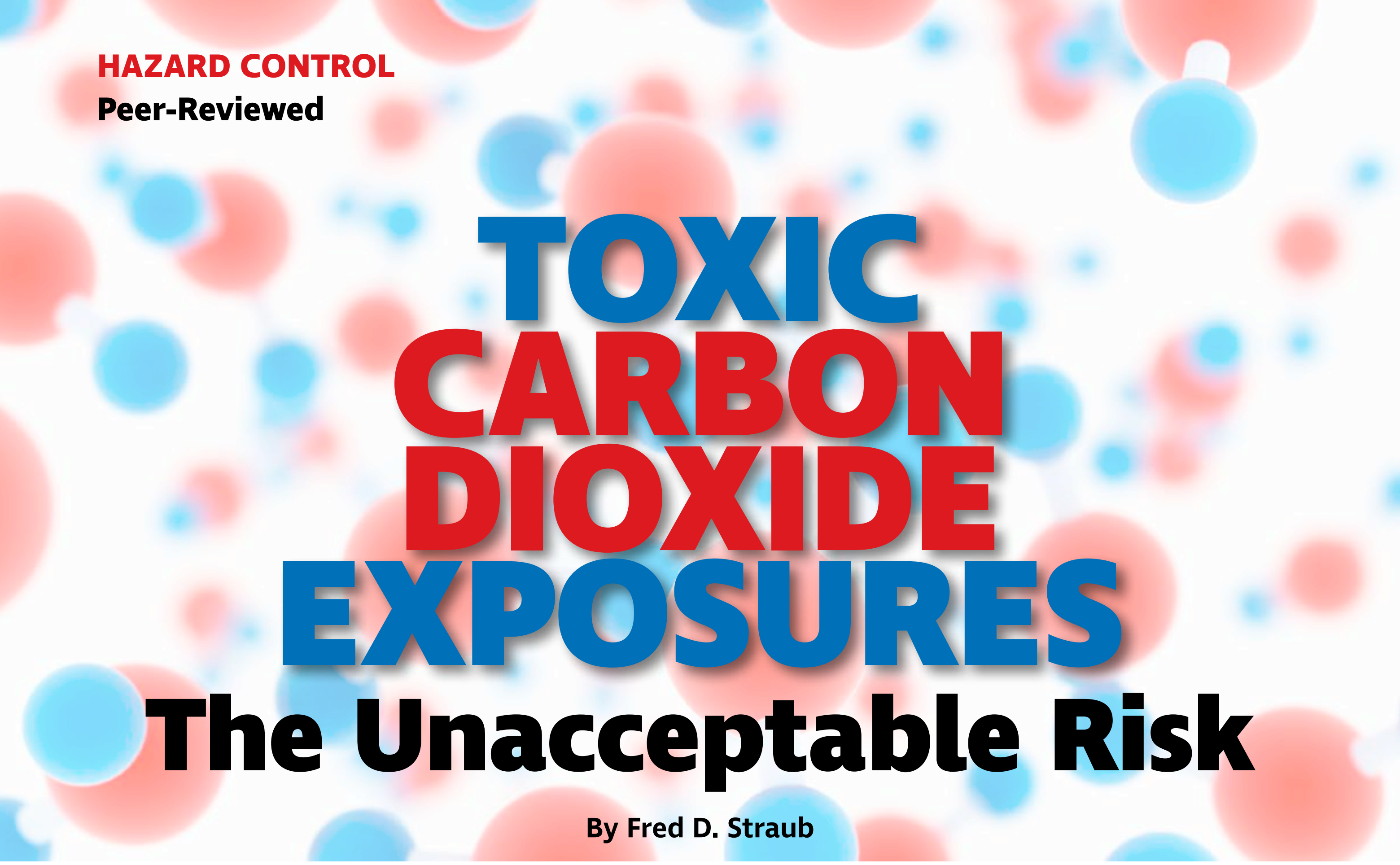

BEHOLDINGEYE/ISTOCK/GETTY IMAGES PLUS

TOXIC CARBON DIOXIDE EXPOSURES
The Unacceptable Risk

By Fred D. Straub

WHAT DOES THE LOCAL MICROBREWERY down the street have in common with underground confined spaces, landfills, slaughterhouses and fire extinguishing systems? Answer: Potentially dangerous carbon dioxide exposures.

Carbon dioxide is a product of combustion and fermentation and is widely used in manufacturing and food industries. It is a by-product of bacterial decomposing organic materials in landfills, wastewater treatment plants and feed storage bins. It occurs in geothermal venting, and it may be in a work site's fire extinguishing system. It is also present in the healthy atmosphere that workers normally breathe and is a physiologically important gas produced by the body because of cellular metabolism (Langford, 2005).

While carbon dioxide can be toxic at elevated concentrations, it is a natural component of the atmosphere. And whereas its main hazard of action is often misunderstood as a simple asphyxiant, it has the distinct potential to exert powerful toxic effects on unsuspecting workers (Permentier et al., 2017). Few employers have assessed their workplaces for carbon dioxide or have suitable meters with carbon dioxide sensors. This knowledge gap can allow affected workers to be put at unacceptable risk. This article is intended to educate the OSH professional to become prudent in understanding that carbon dioxide is a toxic gas: a poison, not "just" an asphyxiant.

KEY TAKEAWAYS

- **Carbon dioxide is often misunderstood as being a simple asphyxiant when, in reality, it is a potent toxic substance of significance.**
- **Deadly levels of toxic carbon dioxide at nearly twice the immediately dangerous to life or health level can still present adequate oxygen concentrations—a hazard of high risk not detected by most atmospheric sampling meters.**
- **Overexposure to carbon dioxide is a common problem in U.S. workplaces, as many employers, chemical suppliers and regulatory agencies remain unaware of the risk.**
- **The risk from carbon dioxide may be significantly reduced by implementing a carbon dioxide exposure control program.**

Carbon Dioxide Exposure Control Program

Work site operations with elevated carbon dioxide potentials present serious injury and fatality (SIF) exposures. A carbon dioxide exposure control program (CDECP) may protect affected employees from the hazards of carbon dioxide and thereby support a company's goals of reduced risk and safer work environments. Adhering to the plan-do-check-act (PDCA) loop of an effective safety and health management system, the elements of a CDECP include hazard recognition, workplace hazard analysis and risk assessment, implementation of risk controls and program audit.

Hazard Recognition

As DeVany (2015) explains:

> The molecule carbon dioxide has the chemical formula CO_2 and is made of one atom of carbon covalently bonded to two atoms of oxygen. At the normal range of temperatures on earth (from -60 °F to 140 °F), carbon dioxide is a gas.

Its mere 0.04% concentration is far below the three most common gases in the atmosphere, which are nitrogen (78%), oxygen (20.9%) and argon (0.8%). It is colorless and odorless. Resultingly, affected workers have no way to detect its presence (DeVany, 2015).

Carbon dioxide (a.k.a., carbonic acid gas, chokedamp, blackdamp and dry ice) is also a toxic waste product that the human body must normally eliminate. With every exhaled breath, we release carbon dioxide into the atmosphere with an average concentration of about 3.8% (Henderson, 2006). As the carbon dioxide content of exhaled air is greater than that of outdoor air, we can quickly encounter a rise in the carbon dioxide concentration within an enclosed space (Kajtár & Herczeg, 2012). Resultantly, carbon dioxide in exhaled air is lethal in just a few minutes if reinhaled. In the absence of fresh air, the blood's carbon dioxide level can increase, causing shortness of breath and sedation, resulting in carbon dioxide intoxication or poisoning (Cunha, 2021). Fortunately, as we breathe out, it is typically diluted in the atmosphere, negating its toxic effects.

Since carbon dioxide displays such poor warning properties and a density 53% heavier than air (NIOSH, 2019a), it can accumulate unrecognized in hazardous amounts in low-lying areas, especially inside confined or sealed spaces. Carbon dioxide also has the potential to drift and settle into adjacent areas outside the original release point (NFPA, 2018). In the presence of moisture, carbon dioxide dissolves to form carbonic acid, dissolving underground rock strata in caverns. Quick to release from water under normal atmospheric conditions, the carbon dioxide escapes unless in a sealed container (e.g., why soda pop goes "flat" when the lid is not tightly secured).

Although carbon dioxide occurs naturally in the earth's atmosphere as a trace gas, it does not quickly disperse or mix with the surrounding air sans wind, especially during humid conditions. The carbon dioxide concentration in outdoor air typically ranges from 300 to 400 ppm (0.03% to 0.04%). However, it can be as high as 600 to 900 ppm in metropolitan areas (FSIS, 2000), rising from preindustrial levels of 280 ppm (Eggleton, 2013). Indoor work site levels of carbon dioxide greater than 1,000 ppm (0.1%) are generally presumed to indicate inadequate ventilation (Corsi et al., 2002). In contrast, an atmosphere of 40,000 ppm (4%) is considered immediately dangerous to life and health (IDLH; OSHA, 2015).

Carbon dioxide enters the victim's bloodstream and makes it acidic (acidosis), leading to the host of physiological concerns addressed in the "Symptoms of Carbon Dioxide Intoxication or Poisoning" sidebar (CCOHS, 2017; DeVany, 2015; Helmenstine, 2019; NIOSH, 2019b). At very high levels of carbon dioxide exposure, the body's compensatory mechanisms become overwhelmed, and the central nervous system functions fail, leading to death (DeVany, 2015).

In a cursory review of current safety data sheets (SDSs) online, carbon dioxide was found to be commonly misunderstood as a relatively nontoxic gas, having been improperly classified as a simple asphyxiant in four out of five SDSs reviewed (Airgas, 2018; Air Liquide, 2016; Buckeye Fire Equipment Co., 2019; Praxair, 2016; Sigma-Aldrich, 2016). Even OSHA is complicitous; the agency's 2020 eTool on carbon dioxide fixed extinguishing systems lists the gas as an asphyxiant and fails to warn of its toxicity (OSHA, n.d.). Perhaps this generalization occurs because carbon dioxide is naturally occurring while also part of every breath we exhale. Hence, we may question its toxicity.

An asphyxiant is a nontoxic or minimally toxic gas that reduces or displaces the average oxygen concentration in breathing air, causing unconsciousness or death by suffocation (i.e., asphyxiation). Asphyxiants that have no other adverse health effects are sometimes referred to as simple asphyxiants. However, carbon dioxide is a potent toxic gas at elevated levels despite the absence of oxygen deficiency; it is not a simple asphyxiant (OSHA, 2017). Further recognition of the hazard can be accomplished by understanding the two adverse health effects of carbon dioxide overexposure: intoxication and poisoning.

Carbon dioxide intoxication refers to the condition when the concentration of carbon dioxide begins to increase in a victim's bloodstream. Above-normal carbon dioxide atmospheres affect cerebral physiology by lowering the bloodstream's pH, making it more acidic. This pH lowering, in turn, interferes with the calcium concentration and reduces blood flow to parts of the brain, resulting in confusion, headaches and reduced cognitive function (Brian, 1998). A person suffering from mild carbon dioxide intoxication typically can recover merely by breathing fresh air. Carbon dioxide retention (not exhaling enough carbon dioxide when breathing, such as in persons with chronic obstructive pulmonary disease) or hypoventilation (rebreathing exhaled air such as in a mine, tent or confined space) may also present as carbon dioxide intoxication (Helmenstine, 2019). Intoxication may progress to carbon dioxide poisoning if atmospheric conditions do not improve.

If conditions worsen, carbon dioxide poisoning occurs from the further elevated concentration of carbon dioxide in the bloodstream, progressing to incapacitation and death. Without adequate treatment, victims demonstrate acute reduced cognitive performance, respiratory failure, cerebral ischemia and circulatory arrest (Permentier et al., 2017). Carbon dioxide poisoning requires immediate medical treatment and results in a condition known as hypercapnia or hypercarbia (i.e., excessive carbon dioxide in the bloodstream).

Consider several examples of carbon dioxide fatalities that have occurred:

Three people died from carbon dioxide poisoning in Moscow when 55 lb of dry ice was tipped into an indoor swimming pool to create a visual fog effect (AFP, 2020).

A patron at a Georgia McDonald's restaurant died in the restroom when overcome by carbon dioxide leaking from a hose on the carbon dioxide tank supplying the restaurant's soda fountain, located in the adjacent room. Six others were hospitalized (Reuters, 2011).

OSHA investigated a fatality of a construction foreman who died from carbon dioxide poisoning 20 ft down in a newly constructed, unconnected sewer manhole. The fatality resulted from inadequate confined space monitoring and entry practices (OSHA, 2015).

OSHA investigated the fatality of an employee of a securities firm who died from carbon dioxide poisoning after being inadvertently locked in a vault. The fatality resulted when the trapped employee pulled the manual fire alarm actuation device inside the vault space to summon help, activating the total flooding carbon dioxide system (OSHA, 2001).

OSHA investigated a delivery driver who fatally succumbed to carbon dioxide poisoning while dispensing carbon dioxide from a tanker truck to a restaurant's bulk carbon dioxide system through a fill station located on the wall, below ground level, just outside the basement door. The fatality resulted from a carbon dioxide leak where the hose from the tanker fastened to the fill connection below ground level (OSHA, 1996).

A 2000 EPA study found that 74 fatalities occurred due to carbon dioxide poisoning in workplace settings over 25 years (EPA, 2000).

Now, here is the veiled risk and the reason for this article: Even in the presence of typical, healthy concentrations of oxygen, elevated background concentrations of carbon dioxide (i.e.,

SYMPTOMS OF CARBON DIOXIDE INTOXICATION OR POISONING

Respiratory
- deeper, rapid or labored breathing
- shortness of breath

Central Nervous System
- dizziness
- drowsiness
- confusion/disorientation
- mental depression
- headache
- loss of judgment
- restlessness
- nausea or vomiting
- panic
- unconsciousness
- coma
- death

Auditory
- reduced hearing
- tinnitus

Visual
- dimmed sight
- vertigo
- photophobia (light intolerance)
- transient blindness

Skin
- sweating
- flushed

Heart
- increased blood pressure
- increased heart/pulse rate

Muscular
- shaking
- twitching of muscles
- convulsions

WORK SITES WHERE UNSAFE CARBON DIOXIDE ACCUMULATIONS MAY OCCUR

The hazard recognition process should view carbon dioxide potentials from man-made production, use of the gas and solid, natural sources, and decaying organic materials. This summary is a guide and is not comprehensive; additional work sites may be identified during the assessment process.

1. Locations where carbon dioxide is produced or used during production processes (including low-lying areas indoors and outside):
- **sewage digesters and water treatment facilities**
- **chemical manufacturing and carbonic acid production**
- **oil or gas wells and related refineries**
- **breweries (e.g., fermentation of alcohol, beer, wine)**
- **carbon dioxide capture and sequestering operations**
- **carbonated beverage bottling**
- **ethanol production**
- **energy generation (e.g., fossil fuel, nuclear plants)**
- **bakeries**
- **explosives production**
- **dry ice for refrigeration or theatrical productions**
- **cement and lime manufacturing**
- **poultry and swine slaughterhouse killing rooms**
- **ammonia production**
- **anode baking products**
- **air separation plants**
- **greenhouses (air enrichment)**
- **commercial frying operations**
- **organic composting operations**
- **aerosol propellant manufacturing**
- **trash incinerators**
- **grain and corn elevators, receiving and storage areas**
- **ethylene oxide cold sterilant operations**
- **tank refilling sites (e.g., weapons, paintball)**
- **iron and steel foundries**
- **diving**
- **welding**
- **cloud seeding**
- **hospital operating rooms**

2. permit-required confined spaces in all OSHA-regulated industries

3. work sites subject to carbon dioxide fixed fire extinguishment or suppression

4. areas where carbon dioxide is collected and discharged (e.g., carbon dioxide scrubbers, baghouses, deep well sequestering, pressure relief devices, pressure release valves)

5. locations with restricted or limited ventilation whatever the elevation, especially those areas where workers rarely need to go (e.g., walk-in cooler, basements, marine holds, silos, wells, low-lying areas)

6. forest burning and land clearing operations

7. natural sites capable of producing carbon dioxide outgassing:
- **volcanoes**
- **hot springs**
- **active and abandoned coal mines**
- **caves and caverns**
- **marshes and swamps and bogs**
- **geysers**
- **limnic lakes**

Note. Adapted from "Carbon Dioxide in Workplace Atmospheres: Sampling and Analytical Method (ID-172)," by OSHA, 1990.

> 40,000 ppm or > 4%) can cause convulsions, coma and death in less than a minute. This may explain why victims of accidental carbon dioxide poisoning often do not act to resolve the situation [e.g., open a door, climb a ladder, don a self-contained breathing apparatus (SCBA)]. A small EPA-funded study in 2009 demonstrated that moderate carbon dioxide concentrations as low as 1,000 ppm impair the cognitive actions of thinking, concentration and logical thought processes in six of nine decision-making performance scales (Satish et al., 2012). Results obtained in an earlier study (Kajtár & Herczeg, 2012) found that participants became exhausted and mental tasks required a greater effort when the carbon dioxide concentration increased to 3,000 ppm. Due to the small populations of these studies and their OSH results of concern, the author posits that additional research is warranted.

The seriousness of the symptoms of carbon dioxide poisoning depends mainly on the concentration of carbon dioxide and the length of exposure time (dose = magnitude x duration). Typically, the lighter symptoms would be associated with carbon dioxide intoxication. Also, the adverse response to carbon dioxide may vary greatly, especially to individuals in otherwise good health (FSIS, 2000).

Life on earth as we know it would not exist without carbon dioxide, as this atmosphere-essential gas is a critical component of the carbon cycle, a biogeochemical cycle in which carbon is exchanged between the earth's oceans, soil, rocks and biosphere (DeVany, 2015). As carbon dioxide enters the atmosphere via respiration, burning, decomposition of organics, intentional release or chemical processes, it is then removed from the atmosphere (sequestered) when plants and oceans absorb it as part of the biological carbon cycle (EPA, 2018). With this understanding, the OSH professional's hazard recognition process should view carbon dioxide potentials from man-made production, the use of the gas and solid, natural sources, and decaying organic materials (see "Work Sites Where Unsafe Carbon Dioxide Accumulations May Occur" sidebar; OSHA, 1990). This summary is a guide and is not comprehensive; additional work sites may be identified during an employer's assessment process. Such work sites have been the scene of numerous fatalities across the U.S. (DeVany, 2015).

Produced carbon dioxide is often transported and dispensed from tank cars (rail), cargo tanks (roadway), portable containers or stationary tanks, pipelines and low-pressure delivery systems at consumer sites. Although it is most commonly present and shipped as a liquified compressed gas, carbon dioxide can also exist and be shipped in solid form (i.e., dry ice).

Solid dry ice is used widely as a refrigerant, theatrical performance fog, an abrasive in dry-ice blasting and may cause tissue freeze burns following direct contact. Dry ice undergoes sublimation (conversion) from a solid state into a gas sans a liquid state. If warmed rapidly above 109 °F, large amounts of carbon dioxide gas are generated (Helmenstine, 2019). Dry ice is hazardous in closed environments, such as within confined spaces and low-lying areas. Be aware that carbon dioxide levels directly next to an open bin of dry ice at room temperature can be as high as 11,000 to 13,000 ppm, or 1.1% to 1.3%, respectively (FSIS, 2000).

Natural sources have produced significant outgassing of carbon dioxide, such as the limnic eruption in Cameroon at Lake Nyos in 1986, which killed 1,746 people in a dense cloud of carbon dioxide (Fomine, 2011). Also, active and abandoned underground coal mines have long been known to produce blackdamp or chokedamp, created when the coal is exposed to air and absorbs oxygen, releasing significant quantities of stored carbon dioxide. The damp can then be "exhaled" from the coal in dangerous quantities from mines during sudden changes in atmospheric pressure, potentially causing deadly levels within and on the surface (Hendrick & Sizer, 1992). Carbon dioxide can also be released from calcium carbonate (e.g., limestone) rocks after rainwater or groundwater dissolves them, forming carbonic acid.

Because carbon dioxide is soluble in water, it occurs naturally in groundwater, rivers, lakes (as in the Lake Nyos incident), ice caps, glaciers and seawater. It is also present organically in deposits of petroleum and natural gas. Lastly, carbon dioxide is naturally generated during the bacterial decomposition of decaying organic materials (e.g., landfills, sewer plants, manure collection areas, culverts, composting, biological waste collection points, swamps, marshes, bogs) and fermentation, when yeast converts sugars into alcohol for beer and winemaking. Even grains undergo respiration as they sit in grain silos, generating atmospheric carbon dioxide concentrations as high as 90% within enclosed areas (DeVany, 2015).

Unique sources of carbon dioxide used for beneficial purposes must also be assessed for OSH. For example, carbon dioxide may be collected as a waste product from various industrial facilities and natural sources for productive use elsewhere. One such example is naturally generated carbon dioxide being collected from the Jackson Dome near Jackson, MS, collected with waste carbon dioxide from nearby production processes and transported for use at exhausted oil fields in Texas via the Green Pipeline (Denbury, 2017). The carbon dioxide is then sequestered deep into old underground oil wells, where it stimulates, loosens and releases oil deposits for recovery that would otherwise be unreachable by traditional oil extraction techniques. This process revitalizes the abandoned wells and produces additional energy resources while sequestering by-product carbon dioxide from manufacturing or energy-generating processes underground to avoid release into the atmosphere as a greenhouse gas. Carbon dioxide has been the leader in global greenhouse gas emissions, at 81% (EPA, 2018).

Lastly, carbon dioxide should be recognized as a potential weapon of mass destruction by terrorist groups that may attempt to release large quantities of the toxic gas into mass assembly areas.

Helpful to the hazard recognition process is understanding the routes of exposure to carbon dioxide ("Routes of Carbon Dioxide Exposure" sidebar). Primarily handled as a gas, the typical route for carbon dioxide exposure is inhalation (Airgas, 2018). Likely the most effective manner that toxic materials can be introduced into the body, inhalation efficiently transports carbon dioxide into the bloodstream.

Research has shown that carbon dioxide is far more hazardous than previously thought. Recall that normal levels of atmospheric carbon dioxide are already around 400 ppm. A jump to 1,000 ppm is not difficult to achieve via reduced HVAC air circulation practices to reduce energy consumption, decomposing organic material within a confined space, a leaking carbon dioxide cylinder or a discharged carbon dioxide extinguishing system.

There is consensus regarding the current occupational exposure limits (OELs) among OSHA (2017), ACGIH (2021) and NIOSH (2019b; Table 1). OSH professionals in the U.S. are presented with an 8-hr time-weighted average (TWA) permissible exposure limit (PEL) of 5,000 ppm (0.5%) and a short-term exposure limit (STEL) of 30,000 ppm (3%) TWA not to exceed 15 min. The NIOSH (2019b) IDLH never to be exceeded is 40,000 ppm (4%).

Acute or short-term exposures to high concentrations of some airborne chemicals have the ability to quickly overwhelm workers, resulting in a wide spectrum of undesirable health outcomes that may include irritation of the eyes and respiratory tract, severe irreversible health effects, impairment of the ability to escape from the exposure environment and, in extreme cases, death.

ROUTES OF CARBON DIOXIDE EXPOSURE

Inhalation
Low concentrations are not harmful. Moderate concentrations will affect cognitive abilities. Higher concentrations can affect respiratory function and cause excitation followed by depression of the central nervous system and death. Extremely high concentration will also displace oxygen in the air, causing an oxygen-depleted atmosphere after death has occurred from the toxicity. Symptoms occur more quickly with physical effort.

Skin Contact
Direct contact with the liquefied gas or solid can chill or freeze the skin (e.g., frostbite).

Eye Contact
Gas may cause mild irritation. Direct contact with the liquefied gas can freeze the eye. Permanent eye damage or blindness can result.

Ingestion; Injection; Skin & Ocular Absorption
Not relevant routes of exposure.

Note. Adapted from "Carbon Dioxide," OSH Answers Fact Sheets, by CCOHS, 2017.

TABLE 1
OCCUPATIONAL EXPOSURE LIMITS FOR CARBON DIOXIDE

Source	8-hr TWA	TWA-STEL	IDLH
ACGIH threshold limit value	5,000 ppm (0.5%)	30,000 ppm (3.0%) 15 min	None
NIOSH recommended exposure limit	5,000 ppm (0.5%)	30,000 ppm (3.0%) 15 min	40,000 ppm (4.0%)
OSHA permissible exposure limit	5,000 ppm (0.5%)	30,000 ppm (3.0%) 15 min	None

The NIOSH (2019b) IDLH air concentration values characterize these high-risk exposure concentrations and conditions.

Worth remembering is that the OSHA PEL of 5,000 ppm for carbon dioxide was established in 1970, and current research studies show that this PEL may not adequately protect the affected worker while performing high-risk work tasks, with cognitive confusion found at levels beginning at 1,000 ppm (Satish et al., 2012).

Because oxygen represents only about 20% of the total fresh air volume, every 5% of a displacing gas introduced into a confined or sealed environment reduces the oxygen concentration by only 1% (Henderson, 2010). Accordingly, the calculations in Table 2 (p. 28) visually display the concentration of carbon dioxide to oxygen and its minor, related gas displacement of oxygen in the breathing atmosphere. Straightforwardly stated, the current technology of quad gas atmospheric meters with no carbon dioxide sensors commonly used for confined space entry is not geared to warn affected workers of the carbon dioxide toxicity. Observe the following:

- At the OSHA PEL of 5,000 ppm carbon dioxide, only 0.01% of the oxygen is displaced for a 20.9% oxygen concentration.
- At the NIOSH IDLH of 40,000 ppm carbon dioxide, only 0.08% of the oxygen is displaced, resulting in 20.2% oxygen concentration.
- At 75,000 ppm of carbon dioxide, 1.5% of the oxygen is displaced, for a resulting oxygen concentration of 19.5%, the OSHA minimum permissible level for oxygen and the level at which most current atmospheric meters will first alarm, indicating an oxygen deficiency.

These observations are essential in the hazard recognition process. Point of fact: the OSHA minimum oxygen level of 19.5% is not reached in a carbon dioxide contaminated atmosphere until 1.5% of the oxygen is displaced by 75,000 ppm of

TABLE 2

SUMMARY MATRIX OF OXYGEN DISPLACEMENT VIA CARBON DIOXIDE

% O_2 in atmosphere [a]	CO_2 gas causing displacement of O_2 (ppm)	CO_2 gas displacement % of atmosphere	% O_2 reduced [b]	% O_2 in atmosphere after reduction
21%	100,000	10.00%	2.00%	19.00%
21%	95,000	9.50%	1.90%	19.10%
21%	90,000	9.00%	1.80%	19.20%
21%	85,000	8.50%	1.70%	19.30%
21%	80,000	8.00%	1.60%	19.40%
21%	75,000	7.50%	1.50%	19.50% [c]
21%	70,000	7.00%	1.40%	19.60%
21%	65,000	6.50%	1.30%	19.70%
21%	60,000	6.00%	1.20%	19.80%
21%	55,000	5.50%	1.10%	19.90%
21%	50,000	5.00%	1.00%	20.00%
21%	45,000	4.50%	0.90%	20.10%
21%	40,000 [d]	4.00%	0.80%	20.20%
21%	35,000	3.50%	0.70%	20.30%
21%	30,000 [e]	3.00%	0.60%	20.40%
21%	25,000	2.50%	0.50%	20.50%
21%	20,000	2.00%	0.40%	20.60%
21%	15,000	1.50%	0.30%	20.70%
21%	10,000	1.00%	0.20%	20.80%
21%	5,000 [f]	0.50%	0.10%	20.90%
21%	2,000	0.20%	0.04%	20.96%
21%	1,000	0.10%	0.02%	20.98%

Note. P. Allen, personal communication, Feb. 18, 2020.
[a] Rounding up from 20.95% per AIHA (2011). [b] 5% total atmosphere gas displacement reduces O_2 % by 1%. [c] OSHA minimum O_2 level. [d] NIOSH IDLH. [e] OSHA STEL. [f] OSHA PEL TWA.

carbon dioxide (7.5%)—almost double the IDLH limit. At that moment, we have personnel down, and the chain of a major emergency response is activated. How many employers know this? How many OSH professionals? Recall that death is likely in seconds following a rapid loss of cognitive abilities at this level of carbon dioxide. Why is this important to the reader?

Consider a permit-required confined space; decomposing organic material could produce 40,000 ppm (or 4%) carbon dioxide levels, where 0.8% oxygen is displaced, resulting in a 20.2% oxygen concentration. In this most realistic scenario, deadly IDLH levels of carbon dioxide would fail to activate a typical quad gas atmospheric meter with an oxygen sensor for oxygen deficiency and no carbon dioxide sensor. Further relying on this meter, an employer that believes carbon dioxide is only a simple asphyxiant could essentially expose workers to fatal IDLH levels of carbon dioxide. Activating the meter's alarm for oxygen deficiency would essentially require nearly double the IDLH concentration of carbon dioxide. This scenario describes the all too common but incorrect atmospheric monitoring system in use today for the hazard of carbon dioxide. This error and lack of comprehension present an unacceptable risk.

In 2012, OSHA cited a Texas brewery with one alleged willful and five alleged serious violations for failing to consider the carbon dioxide atmosphere in the brewing cellars to be IDLH while also failing to identify related respiratory hazards (OSHA, 2013).

Noteworthy is the attempt by the Beer Institute and the Brewing Industry Safety Advisory Committee to press OSHA to double its existing PEL to a transitional limit of 10,000 ppm in 1989 (when OSHA attempted to amend 212 existing PELs) with a 1979 study on the carbon dioxide exposure of brewery workers (OSHA, 1993). That study monitored brewery workers' full-shift exposures to carbon dioxide and determined that they averaged 10,800 ppm (NIOSH, 2011). After reviewing the record evidence submitted in response to OSHA's proposal for carbon dioxide, NIOSH mistakenly determined that exposure limits of 10,000 ppm (8-hr TWA) and 30,000 ppm (15-min STEL) were appropriate (NIOSH, 2011). Thankfully, this action was remanded by the U.S. Circuit Court of Appeals (NIOSH, 2011). From this judicial action, OSHA decided that workplaces where the employer has instituted a monitoring and compliance program (to confirm worker exposures do not exceed a 30,000 ppm STEL), a de minimis notice may be issued when the 8-hr TWA is between 5,000 and 10,000 ppm; however, when the employer has instituted such a program and the 8-hr TWA exceeds 10,000 ppm, a serious citation may be issued (OSHA, 1993).

The potential for fatality within enclosed, sealed, confined or low-lying spaces due to carbon dioxide is a valid threat with SIF potential. OSH professionals completing workplace hazard analyses and risk assessments may now determine that this risk is unacceptable, even to those employers and workers with an elevated risk appetite. The risk should be reduced with affected worker training and forthcoming recommended risk controls for susceptible work sites.

Workplace Hazard Analysis & Risk Assessment

OSH professionals must identify operational areas where carbon dioxide can collect, assess the risk of injury or illness, then develop procedures and methods to eliminate, prevent or control hazardous levels of carbon dioxide accumulation.

> Determine the lowest acceptable level of CO_2 that your facility can operate under to effectively protect workers' thinking and cognitive abilities. Keep in mind that the 8-hr time weighted average workplace exposure level established by OSHA in 1970 was 5,000 ppm, so under no circumstances should this level be higher than this. (DeVany, 2015)

Numerous areas exist where, under the right conditions, carbon dioxide can quickly reach dangerous levels. Hazard assessments are critical for evaluating where carbon dioxide can be generated and collected. The Work sites identified as examples of where carbon dioxide accumulations may occur are presented in the "Work Sites Where Unsafe Carbon Dioxide Accumulations May Occur" sidebar on p. 26.

Affected workers should be interviewed during the assessment phase for their input on current or needed risk controls over carbon dioxide. A carbon dioxide-specific OSH perception survey may benefit this process. A review of all past loss event investigations involving carbon dioxide is necessary. Be sure to view investigations and reports of both recordable and near-hit events.

When conducting a comprehensive walk-through survey of an entire work site, look for areas where carbon dioxide can collect, including areas of partial air exchange, low-lying areas, places where organic waste and wastewater are stored and can collect, carbon dioxide storage rooms, and process areas known to have the potential for elevated carbon dioxide levels. This assessment must include indoor and outdoor spaces and aids in the subsequent placement of appropriate warning placards.

A common misunderstanding is that unsafe levels of carbon dioxide are only present in confined areas with no incoming fresh air. However, depending on weather and other conditions, unhealthy carbon dioxide levels can be found in nearly all occupational areas of susceptible work sites. Although carbon dioxide is heavier than air, warm or heated carbon dioxide rises and floats away. It can then travel to remote locations, collecting in unsuspected low areas as it cools, depending on air temperature, wind direction and speed (DeVany, 2015). Assess conditions on a day when the air is still (i.e., little wind, < 5 mph) to detect pockets where carbon dioxide can collect. Recall that wind plays an integral part in dissipating carbon dioxide (e.g., low winds can move carbon dioxide to remote areas, whereas high winds can safely disperse it into the atmosphere).

Survey the site under both normal and abnormal process conditions to establish normal versus abnormal carbon dioxide levels. Conduct multiple surveys as needed throughout the year and repeat atmospheric sampling during various weather conditions to understand effects of ambient temperatures and humidity on carbon dioxide levels (DeVany, 2015).

As deemed appropriate from the workplace hazard assessment, arrange and implement industrial hygiene sampling to assess and monitor the general workplace atmosphere for carbon dioxide. While OSHA recommends local ventilation or other controls where levels may exceed its 8-hr TWA PEL of 5,000 ppm, the author recommends the same at 1,000 ppm 8-hr TWA. Direct-read carbon dioxide meters may be used to sample suspected work areas and job tasks. If carbon dioxide levels are near or above unhealthy levels, conduct personal sampling over the shift, or draw a known air volume into a five-layer gas sampling bag for laboratory analysis (OSHA, 1990). Learn how and when to use the available industrial hygiene sampling methods to review the work site's exposures, then decide how best to apply this technology.

•Single-gas or multigas carbon dioxide direct read meters are used for immediate sampling results during site hazard assessments.

•Single-gas or multigas carbon dioxide direct read meters, detector tubes or dosimeter diffusion tubes are used during continuous sampling of operations in high-risk areas.

•Mounted carbon dioxide detectors are used for high-risk, fixed areas where carbon dioxide levels can be monitored continuously and remotely and, in some cases, interlocked with ventilation equipment and alarm systems.

•Handheld, multigas (five-gas) portable atmospheric meters with a carbon dioxide sensor are typically needed for confined space entries.

Of particular concern for the author are confined spaces. Apprise and upgrade existing confined space procedures within the permit-required confined space program to require that suspected confined spaces be tested for carbon dioxide during the initial assessment, before entry and continuously while the space is occupied. *Do not depend on sampling for carbon dioxide using the space's oxygen content, as elevated levels of carbon dioxide can be highly toxic, even though there appear adequate oxygen concentrations for life support.*

Should any tanks of carbon dioxide (e.g., high-pressure fixed extinguishing systems or larger low-pressure holding tanks) be discovered during this assessment, the OSH professional should calculate the anticipated carbon dioxide concentration resulting from a potential discharge or containment failure in that space. If the maximum anticipated release would reach or exceed the OSHA STEL of 30,000 ppm (3%), risk controls must be deployed in advance to protect affected workers.

In the final assessment steps, employ the PDCA loop process via risk avoidance and elimination. Any changes to those operations using or producing carbon dioxide must undergo a management of change process. Similarly, any new processes using or producing carbon dioxide must undergo a prevention through design process.

Implementation of Risk Controls

Workplace hazards and their related risks are identified, assessed, prioritized and reduced to the lowest acceptable level by taking preventative (and, in some cases, reactive) measures in order of risk-classified priority. Using the ANSI Z10-2012 hierarchy of risk controls as a starting point, consider the following risk controls to reduce the risk from carbon dioxide in the work site.

•**Avoidance** prevents hazards from entering the workplace and may include inherent safety controls such as conducting a prevention through design analysis for a proposed new process involving carbon dioxide.

•**Elimination** excludes employee exposure by removing the hazard at the source, such as discontinuing the bottling of carbonated beverages or eliminating job tasks that expose workers to carbon dioxide.

•**Substitution** involves replacing harmful toxic materials with less hazardous ones and may possibly include using Class K extinguishing agents instead of carbon dioxide.

•**Engineering controls** isolate the worker from the hazards and may include enclosing work processes, diverting carbon dioxide discharges, confining work operations, and installing general and local ventilation systems.

•**Warnings** may consist of written or verbal warnings to employees about a particular workplace hazard. They may include a warning placard reminding employees of the potential for carbon dioxide in a work area.

•**Administrative controls** include safe work practices (SWPs) that may alter how a task is performed, a job hazard analysis (JHA), affected worker rotation, or preventive and predictive maintenance programs on carbon dioxide systems and tanks.

•**Behavioral controls** motivate affected workers to perform tasks in a safe manner. This control may include periodic positive reinforcement by line management for observed SWPs associated with carbon dioxide.

•**PPE controls** may include the use of employer-provided insulated gloves, face shield and atmosphere-supplied respirators.

Layering several categories of risk controls is ideal for deep risk reduction. Contemplate implementing the controls in the descending order listed, rather than naively selecting the easiest control measures to implement first.

Seasoned OSH professionals recognize that layering the risk controls of avoidance, elimination, substitution and engineering controls should initially be the primary means of reducing employee occupational exposure to carbon dioxide hazards. PPE is always the last resort. Additionally, by risk scoring the recommended risk controls, top management quickly grasps which risk controls to implement first to reduce the severity or probability of adverse carbon dioxide exposure. Such risk scoring is not a stochastic process; instead, it should adhere to a company's standardized approach to assessing severity and probability.

Primary risk controls discussed here and typically included within a CDECP to prevent or reduce harmful occupational carbon dioxide exposures include ventilation, atmospheric monitoring, inspections, storage and handling, lone work, warnings, extinguishing systems, alarms, SWPs and JHAs, emergency response, training and PPE.

Ventilation

If general ventilation is not adequate to control the amount of carbon dioxide in the air, deploying local exhaust ventilation is a key control layer to reduce the risk. Properly balance the mechanical ventilation within carbon dioxide-affected work areas, especially those in corners or the sides of buildings and vessels where carbon dioxide can collect. The ventilation may not need to run continuously; however, perhaps it should be activated remotely before affected workers enter those areas or be automatically activated when a fixed carbon dioxide detector registers levels that, at a minimum, exceed OSHA's PEL of 5,000 ppm (DeVany, 2015).

When installing new carbon dioxide receiving receptacles (as in new construction or remodeling), they should be installed at ground level in an open area. If feasible, it is recommended that existing carbon dioxide fill stations be relocated to at- or above-grade locations to prevent dangerous accumulations of carbon dioxide in below-grade areas. Where fill stations are located in confined spaces, the permit's requirements within the site's permit-required confined space program must be followed (OSHA, 1996).

Even when carbon dioxide is delivered to enclosed areas or below-grade locations that are not confined spaces, to maintain a safe working environment for personnel such areas must be adequately ventilated. Ventilation systems should be designed to exhaust from the lowest level and allow make-up air to enter at a higher point (OSHA, 1996).

Off-gassing from sewage digesters, production fermenters and animal slaughter operations can suddenly produce localized areas of lethal carbon dioxide concentrations.

Pressure relief devices (PRDs) or pressure release valves (PRVs) allow carbon dioxide to be vented directly out of their respective process vessel or room. The released carbon dioxide is a significant source of fugitive emissions within any production facility. If possible, PRDs/PRVs should be directed to a safe release point such as a scrubber, collection system or elevated exhaust stack so that carbon dioxide dispersion does not present a safety hazard. Never allow PRDs/PRVs to discharge to interior work areas (DeVany, 2015).

Open manways and venting PRDs/PRVs from these systems can result in transient but catastrophically high carbon dioxide levels. PRDs/PRVs can sometimes stick open or be inadvertently left open. The areas around these devices can then quickly accumulate IDLH carbon dioxide concentrations. The exhaust stacks of a carbon dioxide scrubber should be installed well above the highest structure. Before its installation, consider how carbon dioxide disperses from the area, including determining the prevailing wind directions, terrain, relative elevations and other factors that may impact dispersion (DeVany, 2015).

Atmospheric Monitoring

Ongoing industrial hygiene air monitoring is a valuable risk control over specific occupational carbon dioxide exposures where elimination is not possible. Electronic, direct-read, nondispersive, infrared meters, detector tubes or dosimeter diffusion tubes may be worn by workers at elevated risk and provide immediate results in high-risk areas. Sampling devices should be calibrated, operating continuously and not positioned within 2 ft of the worker's breathing zone. A competent OSH professional should identify those work exposures during which personal monitoring is required. Consider work shift sampling to account for carbon dioxide fluctuations from room occupancy, process operations and HVAC operations. Such ongoing sampling is in addition to attempts at prior layers of more effective risk controls (e.g., avoidance, substitution, engineering).

Calibrated, portable, single-gas or multigas atmospheric meters with a carbon dioxide sensor are needed for confined space entry. *Never rely on measuring for carbon dioxide using the oxygen content in a confined space.* Ensure that affected confined space entry supervisors are thoroughly trained in the use of these meters and that other entry team members are educated in actions to be undertaken in the event that carbon dioxide levels above 1,000 ppm are sensed by the unit.

Fixed carbon dioxide detectors are suited for monitoring high-risk operations continuously and, as suggested, should be interlocked to personnel alarms and ventilation exhaust systems. The author recommends that fixed detectors be installed where the contaminant levels may exceed 1,000 ppm or 20% of the current OSHA PEL. Carefully consider the placement of detectors.

Fixed carbon dioxide detectors are commonly placed in the middle of buildings to obtain broad representative readings of the general work area. However, this practice can result in placing detectors along walkways and open areas that already have proper ventilation and may provide workers a false sense of security. Instead, additional detectors should be placed in dead areas (e.g., remote corners of buildings, areas where little ventilation is present). This gives a better indication of actual carbon dioxide accumulations in all spaces that can jeopardize worker safety. Consider locating one carbon dioxide detector at the supplied air fan point of entry (discharging into the workplace) to determine whether carbon dioxide is being blown into the work area (DeVany, 2015).

Inspections

Institute a documented routine inspection process and a preventative and predictive maintenance program per manufacturer's instructions for all equipment involving carbon dioxide, including process vessels and related piping, valves, pressure relief systems, tubing, hoses, manifold systems or piping from beverage dispensing machines, ventilation systems, fittings and detection instruments. Ongoing leak testing of systems of concern should be applied in addition to tabletop audits and on-site inspections.

Storage & Handling

Trained personnel working on carbon dioxide systems or related piping must employ lockout/tagout and line break permit controls to ensure their safety. All carbon dioxide equipment and lines must be safely reduced to a zero-energy state, blocked or blanked, and adequately locked and tagged out of service before the work begins (DeVany, 2015). When moving carbon dioxide on roadways, avoid transport on vehicles where the load space is not separated from the driver's compartment (Praxair, 2016).

A pressure regulator appropriate for carbon dioxide cylinder/tank pressures and contents should be utilized, and portable cylinders secured in an upright position with caps screwed in place when not in use. Store carbon dioxide in an area out of direct sunlight that is cool (e.g., below 125 °F), dry and away from heat sources. To control the potential for leakage, store carbon dioxide in well-ventilated areas separate from active work sites. If storing in large volumes, store on the ground floor or preferably in an isolated, detached building.

Gas and liquid carbon dioxide under pressure (e.g., 830 psi) can rapidly release gaseous carbon dioxide through a PRD or PRV, resulting in the forcible ejection of high-pressure streams of the toxic gas and the formation of dry ice and freezing pressure streams, which can cause frostbite (Praxair, 2016). Suitable PPE and incompatible materials must also be considered.

When suspended in carbon dioxide, dusts of several metals (e.g., aluminum, chromium, magnesium, manganese, titanium, zirconium) can ignite and are explosive. Carbon dioxide is also incompatible with some oxidizers (e.g., permanganates, perchlorates, peroxides, chlorates, nitrates, fluorine, chlorine, bromine); certain reducers (e.g., lithium, sodium, aluminum and their hydrides); metal carbides, metal salts and strong bases [e.g., sodium hydroxide (caustic soda or lye), potassium hydroxide] (DeVany, 2015).

Since carbon dioxide cylinder storerooms are often relatively small compared to the overall work site, inadvertent discharges in these storerooms produce deadly levels, warranting additional ventilation (EPA, 2000). The security of these storerooms is critical to ensure that illegal release of the gas cannot be perpetrated by criminal elements. To that end, evaluate the physical security of on-site storerooms and production cylinders/tanks, transportation of carbon dioxide and the integrity of workers allowed access to these operations. Where carbon dioxide is used for legal purposes in mass assembly areas (e.g., carbonated soda sales in an indoor stadium), security should be stringent and other CDECP risk controls fully implemented.

Lone Work

Because of the unacceptable risk of high-risk work tasks involving SIF carbon dioxide exposure potentials exceeding the suggested OEL of 1,000 ppm, such tasks should not be accomplished by a lone worker (Straub, 2018a). Because of the poor warning properties of carbon dioxide, lone workers in closed vehicles, unventilated rooms, tight work sites with inadequate fresh air exchange and sealed areas may inadvertently find themselves in high carbon dioxide concentrations without realizing it (DeVany, 2015). A working alone safety program can reduce this risk factor associated with carbon dioxide (Straub, 2018a).

Warnings

SDSs are typically an excellent first step toward communicating the hazards of carbon dioxide with affected workers. However, as noted, a cursory review of applicable SDSs revealed that carbon dioxide's toxic hazard continues to be underreported, with most suppliers still classifying carbon dioxide as a simple asphyxiant. Even the U.S. DOT hazard classification system (i.e., 49 CFR 172) categorizes carbon dioxide as a Class 2.2 HazMat (i.e., nontoxic, nonflammable gas), worthy of a green placard. The author posits that carbon dioxide should be reclassified to a 2.3 hazard class (i.e., toxic gas), with the skull and crossbones placard suitable for its toxicity.

Until such SDSs and placards are corrected, they fail to adequately communicate the toxicity of carbon dioxide. Affected employers must bridge this gap with adequate training, in addition to ensuring the emplacement of suitable globally harmonized system (GHS) hazard warning labels on process vessels, tanks and related piping.

Standardized warning placards or signs are to be affixed outside and inside of those areas where high concentrations of carbon dioxide gas can accumulate and present carbon dioxide intoxication or poisoning to workers (NFPA, 2018). Lastly, adequate safeguards to warn workers (e.g., physical barricades) are necessary when the atmosphere of a protected area remains hazardous to their safety or health due to a system discharge (OSHA, n.d.).

Extinguishing Systems

A fire extinguishing system is an engineered set of components that work together to quickly detect a fire, alert occupants and extinguish the fire before extensive damage can occur (OSHA, n.d.). Portable and fixed extinguishing systems produce unique and adverse health exposures in which carbon dioxide can be forcibly injected into a workplace atmosphere. The amount of carbon dioxide needed to reduce the oxygen level to a point at which various fuels are prevented from burning is relatively high (34%), a level at which humans suffer death (EPA, 2000). U.S. industries have recognized the environmental importance of using carbon dioxide extinguishing systems over halon alternatives and increased use of the same is anticipated (EPA, 2000).

Since NFPA 12 (2018) requires a carbon dioxide concentration of at least 34% to be quickly introduced (i.e., within 30 s) to provide a suitable extinguishing concentration and overcome system leakage, it can be extrapolated that the protected work space immediately surrounding and adjacent to the extinguishment will subsequently and rapidly contain lethal levels of toxic carbon dioxide during fire activation or accidental discharge. Research finds that most carbon dioxide fatalities in the U.S. occur during testing and servicing of fixed extinguishing systems (EPA, 2000). Causal factors were identified as inadequate hazard communication training, nonexistent or ignored safe work procedures and improper testing practices.

Per OSHA's 29 CFR 1910.160 and 1910.162, employees must have a safe and readily available means of evacuation when a fixed carbon dioxide extinguishing system activates. This requires a distinctive predischarge employee alarm capable of being perceived above ambient light or noise levels. The alarm must provide affected employees ample time to exit the work space safely before system discharge. The timing to delay system discharge is established by conducting dry runs in the work site to establish the time needed for workers to evacuate the hazard area (NFPA, 2018). Further customization may be necessary when unique security concerns are present.

In exceptional situations (e.g., locked vaults), alternative protective means such as an emergency intercom system, sign-in log, video or manual surveillance, and a procedure to ensure that all employees have cleared vault spaces before actuating the fire-extinguishing system should be communicated, implemented and followed (OSHA, 2001).

Doors leading from the protected area should swing outward, be self-closing and possess panic hardware if positive latching. Affected employees should be evacuated from the zone whenever maintenance, servicing or testing on a fixed system is planned. Properly mark/label pull stations and other actuation devices of fixed carbon dioxide extinguishing systems to indicate their unique function. Train all employees to the type of systems installed in the workplace, the hazards involved, proper activation of the manual pull stations after verifying all other persons are out of the protected zone, and the correct response to audible and visual predischarge alarms. Post-discharge capabilities should include the in-house emergency rescue of trapped workers and forced ventilation to evacuate the gas. Lastly, conduct semiannual system inspections to verify that the fixed extinguishing system is maintained in good operating condition.

Alarms

OSH professionals should use the risk control of carbon dioxide alarm systems when the threat of overexposure exists. Alarms may include a predischarge alarm, as described, or alarms actuated by mounted carbon dioxide detectors in a high-risk work space. In most cases, alarms should be connected to ventilation systems, which initiate if an extinguishing system activates or detected carbon dioxide levels exceed 20% of the OSHA PEL, or 1,000 ppm. Alarms in carbon dioxide storage areas are suggested if the storage capacity exceeds 100 lb of gas (CO2meter, 2021).

Safe Work Practices & Job Hazard Analyses

SWPs should be in place for current and planned SIF operations involving carbon dioxide. Conduct JHAs to evaluate these SWPs via an annual tabletop audit process. JHAs may aid in designing new practices or behaviors to eliminate or at least reduce these exposures. SWPs and JHAs should also be accomplished for work areas and job tasks that may not be routine yet could present a higher risk of significant carbon dioxide exposure to affected workers (e.g., semiannual carbon dioxide fixed extinguishing system inspections). Lastly, should a loss event involving carbon dioxide occur, the SWP and JHA for that operation should be reviewed and updated as needed by a competent person.

Emergency Response

Emergency responders must pay attention to the possible risks of carbon dioxide intoxication or poisoning for their personal safety. Rescue from carbon dioxide events should be performed only by trained first responders with an atmosphere-supplied SCBA due to the potential IDLH environment. NFPA 12 and OSHA require an employer to have an emergency action plan for prompt rescue if there is a potential for workers to become trapped in a carbon dioxide environment. Placement of an emergency-use SCBA or 5-/10-min escape packs outside an identified high-risk carbon dioxide work space may be appropriate.

When confronted with a carbon dioxide victim, the individual should be removed from the dangerous area as fast as possible (Permentier et al., 2017). A person suffering from mild carbon dioxide intoxication typically can recover merely by breathing fresh air. However, it is essential to communicate any suspicion of carbon dioxide intoxication in case the symptoms worsen so that proper medical treatment may be administered. If severe or multiple symptoms are seen, call for emergency medical help.

Carbon dioxide poisoning requires the immediate administration of oxygen and appropriate supportive care. In severe cases, mechanical ventilation may be required. Begin immediate first aid and CPR if the victim is unresponsive. There is a potential risk to first responders providing rescue breaths to carbon dioxide victims. Instead, use a bag valve mask (e.g., Ambu bag, a squeezable bag with a one-way valve and face mask). Successful CPR is significantly complicated with carbon dioxide poisoning victims as high concentrations of carbon dioxide in the bloodstream can interfere with successful resuscitation (Henderson, 2010). As is the case with other SIF exposures, prevention is more valuable than the rescue plan.

Once the victim has been safely evacuated, increase ventilation to the emergency area and move any leaking containers outside to a well-ventilated area. Recall that heavier-than-air carbon dioxide gas may accumulate in hazardous amounts in low-lying areas, especially inside buildings and enclosed spaces. Lastly, keep unnecessary and unprotected personnel from entering the site while accomplishing adequate ventilation.

Training

Affected personnel who handle or are exposed to carbon dioxide should be thoroughly familiar with the hazards associated with this poison. Refer to the work site's hazard communication program for more specific training details beyond the CDECP and ensure that a correct SDS for carbon dioxide is placed within the work site's SDS binder/system. Ensure that training for non-English-speaking employees is presented in languages understood by the affected employees and others exposed to the hazard (OSHA, n.d.). The OSH professional should coordinate training before the assignment of duties, with retraining annually or whenever:

- a change in job assignments occurs,
- a change in equipment or process is made that presents a new hazard,
- a change is made in the CDECP, or
- periodic inspection reveals, or there is a reason to believe, that there are deviations from or inadequacies in an affected employee's knowledge of the CDECP.

Communicate any potential carbon dioxide hazards to visiting contractors or vendors having potential exposure (e.g., confined space entry, carbon dioxide system/tank refilling, carbon dioxide piping repairs, fixed extinguishing system maintenance).

PPE

The employer is required to provide the needed PPE and related user preassignment training to affected employees exposed to carbon dioxide as a gas, liquid or solid. PPE is intended to supplement prior layers of risk controls in fully implementing the CDECP. PPE examples for consideration include:

- eye/face protection: chemical vapor-proof safety goggles or face shield
- skin protection: insulated protective gloves with gauntlets to the mid-forearm and a resistant apron if contact with pressurized gas or dry ice is possible
- respiratory protection: atmosphere-supplied SCBA for emergency rescue

Program Audit

Following the ISO 45001:2018-recommended PDCA loop, the effectiveness of the entire CDECP is best ensured by periodically auditing and evaluation by a qualified person other than those utilizing the CDECP being audited. An annual CDECP audit is a proactive, leading safety performance indicator to evaluate and score worker performance pertaining to carbon dioxide safety. All five top-favored safety and health management system models promote leading safety performance indicators to evaluate and predict OSH performance (Straub, 2018b). Strive to ensure that the CDECP is functional to reduce risk and be fully interconnected with the work site's safety and health management system. Any deviations or inadequacies are documented, communicated to top management and tasked for correction.

An audit is best conducted each year and documented for follow-through (Figure 1). During the audit process, at least 50% of affected employees should be interviewed for their insights into the effectiveness of the CDECP's risk controls. The author finds that affected worker interviews are best accomplished during an annual refresher training session in which all affected employees review the parameters of the CDECP and any previous loss events in which carbon dioxide played a role. The OSH professional may also wish to redeploy the carbon dioxide perception survey described in this article. Lastly, any applicable new regulations or improved industry best practices involving carbon dioxide safety should enhance the CDECP.

Conclusion

Carbon dioxide is not a simple asphyxiant but rather a potent, potentially fatal poison. While occupational exposure to carbon dioxide is often underestimated, proactive OSH professionals may educate employers to the actual unacceptable risk involved. Affected employers should consider pursuing the following actions over carbon dioxide exposures to reduce this SIF risk and enhance regulatory compliance:

- Assess the work site for carbon dioxide potentials and implement a CDECP to reduce the risk.
- Provide modified processes to remove or reduce elevated carbon dioxide exposures.
- Provide appropriate carbon dioxide meters for confined space entry personnel.
- Provide engineered ventilation systems to keep carbon dioxide levels below 1,000 ppm.
- Provide carbon dioxide monitors, meters and detectors to protect workers in identified high-risk carbon dioxide work spaces.
- Provide visual and audible carbon dioxide alarms, related warning signage and evacuation drills for high-risk carbon dioxide work spaces.

FIGURE 1
CARBON DIOXIDE EXPOSURE CONTROL PROGRAM AUDIT

Date: ____________________ Auditor/Company: ____

OK Problem N/A **Address all "Problems" under "Comments"**

❐ ❐ Written carbon dioxide exposure control program (CDECP) present and implemented.
❐ ❐ ❐ Written CDECP meets OSHA's 29 CFR 1910.1001 requirements.
❐ ❐ Written CDECP available to all affected employees.
❐ ❐ Affected employees able to locate written CDECP.
❐ ❐ Affected employees able to explain the CDECP upon interview.
❐ ❐ Initial carbon dioxide hazard assessment completed by a competent person. Date: ________
❐ ❐ Assessments of carbon dioxide levels accomplished during various weather conditions.
❐ ❐ IH air sampling assessment conducted during routine and nonroutine production periods.
❐ ❐ ❐ Work site hazard assessment identified areas having potential adverse carbon dioxide levels:

1. ____
2. ____
3. ____

❐ ❐ Work sites with carbon dioxide exposures are placarded to warn workers of the hazard.
❐ ❐ Competent person prevents access to carbon dioxide areas by unauthorized persons.
❐ ❐ ❐ Work site areas with carbon dioxide fixed extinguishing systems have predischarge alarms distinct from ambient noise and other site alarms.
❐ ❐ ❐ Carbon dioxide fixed extinguishing systems have distinct pull stations for manual deploy.
❐ ❐ ❐ Evacuation timing for carbon dioxide system activation delays established by dry runs.
❐ ❐ ❐ Carbon dioxide detectors in place in high-risk areas and serviced at least annually.
❐ ❐ Doors leading out of carbon dioxide areas open outward, self-close with panic hardware.
❐ ❐ Competent person conducts work site inspections to verify that CDECP controls over carbon dioxide are in effect.
❐ ❐ Emergency action plan in effect for emergency rescue of trapped workers.
❐ ❐ Evacuation of workers in protected areas during system testing, repairs and servicing.
❐ ❐ ❐ Affected employees observed working safely in carbon dioxide areas during this audit.
❐ ❐ Written hazard communication program implemented for carbon dioxide.
❐ ❐ Written respiratory protection program present and implemented for respirator users.
❐ ❐ Emergency-use atmosphere-supplied respirators visible and accessible outside protected spaces.
❐ ❐ All affected employees donning respirators are using SCBA respirators.
❐ ❐ All affected employees donning respirators trained prior to assignment.
❐ ❐ All affected employees donning respirators retrained annually.
❐ ❐ All new employees trained in carbon dioxide awareness.
❐ ❐ Affected employees trained in carbon dioxide safety prior to assuming their duties.
❐ ❐ Affected employees retrained in carbon dioxide safety annually.
❐ ❐ Competent person performs or oversees carbon dioxide training sessions.
❐ ❐ Training documented with both the date and the names of those in attendance.
❐ ❐ Written record made of this annual audit, which includes the date, the employee(s) interviewed, person making the evaluation and suggested risk controls.

Employees interviewed – list here or on reverse side:
Comments:

____
Signature of auditor

- Prohibit high-risk lone work involving elevated carbon dioxide potentials.
- Provide affected workers with comprehensive training in the hazards and controls associated with their occupational exposure to carbon dioxide.
- Encourage suppliers to update their SDSs to reflect the toxicity of carbon dioxide.
- Encourage OSHA to update its fire extinguishing system eTool to reflect the toxicity of carbon dioxide.
- Support NIOSH research on carbon dioxide toxicity and OSHA in lowering its PEL for carbon dioxide to better protect affected workers.
- Encourage the U.S. DOT to reclassify carbon dioxide to a 2.3 hazard class. PSJ

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Fred Straub, Ph.D., M.S., CSP, ARM, is the president and principal consultant of Prospering Safely: Safety & Risk Management Services LLC. With more than 35 years of practical safety and health experience, he holds doctorate, master's and undergraduate degrees in Safety Sciences from the Indiana University of Pennsylvania. He is a past contributor to Professional Safety and is a speaker at ASSP conferences and for private clients nationwide. Straub is a professional member of ASSP's Central Pennsylvania Chapter, which he has also served as president, and was recognized as ASSP Region VIII Safety Professional of the Year in 1997.