and increasing CO_2 concentrations are shown. Studies which reported only a change in ventilation and not corresponding CO_2 measurements were not included, nor were studies that reported only the difference between indoor and outdoor CO_2 concentration rather than the absolute indoor concentration. More details on each study can be found in Appendix B.

Table 3. Health effects associated with increasing CO_2 concentrations in human studies*

Health outcomes	Effects	CO_2 level (ppm)	References and comments
Respiratory effects or mucous membrane symptoms	Eye irritation, sore or dry throat, stuffy, congested or runny nose, sneezing, coughing in the current work week	> 800 compared to < 500 (mean levels were 431 and 876 on the first and second study days)	Tsai, Lin and Chan (2012) Workers (n=111) were more likely to report these effects on the second study day compared to the first. No difference in other symptoms (including wheezing, shortness of breath, dizziness, tiredness)
	"Breathing difficulty" in the past hour	867 compared to 655 (mean levels in the two classrooms)	Norbäck et al. (2011) Students in one classroom (n=26) had a higher score (1.4 on a scale of 0–6) compared to the other (n=35, score 0.2). No difference in medical tests including rhinometry or other symptoms (including eye, nasal or throat symptoms, headache, tiredness)
	Dry cough, Rhinitis (sneezing or a runny or blocked nose) in the past 12 months	> 1000 compared to < 1000 (The CO_2 concentrations were divided into those above and those below the ASHRAE standard)	Simoni et al. (2010) In a study of 654 children, those in classrooms with > 1000 ppm CO_2 had a significantly higher prevalence of dry cough at night and rhinitis compared to those in classrooms with < 1000 ppm CO_2
	Wheeze	Study range 907–4113	Kim et al. (2011) Increased odds of wheeze per 100 ppm increase in CO_2 in a study of 1028 students
	Dry throat	Study range 467–2800	Lu et al. (2015) Increased odds of dry throat per 100 ppm increase in CO_2 in a study of 417 workers
	Allergies, nose irritation	Study range 750–2100	Dorizas et al. (2015) Correlation between symptoms (allergies and nose irritation) and CO_2 concentration in a study of 193 students

Health outcomes	Effects	CO_2 level (ppm)	References and comments
Neurocognitive effects	Decreased performance in school or office settings (e.g., decision-making, task performance, standardized test scores)	945 compared to 550 (CO_2 was added to increase the concentration by 400 ppm)	Allen et al. (2016) In a controlled exposure study (n=24), SMS test scores were 15% lower on 7 of 9 tasks
		1000 compared to 600 (CO_2 was added to increase the concentration by 400 ppm)	Satish et al. (2012) In a controlled exposure study (n=22), mean SMS test scores were 11–23% lower for 7 of 9 tasks
		> 1000 compared to < 1000 (classroom CO_2 concentrations were divided into those above and those below 1000 ppm)	Myhrvold, Olsen and Lauridsen (1996) In a study of 550 students, there was a slight, non-statistically significant decrease in performance on a standardized test for children in classrooms with CO_2 concentration > 1000 ppm compared to those < 1000 ppm
		1300 compared to 900 (ventilation changed)	Wargocki and Wyon (2007a, 2007b) In a study of 46 students, performance (speed) on numerical or language-based tasks improved when ventilation increased (and therefore decreased CO_2)
		1800 compared to 900 (ventilation changed)	Maddalena et al. (2015) In a study of 16 subjects in a simulated office, decrease in score on decision-making performance test
		2115 compared to 1045 (ventilation changed)	Twardella et al. (2012) In a study of 417 students, total number of errors on a test decreased when ventilation was improved (and therefore decreased CO_2)
		2260 compared to 540 (ventilation changed)	Maula et al. (2017) In a study of 36 subjects in a simulated office, decreased scores in 2 of 7 tests
		2909 compared to 690 (ventilation changed)	Coley, Greeves and Saxby (2007) In a study of 18 students, significantly better results on several cognitive tests when windows were open (resulting in decreased CO_2) compared to closed
		3000 compared to 500 (ventilation changed)	Zhang et al. (2017) In a study of 25 subjects in a simulated office, decreased scores on 2 tests
		3000 compared to 600 (CO_2 was added to increase the concentration)	Kajtar and Herczeg (2012) In a study of 10 subjects in chamber study, decreased performance on mental task
		Study range 750–2100	Dorizas et al. (2015) Decreased test performance with increase in CO_2 concentration in a study of 193 students
Neurophysiological effects	Headache, tiredness	809 compared to 784 (ventilation changed)	Norbäck Nordstrom and Zhao (2013) In a study of 62 students, more reports of headaches when the classroom CO_2 concentration was 809 ppm compared to 784 ppm
	Lack of concentration	> 984 compared to < 984 (the mean CO_2 concentrations were divided into those above and those below the maximum reference level according to Portuguese law)	da Conceição Ferreira and Cardoso (2014) Parents of students in classrooms with higher CO_2 (n=856) were more likely to report a lack of concentration than those with lower classroom CO_2 (n=163). There were no associations with CO_2 and asthma or other respiratory diseases and symptoms, dizziness, headache

Health outcomes	Effects	CO_2 level (ppm)	References and comments
	Headaches, dizziness, heavy headedness, and tiredness	> 1500 compared to < 1500 (classroom CO_2 concentrations were divided into those above and those below 1500 ppm)	Myhrvold, Olsen and Lauridsen (1996) In a study of 550 students, there was an increase in the grade and number of symptoms for children in classrooms with CO_2 concentration > 1500 ppm compared to those < 1500 ppm
	Fatigue	2260 compared to 540 (ventilation changed)	Maula et al. (2017) In a study of 36 subjects in a simulated office, increased reports of fatigue
	Headache, sleepiness	2756 compared to 906 (ventilation changed)	Vehviläinen et al. (2016) In a study of 4 subjects in a simulated meeting room, increased reports of headache and sleepiness
	Headache, fatigue, sleepiness	3000 compared to 500 (ventilation changed)	Zhang et al. (2017) In a study of 25 subjects in a simulated office, increased reports of headache, fatigue and sleepiness
	Fatigue	5000 compared to 600 (CO_2 was added to increase the concentration)	Kajtar and Herczeg (2012) In a study of 10 subjects in chamber study, increased reported fatigue
	Difficulty concentrating, headache, fatigue	Study range 352–1591	Musciatello et al. (2015) Increased odds of difficulty concentrating, headache and fatigue per 100 ppm increase in CO_2 in a study of 68 teachers
	Tiredness, dizziness	Study range 467–2800	Lu et al. (2015) Increased odds of tiredness and dizziness per 100 ppm increase in CO_2 in a study of 417 workers
	Fatigue	Study range 750–2100	Dorizas et al. (2015) Correlation between symptoms (fatigue) and CO_2 concentration in a study of 193 students
	Headaches, fatigue, visual impairment, temporarily increased cerebral blood flow velocity	6000–45 000	Carr (2006); Manzey and Lorenz (1998); Sliwka et al. (1998); Radziszewski, Giacomoni and Guillerm (1988); Sinclair, Clark and Welch (1969)
Cardiovascular or physiological effects	Reduced diffusing capacity for CO, fall in cardiac output, increased ventilation (air exchange between the environment and the lungs), temporarily increased heart and respiratory rates	7000–45 000	Elliot et al. (1998); Gundel, Drescher and Weihrauch (1998); Hoffmann et al. (1998); Sexton et al. (1998)
Effect on blood chemistry	Acidosis	≥ 7000	Schaefer (1982); Messier et al. (1979); Schaefer et al. (1963)

* Epidemiological studies in schools or offices and controlled exposure studies (1- to 5-hour exposure). See section 5.1 for study details and limitations. No causality was determined.

As indicated in Table 3, based on the studies which investigated the effects of exposure to CO_2 in humans at relevant concentrations (i.e., expected indoors under normal circumstances), it appears that the risk of experiencing health effects (such as mucous membrane, respiratory or neurophysiological symptoms, or decreased cognitive performance) begins to increase at CO_2 concentrations greater than about 800 ppm. However, limitations with the available studies have been noted. For example, of all the studies which reported relationships between symptoms or task performance and elevated indoor CO_2 concentrations, and which specified the CO_2 exposures (rather than ventilation rates), only a handful were carried out at CO_2 concentrations below 1000 ppm. In addition, co-pollutants and other confounding factors were not, for the most part, measured nor taken into account in the prolonged or repeated exposure studies. Another limitation of the available studies is the fact that many of the health outcomes were measured subjectively (e.g., self-reported symptoms) or using different methods (e.g., cognitive task evaluations included standardized knowledge tests, office-like tasks, and SMS tests). The relevance of these types of outcomes to long-term health effects is also not clear. Furthermore, many of the available studies were conducted with a small number of participants. Finally, in some studies, the CO_2 concentration measurements did not align temporally with the administration of the questionnaire and/or cognitive task performance test.

Effects of repeated or prolonged inhalation exposure to higher CO_2 concentrations (between approximately 6000 and 45 000 ppm for 1 to 30 days) in humans include cardiovascular effects such as a reduced diffusing capacity for CO and a fall in cardiac output (Sexton et al. 1998), increased ventilation (air exchange between the environment and the lungs) (Elliot et al. 1998; Hoffmann et al. 1998), temporarily increased heart and respiratory rates (Gundel, Drescher and Weihrauch 1998), and neurophysiological effects (e.g., headaches, fatigue, visual impairment, and difficulty concentrating) as well as temporarily increased cerebral blood flow velocity (Carr 2006; Manzey and Lorenz 1998; Sliwka et al. 1998; Radziszewski, Giacomoni and Guillerm 1988; Sinclair, Clark and Welch 1969).

Studies in laboratory animals were generally at high concentrations; however, the results from studies investigating the neurological effects of CO_2 exposure or its effects on the developing brain support the observations from human studies.

5.4 VULNERABLE AND SUSCEPTIBLE POPULATIONS

Indigenous peoples may be considered more vulnerable to the health effects of CO_2, as according to 2016 Census data, close to one-fifth (18.3%) of the Indigenous population lived in crowded housing[1] (on and off reserve), which is higher than the non-Indigenous population (8.5%), and the portion of First Nations people with registered or treaty Indian status living in a crowded dwelling was higher on reserve (36.8%). Crowding and inadequate ventilation have also been identified as characteristics of First Nations and Inuit housing in certain communities (CMHC 2019, 2005; Statistics Canada 2017; Health Canada 2007b; Kovesi et al. 2007). These factors could explain in part the higher levels of CO_2 measured in homes of First Nations and Inuit communities (Health Canada 2018a; 2007a; Weichenthal et al. 2012; Kovesi et al. 2007) compared to the concentrations measured in other Canadian residences. Individuals living in low income housing are also considered to be more vulnerable to the health effects of air pollution in general, as they are more likely to live in homes with poor conditions.

Infants and children are also considered a vulnerable population, as they may be exposed to elevated indoor CO_2 levels in environments outside of their home, such as schools and daycare centres. In addition, because of their size, children inhale more air in relation to their body weight than adults. Infants and children may also be more susceptible than adults to the health effects of air contaminants due to differences in their ability to metabolize, detoxify, and excrete contaminants, and because they undergo rapid growth and development (Suk, Murray and Avakian 2003; Faustman et al. 2000). Infants of mothers who smoked or misused substances during pregnancy were found to be more susceptible to the adverse effects of hypercapnia than control subjects (Ali et al. 2014).

Individuals with pre-existing health conditions (such as allergies and asthma) were found to be more susceptible to the mucous membrane and respiratory effects of CO_2 than those without these conditions (Erdmann and Apte 2004). Due to the physiological and metabolic actions of CO_2 in the body, it is expected that individuals with cardiovascular conditions may also be more susceptible to the health effects of elevated CO_2 exposure. Patients suffering from panic disorder or separation anxiety disorder were found to be more susceptible to the anxiogenic effects of CO_2 compared to healthy subjects (Atli, Bayin and Alkin 2012; Roberson-Nay et al. 2010; Pine et al. 2000; Beck, Ohtake and Shipherd 1999; Antony, Brown and Barlow 1997; Woods et al. 1988).

[1] See **Housing suitability** as a measure of crowding.

6 RISK CHARACTERIZATION

6.1 DERIVATION OF THE RECOMMENDED LONG-TERM EXPOSURE LIMIT

Epidemiological and controlled exposure studies examining CO_2 concentrations and health effects in school or office environments have shown associations between increases in CO_2 levels and the odds of experiencing mucous membrane or respiratory symptoms (e.g., eye irritation, sore or dry throat, stuffy, congested or runny nose, sneezing, coughing, and rhinitis); an increased prevalence of neurophysiological symptoms (such as headache, tiredness, fatigue, dizziness or difficulty concentrating); and decreased test performance (e.g., decision-making, task performance, standardized test scores) (see section 5.1). In many of these studies, CO_2 was used as a measure of ventilation, and other indoor pollutants are also increased under conditions of low ventilation. Therefore this needs to be taken into consideration when attributing health effects directly to CO_2 exposure. Studies in laboratory animals support the observations reported in human studies (see section 5.2).

There are limitations to the available human studies examining associations between health effects and CO_2 concentrations relevant to indoor exposure (≤ 3000 ppm) (see section 5.3 for details). Although associations have been observed between increased CO_2 concentrations and increased reporting of respiratory or neurophysiological symptoms and decreased performance on tasks and tests, no causality can be determined. However, despite database deficiencies and issues with the data collection and analysis of many of the human studies, available studies suggest a trend of increasing odds of symptoms with increasing indoor CO_2 concentration. Although a few studies showed associations between effects and concentrations below 1000 ppm, most used test concentrations that were above this level.

No individual study was considered strong enough on its own to be selected as the basis for a recommended exposure limit, however, taken as a whole the database indicates that there may be comfort benefits (i.e. improved perception of indoor air quality) and health benefits to reducing indoor CO_2 concentrations, and that 1000 ppm could be considered a suitable exposure limit. This level is in line with the ASHRAE standard as well as standards from other countries. It should be noted that these other existing standards also use CO_2 as a surrogate for overall indoor air quality, and were not derived based on direct health effects. Therefore, the recommended long-term exposure limit for CO_2 is 1000 ppm.

6.2 EXPOSURE IN CANADIAN HOMES IN RELATION TO RECOMMENDED EXPOSURE LIMIT

Results from the Canadian Human Activity Pattern Survey 2 indicate that Canadians spend approximately 90% of their time indoors (Matz et al. 2014), most of which (70%) is indoors at home, with less time (19%) spent at other indoor locations such as schools, public buildings, offices, factories, stores, and restaurants. Given the proportion of time spent indoors and the fact that most of the CO_2 indoors comes from indoor sources—primarily occupant respiration—the concentration of CO_2 in the indoor environment is an important consideration for the health of Canadians.

Health Canada has completed several indoor exposure studies in multiple Canadian cities or regions. The results of these studies include residential indoor CO_2 concentrations as well as levels in schools and daycare centres. Median CO_2 levels measured in Health Canada studies in Canadian homes in six cities ranged from 418 to 729 ppm, and 95th percentiles from 477 to 1483 ppm (see Table 2). Based on existing data, overall, CO_2 levels measured in on-reserve First Nations homes in Ontario and Manitoba and in Inuit communities in Nunavut were higher than those measured in other Canadian residences, with median and 95th percentiles ranging from 1058 to 1139 ppm, and from 2121 to 2436 ppm, respectively. Carbon dioxide levels measured in Health Canada studies in schools and daycare centres fell within the range of residential values (i.e., median and 95th percentile in four schools were 491 and 1171 ppm, respectively; mean in 21 daycare centres was 1333 ppm, with a standard deviation of 391 ppm).

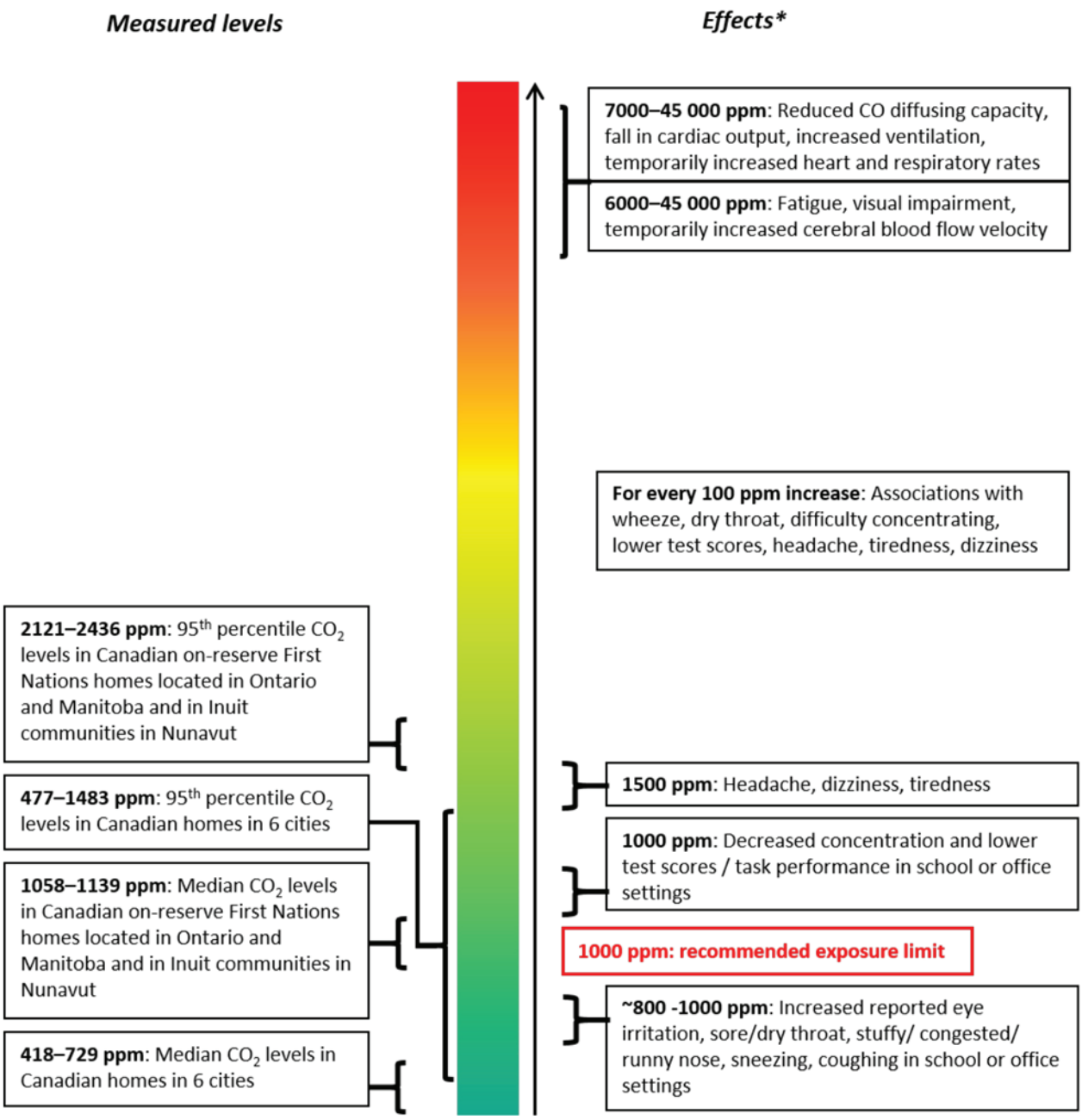
Figures 1 and 2 show a comparison between CO_2 concentrations measured in Health Canada studies in Canadian homes (including on-reserve First Nations homes located in Ontario and Manitoba and in Inuit communities in Nunavut), schools, and daycare centres (see Table 2), and the range of concentrations associated with health effects in human studies (see Table 3). Median CO_2 levels measured in Canadian homes in six cities are below the lowest level at which there was an association with any effects. However, median CO_2 levels in on-reserve First Nations homes located in Ontario and Manitoba and in Inuit communities in Nunavut are slightly above levels at which associations with respiratory and mucous membrane symptoms, decreased concentration and lower test scores in school and office settings were observed (see Figure 1). When considering the range of 95th percentiles, the upper end of the measured levels in six cities is slightly above levels at which these associations were observed. The 95th percentiles in on-reserve First Nations homes located in Ontario and Manitoba and in Inuit communities in Nunavut are also above the range of concentrations associated with increased reports of headache, dizziness and tiredness.

With respect to the small number of Canadian schools (4) and daycare centres (21) studied by Health Canada, the median CO_2 level measured in occupied schools is below the CO_2 concentrations associated with health effects. However, the 95th percentile CO_2 level measured in schools and the mean CO_2 level measured in daycare centres fall within the range of concentrations associated with increased reports of respiratory and mucous membrane symptoms, decreased concentration, lower test scores in school and office settings, headache, dizziness and tiredness (see Figure 2).

These results suggest that there are likely Canadian homes, schools, and daycare centres in which the recommended exposure limit of 1000 ppm is exceeded. On-reserve First Nations homes located in Ontario and Manitoba and in Inuit communities in Nunavut are more likely to have measured levels of CO_2 that are above the recommended exposure limit than other Canadian homes. However, as noted in sections 5.3 and 6.1, interpretation of the studies on which the recommended exposure limit is based is limited by multiple factors. In addition, it cannot be determined from the available evidence whether CO_2 or some other factor causes the observed effects. Nevertheless, as Figures 1 and 2 suggest, lowering CO_2 concentrations in homes, schools, and daycare centres to below the recommended exposure limit could decrease the risk of symptoms associated with increased CO_2 concentrations.

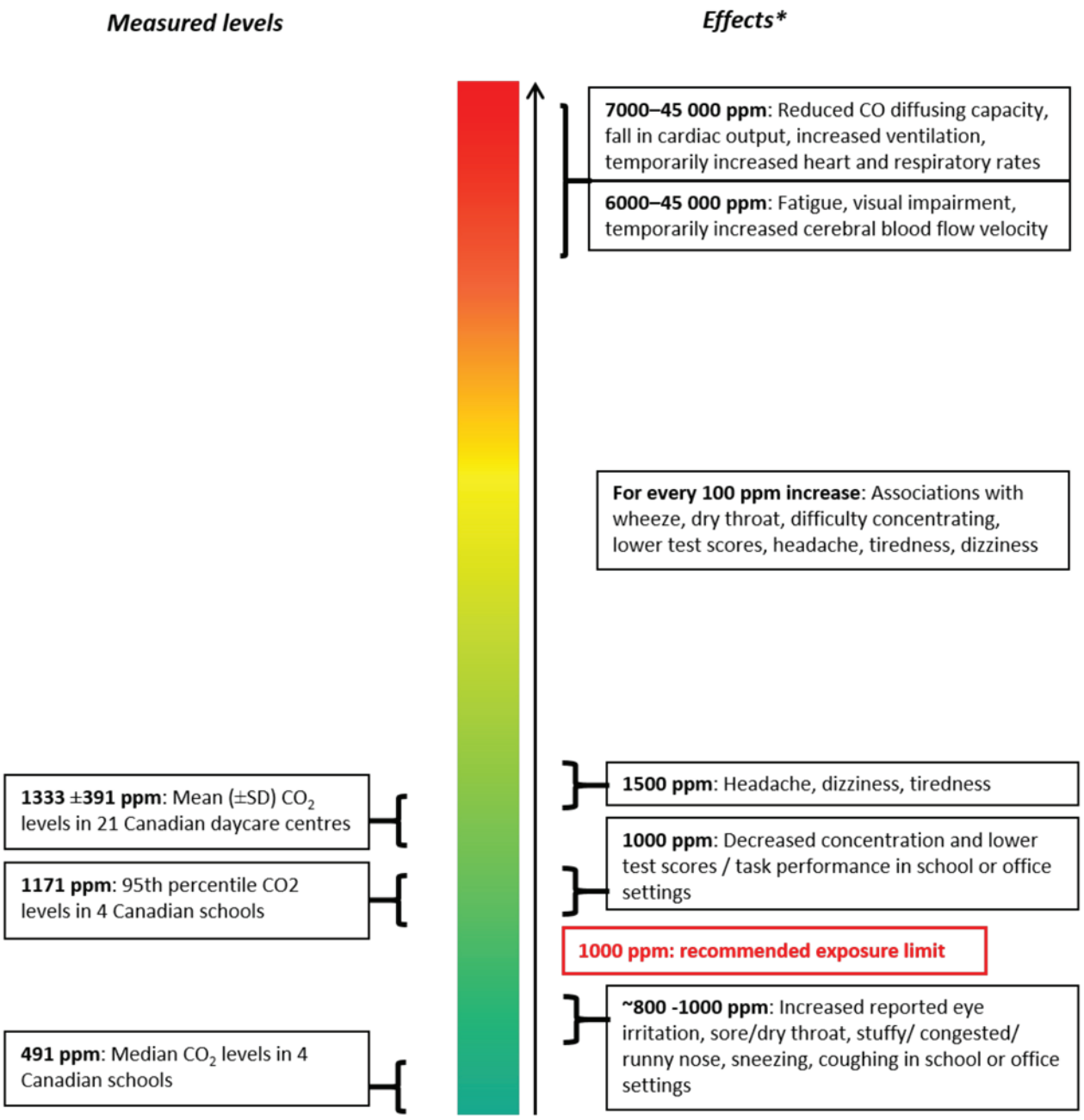
Atypical exposure scenarios, including during the use of emergency shelters, which involve non-routine use of municipal infrastructure, have also been considered. As no indoor CO_2 exposure concentrations were found in Health Canada studies or in the published literature for emergency situations, CO_2 exposure from atypical exposure scenarios could not be characterized as part of this assessment.

Figure 1. Comparison of CO_2 concentrations in Canadian homes to CO_2 concentrations associated with health effects



* Some associations were observed in epidemiological studies (in offices and schools) and controlled exposure studies (generally 1- to 5-hour exposures). However, many study limitations were noted, and causality was not linked to CO_2. Carbon dioxide levels closer to the bottom (green) represent the lowest potential risk of health effects.

Figure 2. Comparison of CO_2 concentrations in a limited number of Canadian schools and daycare centres to CO_2 concentrations associated with health effects



* Some associations were observed in epidemiological studies (in offices and schools) and controlled exposure studies (generally 1- to 5-hour exposure). However, many study limitations were noted, and causality was not linked to CO_2. Carbon dioxide levels closer to the bottom (green) represent the lowest potential risk of health effects.

6.3 UNCERTAINTIES AND AREAS OF FUTURE RESEARCH

Areas for future research that have been identified by this assessment include the following:

- Human studies investigating the health effects of indoor CO_2 concentrations relevant to indoor environments (especially < 1000 ppm), which control for potential confounders, including other indoor pollutants, and use standard test methods.
- Studies exploring the relative contribution of CO_2 and other pollutants on respiratory, mucous membrane, and neurophysiological symptoms or neurocognitive performance at CO_2 exposure levels relevant to indoor environments.
- Studies in potentially sensitive populations (e.g., individuals with pre-existing health conditions) investigating the health effects of indoor CO_2 concentrations relevant to indoor environments (especially < 1000 ppm).
- Characterization of the relative contributions of potential sources of indoor CO_2.
- Characterization of indoor exposures to CO_2 in non-residential indoor settings (such as schools and daycare centres) in Canada.

7 GUIDELINES

7.1 RECOMMENDED LONG-TERM EXPOSURE LIMIT

Table 4. Recommended long-term exposure limit for CO_2 in indoor environments

Exposure Limit	Concentration		Critical effect(s)*
	mg/m³	ppm	
Long-term (24 h)	1800	1000	As CO_2 increases, there may be an increased risk of: • mucous membrane or respiratory symptoms (e.g., eye irritation, sore or dry throat, stuffy, congested or runny nose, sneezing, coughing, and rhinitis) • decreased test performance (e.g., decision-making, task performance, standardized test scores) • neurophysiological symptoms (headache, tiredness, fatigue, dizziness or difficulty concentrating)

* The recommended guidelines are based on effects observed in epidemiological studies in schools or offices and controlled exposure studies. Due to limitations in the database, effects cannot with certainty be attributed directly to CO_2 exposure; rather they may result from poor indoor air quality in general.

When comparing a measured CO_2 concentration with the long-term exposure limit, the sampling time should be at least 24 hours, taken under normal conditions. Moreover, the averaging of results of repeated samples taken at different times of the year will provide a more representative estimate of the long-term exposure.

7.2 RISK MANAGEMENT RECOMMENDATIONS

Measured data confirms there are Canadian homes, schools, and daycare centres in which the recommended exposure limit for CO_2 is exceeded. Based on existing data, on-reserve First Nations homes located in Ontario and Manitoba and in Inuit communities in Nunavut are more likely to have measured levels of CO_2 that are above the recommended exposure limit than other Canadian homes. Therefore, there may be an increased risk of respiratory symptoms, decreased test performance, headaches, dizziness and tiredness.

The primary source of CO_2 in Canadian homes is occupant respiration, and other sources include unvented or poorly vented fuel-burning appliances and cigarette smoking. In most residential situations, identifying potential sources of CO_2 and reduction measures is more informative and cost-effective for improving indoor air quality than air testing and comparing measured concentrations to the recommended exposure limit. Therefore, Health Canada recommends that individuals take actions to reduce indoor levels of CO_2.

Carbon dioxide concentrations in indoor air are often used as a measure of ventilation, and ensuring adequate ventilation will help reduce CO_2 levels in the home. Strategies to increase ventilation in the home include the following:

- increasing natural ventilation by opening windows (taking into consideration ambient air quality);
- setting the mechanical ventilation system to a higher setting or letting it run longer;
- having the ventilation system checked regularly by a qualified ventilation contractor;
- running the kitchen range hood exhaust fan when cooking; and
- using the furnace fan or, if necessary, a separate fan or air supply to make sure air is distributed throughout the home.

Additional information on measures to improve ventilation in homes can be found in the technical document Ventilation and the Indoor Environment (Health Canada 2018c).

In terms of source control, the production of residential indoor CO_2 may be reduced by:

- ensuring fuel-burning appliances are in good working order and properly vented;
- avoiding the use of unvented fuel-burning appliances (e.g., space heaters) indoors;
- not smoking indoors; and
- avoiding crowded living situations, if possible.

In terms of implementation of CO_2 reduction strategies, specifically increased ventilation, ambient air quality must be considered. During periods of poor ambient air quality, such as those experienced during forest fire events, reducing air intake and thus infiltration of ambient air pollutants may be more beneficial from a health risk perspective, compared to reducing indoor CO_2 levels to below the recommended exposure limit. The information contained within this document may be used to inform the development of additional scenario-specific CO_2 exposure limits, such as for homes during smog events or emergency shelters during wildfires.

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APPENDICES

APPENDIX A: LIST OF ACRONYMS AND ABBREVIATIONS

ACH	Air changes per hour
AER	Air exchange rate
ALTER	Acceptable long-term exposure range
ANSES	Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail (France)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2	Carbon dioxide
CO	Carbon monoxide
DNA	Deoxyribonucleic acid
dUTP	Deoxyuridine Triphosphate
$GABA_A$	Gamma-aminobutyric acid
H^+	Hydrogen ion
H_2CO_3	Carbonic acid
HCO_3^-	Bicarbonate ion
MHPG	3-Methoxy-4-hydroxyphenylglycol
Na^+	Sodium ion
Pa_{CO_2}	Arterial partial pressure of carbon dioxide
PM	Particulate matter
RIAQG	Residential Indoor Air Quality Guidelines
SMS	Strategic Management System
TUNEL	Terminal deoxynucleotidyl transferase dUTP nick end labelling
TVOC	Total volatile organic compounds
VOC	Volatile organic compound

APPENDIX B: HUMAN STUDIES ON THE HEALTH EFFECTS OF CO_2 EXPOSURE

Table B1. Summary of controlled exposure studies

Concentration (ppm)	Duration of exposure	Number of subjects	Study characteristics	Results	Reference
600, 1000, 2500	2.5 hrs	22	600 ppm: outdoor ventilation and occupant-generated CO_2 1000 ppm, 2500 ppm: pure CO_2 injected into chamber SMS test	At 1000 ppm, 6 out of 9 scales of decision-making performance statistically were significantly reduced (relative to 600 ppm) ($p < 0.05$). At 2500 ppm, 7 out of 9 scales of decision-making performance were statistically significantly reduced ($p < 0.01$).	Satish et al. (2012)
600, 1500, 2500, 3000, 4000, 5000	2–3 × 70 min	10	Pure CO_2 injected into chamber Questionnaires, physiological measures, mental work (proofreading)	Series 1: increased reported fatigue, and increased absolute and relative values of MF of HPV (used to measure mental effort required by the task) at 5000 ppm compared to 600 ppm ($p < 0.05$) Series 2: decreased performance on the mental task, and increased mental effort required by the task (as measured by MF of HPV) at 3000 and 4000 ppm compared to 600 ppm ($p < 0.05$)	Kajtar and Herczeg (2012)
1266, 477, 195 above outdoor levels (i.e., low, mid and high ventilation conditions)	275 min	30	Outdoor ventilation and occupant-generated CO_2 Toluene-equivalent TVOC concentration not affected by the ventilation; temperature, relative humidity and noise kept constant Office performance tasks (proofreading, text typing, addition, and creative thinking)	Increasing ventilation increased perceived air quality ($p < 0.002$), decreased symptom reporting (e.g., mouth and throat dryness) ($p < 0.0006$) and eased difficulty in thinking clearly ($p < 0.001$). Task performance improved with increasing ventilation; the effect only reached statistical significance ($p < 0.03$) for text typing	Wargocki et al. (2000)
550, 945, 1400	8 hrs	24	Outdoor ventilation and occupant-generated CO_2 Two ventilation conditions (20 and 40 cfm/person), three different CO_2 concentrations (550, 945, and 1400 ppm), and two VOC conditions (low: TVOC < 60 µg/m^3; elevated: TVOC ~ 500 µg/m^3) were applied over the course of the study. Other parameters (e.g., temperature, humidity, PM levels, and noise) were maintained. SMS test	Ventilation rate and CO_2 concentration were independently associated with cognitive test performance ($p < 0.0001$). A 400 ppm increase in CO_2 was associated with a 21% decrease in test scores and a 20 cfm increase in ventilation rate was associated with an 18% increase in test scores. VOC levels independently associated with performance on cognitive tests ($p < 0.0001$). Cognitive function scores were higher under the low-VOC condition for all nine functional domains.	Allen et al. (2016)
540, 2260	4 hrs	36	Condition A: filtered outdoor air Condition B: occupant-generated CO_2 and bioeffluents Seven cognitive performance tasks (i.e., typing, star counting, operation span, N-back, information retrieval, creative thinking, and long-term memory tasks) and questionnaires	Condition B increased perceived workload and perceived fatigue, and decreased perceived air quality ($p < 0.05$) vs. Condition A. Condition B negatively affected performance on speed in information retrieval ($p = 0.009$) and trended negatively for accuracy in operation span test, with the other five tasks remaining unaffected.	Maula et al. (2017)

Concentration (ppm)	Duration of exposure	Number of subjects	Study characteristics	Results	Reference
900, 1800	4 hrs	16	Outdoor ventilation and occupant-generated CO_2 Low ventilation condition: 2.6 l/sec-person (1100–1800 ppm CO_2, ~ 50 mg/m^3 TVOC) High ventilation condition: 8.5 l/sec-person (800–900 ppm CO_2, ~ 125 mg/m^3 TVOC) Temperature and relative humidity were consistent across all conditions and within each condition. SMS test and questionnaire	Pair-wise analysis of variance revealed a modest but significant ($p < 0.001$–0.299 for the eight performance metrics) decrease in decision-making performance as the ventilation rate per person decreased.	Maddalena et al. (2015)
906 (± 249), 2756 (± 1100)	3 × 4 hrs	4	Outdoor ventilation and occupant-generated CO_2 Condition A: ventilation system off for a one-week period Condition B: ventilation system on for a one-week period Questionnaires, physiological measures	Increases in blood CO_2 concentration, changes in heart rate variability, and increased peripheral blood circulation were measured under non-ventilated conditions. Increased reported headache and sleepiness symptoms under non-ventilated conditions. The observed changes were associated with concomitant increases in concentrations of CO_2, VOCs, and PM as well as with increased temperature and relative humidity.	Vehviläinen et al. (2016)
500, 1000, 3000	255 min	25	500 ppm CO_2: outdoor ventilation 1000 and 3000 ppm CO_2 without bioeffluents: pure CO_2 injected 1000 and 3000 ppm CO_2 with bioeffluents: fresh air intake reduced to allow CO_2 and bioeffluents to build up Questionnaires, physiological measures, "office-like" tasks (e.g., text typing), cognitive tests (e.g., attention level), and neurobehavioral tests (e.g., grammatical reasoning)	Compared to 500 ppm CO_2: At 3000 ppm CO_2 with bioeffluents: reduced perceived air quality, increased intensity of reported headaches, fatigue, sleepiness and difficulty in thinking clearly. At 3000 ppm CO_2 with bioeffluents: decreased speed of addition, increased redirection response time, and decreased the number of Tsai-Partington correct linkages (cue-utilization capacity test). No effect of CO_2 without bioeffluents on perceived air quality, headache, ability to think clearly, fatigue or cognitive performance.	Zhang et al. (2017)
500, 1000, 3000	255 min	25	500 ppm CO_2: outdoor ventilation 1000 and 3000 ppm CO_2 without bioeffluents: pure CO_2 injected 1000 and 3000 ppm CO_2 with bioeffluents: fresh air intake reduced to allow CO_2 and bioeffluents to build up Questionnaires, physiological measures, "office-like" tasks (e.g., text typing), cognitive tests (e.g., attention level) and neurobehavioral tests (e.g., grammatical reasoning)	3000 ppm CO_2 without bioeffluents increased end-tidal CO_2 and heart rate compared to the reference CO_2 condition (500 ppm). 1000 and 3000 ppm CO_2 with bioeffluents significantly increased diastolic blood pressure and reduced nasal peak flow compared to pre-exposure levels, and increased heart rate compared to 500 ppm CO_2 exposure.	Zhang, Wargocki and Lian (2017)

Notes: HPV = heart period variability; MF = mid-frequency component

Table B2. Summary of epidemiological studies

Health outcomes	CO_2 exposure concentration (Mean ± SD [range] ppm)	Population characteristics	Study characteristics	Results	Reference, study location
Respiratory, ocular effects	590–867	61 children	Intervention, school setting 3 days/week for 3 weeks (one control and 2 intervention weeks) Questionnaires, medical testing (tear film stability, nasal patency) Not controlled for other pollutants	When the ventilation system in the intervention classroom was changed from "mixing" (week 1) to "front ventilation," (week 2) mean CO_2 concentration at desk level was reduced from 867 to 655 ppm. The control classroom (front ventilation) was at 590 for the first week and 625 ppm for the second. In week 1, dyspnea was greater in the intervention classroom compared to the control ($p<0.001$), and improved during week 2.	Norbäck et al. (2011), Sweden
Respiratory, ocular effects	431 (± 19) (375–484) 876 (± 48) (658–959)	111 workers	Cross-sectional (repeated), office setting Two study periods: 1 week in August, 1 week in November Questionnaires PM levels kept constant (i.e., air filters)	Responses in week 1 (August): mean concentration 431 ppm compared to week 2 (November): mean 876 ppm Workers exposed to > 800 ppm indoor CO_2 were more likely to report "eye irritation" (OR = 1.7; 95% CI = 1.1–2.7) and "upper respiratory symptoms" (OR = 1.7; 95% CI = 1.0–2.7) than those exposed to CO_2 concentrations < 500 ppm. Workers exposed to > 800 ppm indoor CO_2 were also likely to report more "tired or strained eyes" (OR = 1.7, 95% CI = 1.1–2.7), "dry, itching, or irritated eyes" (OR = 1.8, 95% CI = 1.2–2.8), and "difficulty in remembering things or in concentrating" (OR = 1.7, 95% CI = 1.0–2.9). Headache was marginally increased when the CO_2 concentrations were greater than 800 ppm.	Tsai, Lin and Chan (2012), Taiwan
Respiratory effects	1440 (median)	Phase 1: 3186 children; mean age = 3.1 yrs Phase 2: 1196 children (sub-sample of phase 1 children)	Cross-sectional, daycare centre setting Questionnaires Not controlled for other pollutants	Phase 1: association between wheezing in the previous 12 months and indoor CO_2 concentration (median value = 1440 ppm) (OR = 1.04; p = 0.008). No associations were found between CO_2 level and reported diagnosis of asthma. Phase 2: the association between wheezing and CO_2 concentration in classrooms was not found to be significant.	Carreiro-Martins et al. (2014), Portugal
Respiratory effects	dCO_2 (average indoor minus average outdoor) 6–418 ppm	1970 workers	Cross-sectional, office setting Assessment of data from the Building Assessment Survey and Evaluation study Not controlled for other pollutants	Statistically significant dose-response relationship between differential CO_2 concentration (i.e., difference between indoor and outdoor CO_2) and respiratory symptoms (e.g., sore throat, nose/sinus symptoms, tight chest, and wheezing). For every 100 ppm increase in indoor CO_2 relative to outdoor, ORs for those symptoms increased between 1.2 and 1.5 ($p < 0.05$).	Apte, Fisk and Daisey (2000), United States

Health outcomes	CO_2 exposure concentration (Mean ± SD [range] ppm)	Population characteristics	Study characteristics	Results	Reference, study location
Respiratory effects	dCO_2 (average indoor minus average outdoor) 40–610 ppm (mean 260)	Not specified	Cross-sectional, office setting Assessment of data from the Building Assessment Survey and Evaluation study Not controlled for other pollutants	Association between elevated indoor CO_2 levels and increased prevalence of certain mucous membrane and lower respiratory building related symptoms. Adjusted ORs per 100 ppm CO_2 increase were statistically significant ($p < 0.05$) for: mucous membrane = 1.08 (95% CI = 1.02–1.15); dry eyes = 1.09 (95% CI = 1.02–1.17); sore throat = 1.21 (95% CI = 1.091.34); nose/sinus = 1.11 (95% CI = 1.02–1.2); sneezing = 1.09 (95% CI = 1.00–1.19); and wheezing = 1.23 (95% CI = 1.01–1.48). Building occupants with certain environmentally mediated health conditions (e.g., allergies and asthma) were more likely to report that they experienced symptoms than those without these conditions (statistically significant ORs ranged from 1.5 to 11.1, $p < 0.05$).	Erdmann and Apte (2004), United States
Respiratory effects	681–1954 (range: 525–3475)	654 children; mean age = 10 ± 0.8 yrs	Cross-sectional, school setting Questionnaires, clinical tests Controlled for PM_{10}	Based on ASHRAE standard, exposures were grouped into those > 1000 and those < 1000 ppm Children exposed to CO_2 levels > 1000 ppm showed a significantly higher risk of dry cough (OR = 2.99, 95% CI = 1.65–5.44) and rhinitis (sneezing or a runny or blocked nose) (OR = 2.07, 95% CI = 1.14–3.73). By two-level (child, classroom) hierarchical analyses, CO_2 was significantly associated with dry cough (OR = 1.06, 95% CI = 1.00–1.13 per 100 ppm increment) and rhinitis (OR = 1.06, 95% CI = 1.00–1.11). Significant positive associations were found with small 100 ppm increments of CO_2.	Simoni et al. (2010), Italy, France, Norway, Sweden, and Denmark
Respiratory effects	2417 ± 839 (range: 907–4113)	1028 children; mean age = 10 yrs	Cross-sectional, school setting Questionnaires Controlled for co-pollutants (nitrogen dioxide, ozone, ultrafine particles, formaldehyde)	Adjusted significant OR for a 100 ppm increase in CO_2 of 1.03 (95% CI = 1.001–1.06) for wheeze. No significant ORs for other symptoms (e.g., headaches, tiredness).	Kim et al. (2011), Korea
Respiratory, neurological effects	1160 ± 604 (range: 467–2800)	417 workers	Cross-sectional, office setting Questionnaires Controlled for TVOC	Adjusted significant ORs for a 100 ppm increase in indoor CO_2 of 1.10 (95% CI = 1.00–1.22) for dry throat, 1.16 (95% CI = 1.07–1.26) for tiredness and 1.22 (95% CI = 1.08–1.37) for dizziness.	Lu et al. (2015), Taiwan
Respiratory, neurological effects	1250–1500 (median) (range: 750–2100)	193 students, 11 years old	Cross-sectional, school setting Questionnaires, performance tests Controlled for $PM_{2.5}$, PM_5, and PM_{10}	Symptoms (such as allergies, nose irritation, and fatigue) were positively correlated to indoor CO_2 concentration. An increase of 17.01% in indoor CO_2 concentrations (CO_2 range not specified) was determined to decrease performance on tests by 16.13%.	Dorizas, Assimakopoulos and Santamouris (2015), Greece

Health outcomes	CO_2 exposure concentration (Mean ± SD [range] ppm)	Population characteristics	Study characteristics	Results	Reference, study location
Respiratory, neurological effects	601–3827	550 students	Cross-sectional, school setting Questionnaires, performance tests Not controlled for other pollutants	Exposures were grouped into those < 1000 ppm, 1000–1499 ppm and > 1500 ppm. Association between an increased prevalence of health symptoms (i.e., health index 1: headache, dizziness, heavy headedness, tiredness, difficulty concentrating, unpleasant odour) and classroom concentration > 1500 ppm. Association between increased classroom CO_2 concentration and prevalence of upper airway irritation symptoms (i.e., throat/nose irritation, runny nose, coughing, short-winded, runny eyes). Association between decreased performance and increased CO_2 level. Performance decreased at 1000–1499 ppm CO_2 relative to < 999 ppm, and further decrease at CO_2 concentrations > 1500 ppm.	Myhrvold, Olsen and Lauridsen (1996), Norway
Neurological effects	812 (range 352–1591)	68 teachers	Cross-sectional, school setting Questionnaires Not controlled for other pollutants	The odds of reporting neurophysiological symptoms (i.e., headache, fatigue, difficulty concentrating) significantly increased (OR = 1.30, 95% CI = 1.02–1.64) for every 100 ppm increase in maximum classroom CO_2 concentrations. The calculated OR for symptom reporting was increased, but not statistically significant, in classrooms with above-median proportions of CO_2 concentrations > 1000 ppm.	Muscatiello et al. (2015), United States
Neurological effects	Not specified	Students from 54 fifth grade classrooms (number of students not specified)	Cross-sectional, school setting Linear regression analysis of standardized test scores for students who attended monitored classrooms (i.e., tests were not administered on the day of CO_2 monitoring).	Association between ventilation rate and mathematics test scores ($p < 0.10$).	Shaughnessy et al. (2006), United States
Neurological effects	Fall/winter: 1578.16 (± 712.49) Spring/summer: 1152.80 (± 595.41)	1019 students	Cross-sectional, school setting Questionnaires Not controlled for other pollutants	Exposures were grouped into those < 984 and those > 984 ppm (maximum reference level according to Portuguese law) Association between CO_2 levels > 984 ppm and lack of concentration ($p = 0.002$) No statistically significant association was found for other symptoms/illness (such as asthma, bronchitis, wheezing, coughing, headache or stress).	da Conceição Ferreira and Cardoso (2014), Portugal
Neurological effects	Maximum: 661–6000	87 fifth grade classrooms	Cross-sectional, school setting Linear regression analysis of percentage of students scoring satisfactory or above in standardized tests in monitored classrooms and estimated ventilation rates (i.e., tests were not administered on the day of CO_2 monitoring).	A linear relationship (not statistically significant) was found between ventilation and academic achievement for ventilation rates in the range of 0.09 to 7.1 l/sec-person.	Haverinen-Shaughnessy, Moschandreas and Shaughnessy 2011, United States

Health outcomes	CO_2 exposure concentration (Mean ± SD [range] ppm)	Population characteristics	Study characteristics	Results	Reference, study location
Neurological effects	Not specified	3019 fifth grade students	Cross-sectional, school setting Multivariate model analysis of standardized test scores for students who attended monitored classrooms and estimated ventilation rates (i.e., tests were not administered on the day of CO_2 monitoring)	Association between ventilation rates and mathematics scores. For each l/sec-person increase in ventilation, a 0.5% increase in test scores was observed. Similar but more variable effects were observed for reading and science scores.	Haverinen-Shaughnessy and Shaughnessy (2015), United States
Neurological effects	range: 600–7000	5046 (English test) and 5455 (Math test) students from three school districts	Cross-sectional, school setting Multivariate model analysis of standardized test scores for students who attended monitored classrooms and estimated average ventilation rates for 30 days prior to the test or proportion of daily ventilation rates above specified thresholds during the year	Combined-school district models estimated statistically significant increases of 0.6 points (P = 0.01) on English tests for each 10% increase in prior 30-day ventilation rates. Estimated increases in Math scores were of similar magnitude but not statistically significant.	Mendell et al. (2016), United States
Neurological effects	Phase 1, median: 1600 (range: 400–4000) Phase 2, median: 2875 (range: 900–4597)	2192 records of class average test scores from 264 schools	Cross-sectional, school setting Gaussian generalized linear model analysis of achievement indicators (calculated from standardized test scores adjusted for a socioeconomic reference index) and ventilation mode (i.e., mechanical balanced, mechanical exhaust and natural ventilation)	Statistical analysis of phases 1 and 2 merged datasets indicated that the lowest achievement indicators for all subject areas were for students in naturally-ventilated classrooms. There was no consistent association between the achievement indicators and the person specific room volume, construction/renovation year or the occupancy.	Toftum et al. (2015), Denmark
Neurological effects	Variable ventilation flow: 784 (9% of time > 1000) Constant ventilation flow: 809 (25% of time > 1000)	62 students	Intervention, school setting Two weeks (one week with variable flow ventilation, one week with constant flow ventilation) Questionnaires	Reports of headaches and tiredness were increased under constant flow conditions (p = 0.003 and p = 0.007) vs. variable flow conditions. Perceived air quality was worse under constant flow conditions, but was not statistically significant (p = 0.09).	Norbäck, Nordström and Zhao (2013), Sweden
Neurological effects	Estimated range: 365–965[a]	119	Intervention, office setting (call centre) Variations in ventilation conditions over a 3-month period. Differential CO_2 between the return air and the outdoor air was used as a ventilation metric. Individual and group work performance indicators	Association between decreased ventilation rates (i.e., less than 100% outdoor air) and lower work performance.	Federspiel et al. (2004), United States
Neurological effects	690 (± 122)–2909 (± 474)	18	Intervention, school setting Variations in ventilation conditions (i.e., window closed or opened) Cognitive function assessment test Not controlled for other pollutants	Association between increased CO_2 concentration (i.e., 2909 ppm vs 690 ppm) and decreased power of attention (p = 0.004), simple reaction time task (p = 0.02) and choice reaction time (p = 0.08).	Coley, Greeves and Saxby (2007), England

Health outcomes	CO_2 exposure concentration (Mean ± SD [range] ppm)	Population characteristics	Study characteristics	Results	Reference, study location
Neurological effects	904–1296	Two classrooms of 10- to 12-year-old students (up to 46 students)	Intervention, school setting Variations in ventilation conditions Exercises representing numerical- or language-based schoolwork tasks Not controlled for other pollutants	Performance (mainly in terms of speed at which the tasks were performed rather than the error rate) improved when ventilation increased (as measured by decreased CO_2 concentration, i.e., from ~ 1300 to ~ 900 ppm) (p = 0.001–0.039).	Wargocki and Wyon (2007a, 2007b), Denmark
Neurological effects	Median: 1045–2115	417 students (grade 3 or 4)	Intervention, school setting Variations in ventilation conditions Concentration performance test (i.e., d2-test)	No significant effect on concentration performance or total number of characters processed was found, but the total number of errors increased significantly in "worse" compared to "better" ventilation condition.	Twardella et al. 2012, Germany
Neurological effects	790–1610 peak: 1040–2780	Four classrooms of 10- to 12-year-old students (70–79 students)	Intervention, school setting Variations in ventilation conditions (i.e., ventilation with outdoor air or recirculated air) Language and mathematic performance tests, questionnaires	As outdoor fresh air supply rate was increased from an average of 1.7 to 6.6 l/sec-person (estimated by converting measured CO_2 concentration to a per person ventilation rate), the number of correct answers increased by 6.3% in the addition test, by 4.8% in the number comparison test, by 3.2% in the grammatical reasoning test, and by 7.4% in the reading and comprehension test (p < 0.01–0.04).	Pertersen et al. (2016), Denmark
Neurological effects	644–2822 peak: 1115–5000	332 students	Intervention, school setting Variations in ventilation conditions (i.e., ventilation with outdoor air or recirculating air) Performance tests, questionnaires	Performance on four of the tests (choice reaction [by 2.2%], colour word vigilance [by 2.7%], picture memory [by 8%], and word recognition [by 15%]) was improved significantly under higher ventilation conditions (from 1 to 8 l/sec-person) (p < 0.001–0.04).	Bako-biro et al. (2012), United Kingdom

Notes: CI = confidence interval; dCO_2 = differential CO_2 (inside minus outside); HPV = heart period variability; MF = mid-frequency component; OR = odds ratio; $PM_{2.5}$ = particulate matter < 2.5 µm in diameter; PM_5 = particulate matter < 5 µm in diameter; PM_{10} = particulate matter < 10 µm in diameter

[a] Measured dCO_2 ranged between 13 and 611 ppm. If outdoor concentration was approximately in the 350–450 ppm range (i.e., normal average diurnal outdoor ground-level CO_2 concentration) (Haverinen-Shaughnessy, Moschandreas and Shaughnessy 2011; Muscatiello et al. 2015; Ziska et al. 2001), then indoor CO_2 ranged between approximately 365 and 965 ppm in the call centre.

APPENDIX C: INTERNATIONAL GUIDELINES AND STANDARDS FOR CO_2

Indoor CO_2 concentrations are often used as a surrogate for ventilation rate and as an indicator for other occupant-derived pollutant (bioeffluent) concentrations and odours. It is in this context that many building standards and guidelines for CO_2 were established (i.e., they are not based on the intrinsic health effects of CO_2). For example, the ASHRAE standard on ventilation for acceptable indoor air quality recommends maintaining indoor CO_2 levels at no greater than 700 ppm above ambient levels to indicate adequate ventilation for occupant comfort with respect to bioeffluents (ASHRAE 2016). As the outdoor CO_2 level is assumed to range between 300 and 500 ppm, the indoor air concentration of CO_2 should be maintained below 1000 ppm (ASHRAE 2016).

Standards and guidelines for CO_2 in residential, school, and office buildings were summarized as part of the Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail (ANSES 2013) assessment of CO_2 in indoor air. Table C1 presents standards and guidelines set for CO_2 by organizations in member countries of the Organisation for Economic Co-operation and Development (OECD), as reported in ANSES (2013), as well as other standards reported in the published literature. For many countries (e.g., United States, France, Norway, Germany, Portugal, Korea, Japan), the standards or guidelines established for CO_2 were ≤ 1000 ppm (ranging from 600 to 1000 ppm).

ANSES (2013) conducted an assessment of CO_2 in indoor air and its health effects to support the updating of building ventilation regulations. Based on a review of the data available at that time, ANSES concluded that "the available epidemiological data do not enable setting a threshold value for CO_2 that would protect individuals from the effects of closed spaces on health, on perceived comfort (i.e. perception of indoor air quality) and on cognitive performance." On this basis, ANSES recommended that indoor air quality guideline values for CO_2 not be set, neither for its intrinsic effects nor for closed space effects on health.

Table C1. Some international standards and guidelines for CO_2

Country	Value	Organization/ Standard/ Regulation	Reference	Note
United States	No more than about 700 ppm above outdoor ambient levels	ASHRAE	ASHRAE (2016)	Ambient levels: immediate environment levels of air quality (odour)
New Zealand	1000 ppm	Mechanical ventilation standard	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for school buildings
European Union	< 400 ppm above outdoor level	NF EN 13779 standard	CSTB (2011) (cited in ANSES 2013)	Excellent indoor air quality
	400–600 ppm above outdoor level			Average indoor air quality
	600–1000 ppm above outdoor level			Moderate indoor air quality
	> 1000 ppm above outdoor level			Low indoor air quality
France	1000 ppm	Memorandum dated August 9, 1978.	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for school and office buildings
Austria	1000 or 1500 ppm (under discussion)	AIVC 2000	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for school buildings
United Kingdom	1500 ppm (school day average) 5000 ppm (maximum)	Building Bulletin 101	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for school buildings
Belgium (Flemish region)	500 ppm	Flemish government decree	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for residential, school and office buildings
Holland	1000–1500 ppm	Standard NEN 1087	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for residential buildings
	1200 ppm	Standard NEN 1089	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for school buildings
Denmark	1000 ppm with an upper limit of 2000 ppm	AIVC 2000	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for school buildings
Norway	1000 ppm	Regulations for environmental health protection in schools	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for school buildings
Finland	700 ppm as individual indoor climate (S1)	FiSIAQ[a]	FiSIAQ 2002	Category S1: it corresponds to the best quality. The indoor air quality of the space is very good and the thermal conditions are comfortable both in summer and winter.
	900 ppm as good indoor climate (S2)			Category S2: the indoor air quality of the space is good and no draughts occur. The temperature may rise above comfortable levels during the hottest days of summer.
	1200 ppm as satisfactory indoor climate (S3)			Category S3: the indoor air quality and the thermal conditions of the space fulfill the requirements set by the building codes. The indoor air may occasionally feel stuffy and draughts may occur. The temperature usually rises above comfort levels on hot summer days.
	1200 ppm	D2 National Building Code	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for residential, school, and office buildings

Country	Value	Organization/ Standard/ Regulation	Reference	Note
Germany	< 1000 ppm (harmless) 1000–2000 ppm (elevated) > 2000 ppm (unacceptable)	German Committee on Indoor Guide Values	Fromme et al. (2019)	Indoor CO_2 concentrations can be regarded as "harmless" if below 1000 ppm, "elevated" if between 1000 and 2000 ppm, and "unacceptable" if above 2000 ppm.
	1500 ppm	DIN 1946 Standard	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for school buildings
Portugal	≤ 984 ppm	Portuguese Ministry of Public Works, Transport and Communications	Portuguese Decree-law no. 79/2006 (cited in da Conceição Ferreira 2014)	
	1000 ppm	Regulation RSECE	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for school and office buildings
Korea	1000 ppm	KEITI[b]	Jeong (2008); CSTB (2011) (cited in ANSES 2013)	Standard/guideline for residential and office buildings
		Health act in school	CSTB (2011) (cited in ANSES 2013)	Standard/guideline for school buildings
Japan	1000 ppm	MHLW[c]	CSTB (2011) (cited in ANSES 2013)	Building standard law

Note: Acute exposure (i.e., 15-minute average) standards and guidelines were not included in this table.

[a] FiSIAQ: Finnish Society of Indoor Air Quality and Climate

[b] KEITI: Korea Environmental Industry and Technology Institute

[c] MHLW: Ministry of Health, Labor and Welfare

Province of Alberta

OCCUPATIONAL HEALTH AND SAFETY ACT

OCCUPATIONAL HEALTH AND SAFETY CODE

Alberta Regulation 87/2009

With amendments up to and including Alberta Regulation 150/2020

Current as of August 15, 2020

(e) equipment appropriate to the confined space or restricted space, including personal protective equipment, is available to perform a timely rescue, and

(f) a communication system is established that is readily available to workers in a confined space or a restricted space and is appropriate to the hazards.

48(2) An employer must ensure that all personal protective equipment and emergency equipment required for use in a confined space or a restricted space is inspected by a competent person to ensure the equipment is in good working order before workers enter the confined space or the restricted space.

48(3) An employer must ensure that written records of the inspections required by subsection (2) are retained as required by section 58.

Protection — hazardous substances and energy

49(1) An employer must ensure that workers within a confined space are protected against the release of hazardous substances or energy that could harm them.

49(2) An employer must ensure that a worker does not enter a confined space unless adequate precautions are in place to protect a worker from drowning, engulfment or entrapment.

49(3) An employer must ensure that any hazardous energy in a restricted space is controlled in accordance with Part 15.

Unauthorized entry

50 An employer must ensure that persons who are not authorized by the employer to enter a confined space or a restricted space are prevented from entering.

Traffic hazards

51 An employer must ensure that workers in a confined space or a restricted space are protected from hazards created by traffic in the vicinity of the confined space or restricted space.

Testing the atmosphere

52(1) If the hazard assessment identifies a potential atmospheric hazard and a worker is required or authorized by an employer to enter the confined space, the employer must ensure that a competent worker performs a pre-entry atmospheric test of the confined space to

(a) verify that the oxygen content is between 19.5 percent and 23.0 percent by volume, and

(b) identify the amount of toxic, flammable or explosive substance that may be present.

52(2) The employer must ensure that the testing required by subsection (1) is performed using calibrated test instruments appropriate for the atmosphere being tested and the instruments are used in accordance with the manufacturer's specifications.

52(3) The employer must ensure that as often as necessary after the first time a worker enters the confined space, a competent worker

(a) performs the tests specified in subsection (1), and

(b) identifies and records any additional hazards.

52(3.1) The employer must ensure that if there is a potential for the atmosphere to change unpredictably after a worker enters the confined space, the atmosphere is continuously monitored in accordance with subsection (2).

52(4) If tests identify additional hazards, the employer must deal with the identified hazards in accordance with this Code.

52(5) The employer must ensure that the procedures and practices put in place under subsection (4) are included in the code of practice.

52(6) The employer must ensure that the results of tests required by this section are recorded.

Ventilation and purging

53(1) If the atmospheric testing under section 52 identifies that a hazardous atmosphere exists or is likely to exist in a confined space, an employer must ensure that the confined space is ventilated, purged or both before a worker enters the confined space.

53(2) If ventilating or purging a confined space is impractical or ineffective in eliminating a hazardous atmosphere, the employer must ensure that a worker who enters the confined space uses personal protective equipment appropriate for the conditions within the confined space.

53(3) If mechanical ventilation is needed to maintain a safe atmosphere in a confined space during the work process, an employer must ensure it is provided and operated as needed.

53(4) If mechanical ventilation is required to maintain a safe atmosphere in the confined space, the employer must ensure that

(a) the ventilation system incorporates a method of alerting workers to a failure of the system so that workers have sufficient time to safely leave the confined space, and

(b) all workers within the confined space have received training in the evacuation procedures to be used in the event of a ventilation system failure.

53(5) All workers must evacuate a confined space or use an alternative means of protection if a ventilation system fails.

Inerting

54(1) An employer must ensure that a confined space is inerted if it is not reasonably practicable to eliminate an explosive or flammable atmosphere within the confined space through another means.

54(2) If a confined space is inerted, an employer must ensure that

(a) every worker entering the confined space is equipped with supplied-air respiratory protection equipment that complies with Part 18,

(b) all ignition sources are controlled, and

(c) the atmosphere within the confined space stays inerted while workers are inside.

Emergency response

55(1) An employer must ensure that a worker does not enter or remain in a confined space or a restricted space unless an effective rescue can be carried out.

55(2) A worker must not enter or stay in a confined space or restricted space unless an effective rescue can be carried out.

55(3) An employer must ensure that the emergency response plan includes the emergency procedures to be followed if there is an accident or other emergency, including procedures in place to evacuate the confined space or restricted space immediately

(a) when an alarm is activated,

(b) if the concentration of oxygen inside the confined space drops below 19.5 percent by volume or exceeds 23.0 percent by volume, or

(c) if there is a significant change in the amount of hazardous substances inside the confined space.

Tending worker

56(1) For every confined space or restricted space entry, an employer must designate a competent worker to be in communication with a worker in the confined space or restricted space.

56(2) An employer must ensure that the designated worker under subsection (1) has a suitable system for summoning assistance.

Respiratory Protective Equipment

Respiratory dangers

244(1) An employer must determine the degree of danger to a worker at a work site and whether the worker needs to wear respiratory protective equipment if

(a) a worker is or may be exposed to an airborne contaminant or a mixture of airborne contaminants in a concentration exceeding their occupational exposure limits,

(b) the atmosphere has or may have an oxygen concentration of less than 19.5 percent by volume, or

(c) a worker is or may be exposed to an airborne biohazardous material.

244(2) In making a determination under subsection (1), the employer must consider

(a) the nature and exposure circumstances of any contaminants or biohazardous material,

(b) the concentration or likely concentration of any airborne contaminants,

(c) the duration or likely duration of the worker's exposure,

(d) the toxicity of the contaminants,

(e) the concentration of oxygen,

(f) the warning properties of the contaminants, and

(g) the need for emergency escape.

244(3) Based on a determination under subsection (1), the employer must

(a) subject to subsection 3(b), provide and ensure the availability of the appropriate respiratory protective equipment to the worker at the work site, and

(b) despite section 247, when the effects of airborne biohazardous materials are unknown, provide and ensure the availability of respiratory protective equipment appropriate to the worker's known exposure circumstances.

244(3.1) Subsection (3) does not apply when an employer has developed and implemented procedures that effectively limit exposure to airborne biohazardous material.

244(4) A worker must use the appropriate respiratory equipment provided by the employer under subsection (3).

Code of practice

245(1) If respiratory protective equipment is used at a work site, an employer must prepare a code of practice governing the selection, maintenance and use of respiratory protective equipment.

(b) has a capacity of at least 30 minutes unless the employer's hazard assessment indicates the need for a greater capacity,

(c) provides full face protection in situations where contaminants may irritate or damage the eyes,

(d) in the case of an air line respirator, is fitted with an auxiliary supply of respirable air of sufficient quantity to enable the worker to escape from the area in an emergency, and

(e) in the case of a self-contained breathing apparatus, has an alarm warning of low pressure.

Equipment — no immediate danger

252 An employer must ensure that a worker wears self-contained breathing apparatus or an air line respirator having a capacity of at least 30 minutes if

(a) the employer determines under section 244 that conditions at the work site are not or cannot become immediately dangerous to life or health but

(i) the oxygen content of the atmosphere is or may be less than 19.5 percent by volume, or

(ii) the concentration of airborne contaminants exceeds or may exceed that specified by the manufacturer for air purifying respiratory equipment, and

(b) the complete equipment required by section 251 is not provided.

Air purifying equipment

253 An employer may permit workers to wear air purifying respiratory protective equipment if

(a) the oxygen content of the air is, and will continue to be, 19.5 percent or greater by volume,

(b) the air purifying equipment used is designed to provide protection against the specific airborne contaminant, or combination of airborne contaminants, present, and

(c) the concentration of airborne contaminants does not exceed the maximum concentration specified by the manufacturer for the specific type of air purifying equipment, taking into consideration the duration of its use.

Emergency escape equipment

254(1) Despite sections 251 and 252, if normal operating conditions do not require the wearing of respiratory protective equipment but emergency conditions may occur requiring

a worker to escape from the work area, the employer may permit the escaping worker to wear

(a) a mouth bit and nose-clamp respirator if

(i) the respirator is designed to protect the worker from the specific airborne contaminants present, and

(ii) the oxygen content of the atmosphere during the escape is 19.5 percent or greater by volume, or

(b) alternative respiratory protective equipment that can be proven to give the worker the same or greater protection as the equipment referred to in clause (a).

254(2) Before permitting a worker to use the equipment referred to in subsection (1), the employer must consider the length of time it will take the worker to escape from the work area.

Abrasive blasting operations

255 If a worker is performing abrasive blasting, the employer must ensure that the worker wears a hood specifically designed for abrasive blasting, supplied with air that is at a positive pressure of not more than 140 kilopascals.

Standard Interpretations
/ Clarification of OSHA's requirement for breathing air to have at least 19.5 percent oxygen content.

- **Standard Number:** 1910.134 ; 1910.134(d)(2)(i)(A) ; 1910.134(d)(2)(i)(B) ; 1910.134(d)(2)(iii)

April 2, 2007

Mr. William Costello
Vice President
FirePASS Corporation
1 Collins Drive
Carneys Point, NJ 08069

Dear Mr. Costello:

Thank you for your January 8, 2007 letter to the Occupational Safety and Health Administration's (OSHA's) Directorate of Enforcement Programs regarding the Respiratory Protection Standard, 29 CFR 1910.134. This letter constitutes OSHA's interpretation only of the requirements discussed and may not be applicable to any question not delineated within your original correspondence.

In your letter you ask OSHA to revise the Respiratory Protection Standard to state that an atmosphere containing a partial pressure of oxygen at or above 100 mm of mercury is safe for employees when employers demonstrate that, under all foreseeable conditions, they can maintain the partial pressure of oxygen at or above 100 mm of mercury. Although most of your letter argues for the use of "partial pressures of oxygen" to describe atmospheric oxygen concentrations, the expression "percent oxygen" was purposely chosen during the rulemaking for the Respiratory Protection Standard. Oxygen meters used to assess hazardous conditions by safety personnel in both general industry and construction are calibrated in percent oxygen, and employers and employees are familiar with, and prefer, this terminology. This same terminology has been used in the Confined Space Standard, 29 CFR 1910.146, since 1993.

Paragraph (d)(2)(iii) of the Respiratory Protection Standard considers any atmosphere with an oxygen level below 19.5 percent to be oxygen-deficient and immediately dangerous to life or health. To ensure that employees have a reliable source of air with an oxygen content of at least 19.5 percent, paragraphs (d)(2)(i)(A) and (d)(2)(i)(B) of the Respiratory Protection Standard require employers working under oxygen-deficient conditions to provide their employees with a self-contained breathing apparatus or a combination full-facepiece pressure-demand supplied-

air respirator with auxiliary self-contained air supply. In the preamble to the final Respiratory Protection Standard, OSHA discussed extensively its rationale for requiring that employees breathe air consisting of at least 19.5 percent oxygen. The following excerpt, taken from the preamble, explains the basis for this requirement:

> Human beings must breathe oxygen . . . to survive, and begin to suffer adverse health effects when the oxygen level of their breathing air drops below [19.5 percent oxygen]. Below 19.5 percent oxygen . . . , air is considered oxygen-deficient. At concentrations of 16 to 19.5 percent, workers engaged in any form of exertion can rapidly become symptomatic as their tissues fail to obtain the oxygen necessary to function properly (Rom, W., *Environmental and Occupational Medicine*, 2nd ed.; Little, Brown; Boston, 1992). Increased breathing rates, accelerated heartbeat, and impaired thinking or coordination occur more quickly in an oxygen-deficient environment. Even a momentary loss of coordination may be devastating to a worker if it occurs while the worker is performing a potentially dangerous activity, such as climbing a ladder. Concentrations of 12 to 16 percent oxygen cause tachypnea (increased breathing rates), tachycardia (accelerated heartbeat), and impaired attention, thinking, and coordination (e.g., Ex. 25-4), even in people who are resting.
>
> At oxygen levels of 10 to 14 percent, faulty judgment, intermittent respiration, and exhaustion can be expected even with minimal exertion (Exs. 25-4 and 150). Breathing air containing 6 to 10 percent oxygen results in nausea, vomiting, lethargic movements, and perhaps unconsciousness. Breathing air containing less than 6 percent oxygen produces convulsions, then apnea (cessation of breathing), followed by cardiac standstill. These symptoms occur immediately. Even if a worker survives the hypoxic insult, organs may show evidence of hypoxic damage, which may be irreversible (Exs. 25-4 and 150; also reported in Rom, W. [see reference in previous paragraph]).

(*Federal Register*, Vol. 63, p. 1159.) The rulemaking record for the Respiratory Protection Standard clearly justifies adopting the requirement that air breathed by employees must have an oxygen content of at least 19.5 percent. A lesser concentration of oxygen in employees' breathing air could endanger them physiologically and diminish their ability to cope with other hazards that may be present in the workplace. The rulemaking record also demonstrates that any workplace atmosphere controlled at or near your recommended minimal oxygen level of 100 mm of mercury at sea level (equivalent to about 13 percent oxygen at sea level) is not safe and healthful for all employees. Exposing employees to partial pressures of oxygen that approach 100 mm of mercury at sea level leaves them with no margin of safety from potentially debilitating effects, which could appear suddenly and without warning.

OSHA recognizes that, at higher altitudes, oxygen in air has a partial pressure that is less than the partial pressure of oxygen in air at sea level; accordingly, the Respiratory Protection Standard makes allowances for employees who work at altitude. OSHA made these allowances based on record evidence showing that such employees usually are acclimated to the reduced oxygen partial pressures and, as a result, will not experience the physiological dysfunction and performance impairments seen in non-acclimated employees. Nevertheless, when the oxygen concentration at altitude becomes oxygen-deficient, paragraph (d)(2)(iii) of the Respiratory Protection Standard requires employers to provide a supplied-air respirator that delivers at least 19.5 percent oxygen to the employee. In the preamble to the final Respiratory Protection Standard, the Agency explained this requirement as follows:

> OSHA's experience confirms the record evidence that most work at higher altitudes is performed by fully acclimated workers (Exs. 54-6, 54-208). These provisions will allow acclimated workers to continue to perform their work without oxygen-supplying respirators, at any altitude up to 14,000 feet altitude, as long as the ambient oxygen content remains above 19.5% and the employee has no medical condition that would require the use of supplemental oxygen.

(*Federal Register*, Vol. 63, p. 1203.) Therefore, in addition to the protection afforded to them by altitude acclimation, OSHA's Respiratory Protection Standard ensures that employees working under oxygen-deficient conditions at altitude will have an adequate and reliable breathing supply consisting of 19.5 percent oxygen, an oxygen content that will provide the employees exposed to these conditions with a substantial margin of safety.

In conclusion, OSHA would not consider any environments with your suggested oxygen partial pressure of 100 mm of mercury (~13 percent oxygen at sea level) to be safe for all employees. For those employees that can tolerate such levels, a work environment with only 13 percent oxygen provides no margin of safety from the potentially debilitating effects resulting from exposure to low oxygen levels, which could suddenly appear without warning. Accordingly, the Agency will not propose or adopt a revision to the Respiratory Protection Standard that would allow employees to work in such environments, even when the employer can demonstrate that, under all foreseeable conditions, the partial pressure of oxygen can be maintained at 100 mm of mercury.

In several telephone conversations we have had with you since we received your letter, you mentioned studies that purportedly demonstrate the safety of hypoxic environments in the workplace. We would be interested in reviewing any authoritative studies or information that specifically support your claims regarding the safety of such systems.

Thank you for your interest in occupational safety and health. We hope you find this information helpful. OSHA requirements are set by statute, standards, and regulations. Our interpretation letters explain these requirements and how they apply to particular circumstances, but they cannot create additional employer obligations. This letter constitutes OSHA's interpretation of the requirements discussed. Note that our enforcement guidance may be affected by changes to OSHA rules. Also, from time to time we update our guidance in response to new information. To keep apprised of such developments, you can consult OSHA's website at http://www.osha.gov. If you have any further questions, please feel free to contact the Office of General Health Enforcement at (202) 693-2190.

Sincerely,

Richard E. Fairfax,Director
Directorate of Enforcement Programs

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