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Carbon Dioxide as a Fire Suppressant: *Examining the Risks*

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U.S. Environmental Protection Agency
Office of Air and Radiation
Stratospheric Protection Division

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Preface

Under the Clean Air Act Amendments of 1990, the U.S. Environmental Protection Agency (EPA) has the statutory authority to set phase-out dates for ozone-depleting substances (ODS) and to evaluate potential risks posed by proposed ODS substitutes. Under the terms of the Montreal Protocol on Substances that Deplete the Ozone Layer, EPA promulgated regulations to phase out the production of Halon 1301. In response to the halon phase-out effective January 1, 1994, the fire protection industry has been searching for alternatives. A number of alternative technologies have been proposed, including carbon dioxide (CO_2) systems. This report was written to provide users of total flooding halon systems, who may be unfamiliar with total flooding carbon dioxide systems, with information regarding the potential dangers associated with carbon dioxide systems. Appropriate precautions must be taken before switching to carbon dioxide systems and with this report EPA attempts to raise awareness and promote the responsible use of carbon dioxide fire suppression systems.

The authors of this report consulted with experts in the industry during the information-gathering stage for development of the report. An early draft of the document was read by members of the United Nations Environment Programme (UNEP) Halons Technical Options Committee (HTOC). Many experts within the fire protection industry provided data on incidents. The penultimate document was peer reviewed in September 1999 for its technical content by a distinguished group of experts, including:

- **Rich Hansen** (Test Director), United States Coast Guard - R&D Center
- **Matsuo Ishiyama**, member of HTOC, Corporate Advisor and Auditor, Halon Recycling and Banking Support Committee, Japan
- **Joseph A. Senecal, Ph.D.**, Director of Suppression Engineering, Kidde-Fenwal, Inc.
- **Charles F. Willms, P.E.**, Technical Director, Fire Suppression Systems Association
- **Thomas Wysocki, P.E.**, President and Senior Consultant, Guardian Services, Inc.
- **Roy Young**, HTOC member, United Kingdom

Comments were received from all peer reviewers. Some reviewers expressed concern that the document be written clearly enough to lay out the associated risks in a way that neither promoted nor unduly discouraged the use of carbon dioxide-based fire extinguishing systems, and changes were made in the introduction to address this concern. A reviewer described the document as "a very valuable contribution to the safety subject and . . . should be used by carbon dioxide systems providers as a positive tool to promote training, maintenance, and adherence to proven standards." All reviewers were pleased that a report on the risks associated with carbon dioxide systems had been prepared.

One reviewer found the report to accurately reflect current "land-based" requirements, but added information related to the importance of training both new crew and contracted maintenance workers in marine applications. The conclusions of the report were changed to reflect this comment. One reviewer commented that a statement in the report was overly speculative. The report language was edited to clearly indicate that the statement is speculative. Specific technical definitions and information related to an accident event were contributed by one reviewer who also provided consistency between language of the report and correct technical terminology as used in standard National Fire Protection Association (NFPA) documentation. Extensive changes were made to the sections *Extinguishing Mechanisms of Carbon Dioxide* and *Life Safety Considerations of Carbon Dioxide* on the advice of one reviewer. Most other comments were minor editorial remarks generally for clarification. All comments were addressed in the final document.

EPA wishes to acknowledge everyone involved in this report and thanks all reviewers for their extensive time, effort, and expert guidance. EPA believes the peer reviewers provided information necessary to make this document technically stronger. Without the involvement of peer reviewers and industry contacts this report would not be possible. EPA accepts responsibility for all information presented and any errors contained in this document.

Stratospheric Protection Division (6205J)
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Table of Acronyms

AHJ	authorities having jurisdiction
CATAMA	Committee on Aviation Toxicology, Aero Medical Association
CCOHS	Canadian Center for Occupational Health and Safety
CEA	Comité Européen des Assurances
CFR	Code of Federal Regulations
DOE	Department of Energy
EPA	Environmental Protection Agency
GPO	Government Printing Office
GVEq	Gas Volume Equivalent
HAG	Halon Alternative Group
HTOC	Halon Technical Options Committee
IAC	Information Access Company
IMO	International Maritime Organization
IRI	Industrial Risk Insurers
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
NMERI	New Mexico Engineering Research Institute
NTIS	National Technical Information Service
NRC	Nuclear Regulatory Commission
ODS	ozone-depleting substance
OSHA	Occupational Safety and Health Administration
SCBA	Self-Contained Breathing Apparatus
SOLAS	Safety of Life at Sea
UNEP	United Nations Environment Programme
USCG	United States Coast Guard
VdS	VdS Schadenverhütung

Introduction

This paper provides information on the use and effectiveness of carbon dioxide in fire protection systems and describes incidents involving inadvertent exposure of personnel to the gas. Because carbon dioxide fire extinguishing systems will likely be used in place of those based on halon in some applications, this paper attempts to provide an increased awareness of the potential dangers associated with the use of carbon dioxide. EPA recognizes the environmental benefits of using carbon dioxide, but is concerned that personnel accustomed to the use of halon fire suppression systems may not be properly alerted to the special hazards of carbon dioxide. Governmental, military, civilian, and industrial sources were researched to obtain information on deaths and injuries associated with the use of carbon dioxide as a fire extinguishing agent. An examination of the risks associated with carbon dioxide extinguishing systems is also presented.

Carbon Dioxide as an Extinguishing Agent

Fire protection applications generally can be divided into two basic categories: 1) applications that allow the use of water-based sprinklers and 2) special hazards that require the use of some other fire extinguishing agent such as carbon dioxide, halon, halon replacements, dry chemicals, wet chemicals, or foams. According to industry consensus, special hazard applications comprise approximately 20 percent of total fire protection applications. Of the special hazard applications, approximately 20 percent of the market (based on dollars) is protected by carbon dioxide extinguishing agents. Carbon dioxide has been used extensively for many years in the special hazard fire protection industry worldwide. Between the 1920s and 1960s, carbon dioxide was the only gaseous fire suppression agent used to any degree, but halon-based systems were used extensively beginning in the 1960s. Carbon dioxide continues to be used in numerous applications around the world for the extinguishment of flammable liquid fires, gas fires, electrically energized fires and, to a lesser degree, fires involving ordinary cellulosic materials such as paper and cloth. Carbon dioxide can effectively suppress fires of most materials with the exception of active metals, metal hydrides, and materials containing their own oxygen source, such as cellulose nitrate (Wysocki 1992). The use of carbon dioxide is limited primarily by the factors influencing its method of application and its intrinsic health hazards.

Carbon dioxide is used internationally in marine applications in engine rooms, paint lockers, vehicle transport areas on cargo vessels, and in flammable liquid storage areas (Willms 1998). Large marine engine room systems may require as much as 20,000 lb of carbon dioxide per system. Carbon dioxide fire suppression systems are currently being used by the U.S. Navy and in commercial shipping applications.

The steel and aluminum industries also rely heavily on carbon dioxide fire protection. In the aluminum industry, for example, the rolling mill process requires the use of kerosene-like lubricants and coolants. Fires are prevalent in this application, occurring on the average of 1 per week in the typical aluminum plant (Wysocki 1998, Bischoff 1999). One particular aluminum processing company averages about 600 system discharges per year worldwide in all their fire protection applications using carbon dioxide, such as rolling mills, control rooms, and aluminum sheet printing (Stronach 1999). Many carbon dioxide systems in the metal processing industry are rapid discharge local application systems. In these applications, the carbon dioxide storage containers are located close to the outlet nozzles such that liquid carbon dioxide starts to discharge from the nozzle(s) in under 5 seconds (Wysocki 1998, Stronach 1999). These local application carbon dioxide systems range in size from 800 to 10,000 lb of compressed carbon dioxide (Bischoff 1999, Stronach 1999).

Carbon dioxide systems also are used in computer rooms (subfloor), wet chemistry benches, particle board chippers, equipment dust collectors, printing presses, cable trays, electrical rooms, motor control centers, switch gear locations, paint spray booths, hooded industrial fryers, high-voltage transformers, nuclear power facilities, waste storage facilities, aircraft cargo areas, and vehicle parking areas (Willms 1998, Wysocki 1998). Small carbon dioxide systems, such as those protecting paint lockers or fryers, use approximately 50 lb of carbon dioxide. Other systems use an average of about 300 to 500 lb of carbon dioxide (Willms 1998), but can use as much as 2,500 lb (Ishiyama 1998).

Several properties of carbon dioxide make it an attractive fire suppressant. It is not combustible and thus does not produce its own products of decomposition. Carbon dioxide provides its own pressurization for discharge from a storage container, eliminating the need for superpressurization. It leaves no residue, and hence precludes the need for agent clean up. (Clean up of fire-released debris would, of course, still be necessary in the case of a fire event.) Carbon dioxide is relatively nonreactive with most other materials. It provides three-dimensional protection because it is a gas under ambient conditions. It is electrically nonconductive and can be used in the presence of energized electrical equipment.

Extinguishing Mechanism of Carbon Dioxide

Flame extinguishment by carbon dioxide is predominantly by a thermophysical mechanism in which reacting gases are prevented from achieving a temperature high enough to maintain the free radical population necessary for sustaining the flame chemistry. For inert gases presently used as fire suppression agents (argon, nitrogen, carbon dioxide, and mixtures of these), the extinguishing concentration[1] is observed to be linearly related to the heat capacity of the agent-air mixture (Senecal 1999).

Although of minor importance in accomplishing fire suppression, carbon dioxide also dilutes the concentration of the reacting species in the flame, thereby reducing collision frequency of the reacting molecular species and slowing the rate of heat release (Senecal 1999).

Extinguishing Effectiveness of Carbon Dioxide

Carbon dioxide is the most commonly used “inert” gas extinguishing agent, followed by nitrogen (Friedman 1992). On a volume basis, carbon dioxide is approximately twice as effective as nitrogen (e.g., for ethanol fires, the minimum required volume ratios of carbon dioxide and nitrogen to air are 0.48 and 0.86, respectively). However, because carbon dioxide is 1.57 times heavier than nitrogen [44 and 28 molecular weight (MW), respectively] for a given volume, the two gases have nearly equivalent effectiveness on a weight basis.

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[1] As measured by the cup burner method (NFPA 2001).

Gas Volume Equivalent (GVEq) = vol. ratio for N_2 / vol. ratio for CO_2 =1.8

Weight Equivalent = GVEq x $MW_{N\ 2}$ / MW_{CO2} = 1.1

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 and is also at a level where humans will suffer undesirable health effects. Table 1 presents the minimum required ratios of carbon dioxide to air (v/v), the corresponding oxygen concentration that will prevent burning of various vapor fuels at 25^{N}C, the theoretical minimum carbon dioxide concentration, and the minimum design concentration of carbon dioxide for various fuels.

Table 1 refers only to gases or vapors; however, the data are also relevant to liquids or solids because they burn by vaporizing or pyrolyzing. Generally, with a few exceptions such as hydrogen or carbon disulfide, a reduction of oxygen to 10 percent by volume would make fires and explosions impossible.

Use of Carbon Dioxide Extinguishing Systems

Carbon dioxide fire extinguishing systems are useful in protecting against fire hazards when an inert, electrically nonconductive, three-dimensional gas is essential or desirable and where clean up from the agent must be minimal. According to the NFPA, some of the types of hazards and equipment that carbon dioxide systems protect are “flammable liquid materials; electrical hazards, such as transformers, switches, circuit breakers, rotating equipment, and electronic equipment; engines utilizing gasoline and other flammable liquid fuels; ordinary combustibles such as paper, wood, and textiles; and hazardous solids” (NFPA 12).

Table 1. Required Ratios (v/v) and Minimum Carbon Dioxide Concentrations to Prevent Combustion

Vapor Fuels	**CO_2/air[a] (v/v)**	**O_2 Concentration (%)**	**Theoretical Minimum CO_2 Concentration$_b$**	**Minimum Design CO_2 Concentration**
Carbon Disulfide	1.59	8.1	60	72
Hydrogen	1.54	8.2	62	75
Ethylene	0.68	12.5	41	49
Ethyl Ether	0.51	13.9	38	46
Ethanol	0.48	14.2	36	43
Propane	0.41	14.9	30	36
Acetone	0.41	14.9	27	34
Hexane	0.40	15.0	29	35
Benzene	0.40	15.0	31	37
Methane	0.33	15.7	25	34

[a] Friedman 1989.

[b] Coward and Jones 1952.

Life Safety Considerations of Carbon Dioxide

Health Effects

The health effects associated with exposure to carbon dioxide are paradoxical. At the minimum design concentration (34 percent) for its use as a total flooding fire suppressant, carbon dioxide is lethal. But because carbon dioxide is a physiologically active gas and is a normal component of blood gases at low concentrations, its effects at lower concentrations (under 4 percent) may be beneficial under certain exposure conditions.[2]

At concentrations greater than 17 percent, such as those encountered during carbon dioxide fire suppressant use, loss of controlled and purposeful activity, unconsciousness, convulsions, coma, and death occur within 1 minute of initial inhalation of carbon dioxide (OSHA 1989, CCOHS 1990, Dalgaard et al. 1972, CATAMA 1953, Lambertsen 1971). At exposures between 10 and 15 percent, carbon dioxide has been shown to cause unconsciousness, drowsiness, severe muscle twitching, and dizziness within several minutes (Wong 1992, CATAMA 1953, Sechzer et al. 1960). Within a few minutes to an hour after exposure to concentrations between 7 and 10 percent, unconsciousness, dizziness, headache, visual and hearing dysfunction, mental depression, shortness of breath, and sweating have been observed (Schulte 1964, CATAMA 1953, Dripps and Comroe 1947, Wong 1992, Sechzer et al. 1960, OSHA 1989). Exposures to 4 to 7 percent carbon dioxide can result in headache; hearing and visual disturbances; increased blood pressure; dyspnea, or difficulty breathing; mental depression; and tremors (Schulte 1964; Consolazio et al. 1947; White et al. 1952; Wong 1992; Kety and Schmidt 1948; Gellhorn 1936; Gellhorn and Spiesman 1934, 1935; Schulte 1964). Part I of Appendix B discusses human health effects of high-concentration exposure to carbon dioxide in greater detail.

In human subjects exposed to low concentrations (less than 4 percent) of carbon dioxide for up to 30 minutes, dilation of cerebral blood vessels, increased pulmonary ventilation, and increased oxygen delivery to the tissues were observed (Gibbs et al. 1943, Patterson et al. 1955). These data suggest that carbon dioxide exposure can aid in counteracting effects (i.e., impaired brain function) of exposure to an oxygen-deficient atmosphere (Gibbs et al. 1943). These results were used by the United Kingdom regulatory community to differentiate between inert gas systems for fire suppression that contain carbon dioxide and those that do not (HAG 1995). During similar low-concentration exposure scenarios in humans, however, other researchers have recorded slight increases in blood pressure, hearing loss, sweating, headache, and dyspnea (Gellhorn and Speisman 1934, 1935; Schneider and Truesdale 1922; Schulte 1964). Part II of Appendix B discusses these results in greater detail.

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[2] Appendix B discusses the lethal effects of carbon dioxide at high exposure levels (Part I) and the potentially beneficial effects of carbon dioxide at low exposure concentrations, as well as the use of added carbon dioxide in specialized flooding systems using inert gases (Part II).

Safety Measures

As with other fire protection systems, a number of regulatory agencies or authorities having jurisdiction (AHJ) administer the design, installation, testing, maintenance, and use of carbon dioxide systems. The authority that regulates the system depends on where the system is located, the intended scenario, and the type of system. Many AHJs that regulate industrial, commercial, and nonmarine applications utilize the NFPA consensus standard covering carbon dioxide extinguishing systems (NFPA 12). Although the standard itself does not hold the force of law, governments and local authorities adopt the standard as their governing fire code. Marine applications are regulated depending on whether the vessels navigate domestic or international waters. U.S. Coast Guard (USCG) regulations pertain to ships in domestic waters and are published in the Code of Federal Regulations (46 CFR Part 76.15). Internationally registered vessels are covered under the International Maritime Organization's Safety of Life at Sea (SOLAS) (IMO 1992). In workplaces that are land-based, the Occupational Safety and Health Administration (OSHA) regulates the exposure to carbon dioxide in order to ensure worker safety.

Design, Specification, and Component Approval

Generally, the process of acquiring fire suppression system approval starts with the manufacturer "listing" its components through organizations such as Underwriters Laboratory or Factory Mutual in the United States. Part of the listing process is the development of an instruction and maintenance manual that includes a description of the full operation of the system along with system drawings. Specifications or plans for the carbon dioxide system are prepared under the supervision of an experienced and qualified person knowledgeable in the design of carbon dioxide systems and with the advice of the AHJ. The designs are then submitted to the AHJ before installation begins.

Installation and Testing

Installation of the carbon dioxide system is usually performed by manufacturers' representatives or distributors. Although the installers are not given a formal accreditation or certification, they are trained by the manufacturer regarding proper installation of system components.

The completed system is inspected and tested by appropriate personnel to meet the approval requirements of the AHJ. Often these requirements include:

(A) Performance of a full discharge test of the entire design quantity through the piping and into the intended hazard area, for each hazard area, if the system protects more than one. A check to verify that the design concentration is achieved and maintained for the specified hold time applies to total flooding type systems only.

(B) Operational checks of all devices necessary for proper functioning of the system, including detection, alarm, and actuation.

(C) Checks for proper labeling of devices and protected areas warning occupants of the possible discharge of carbon dioxide. In addition, signage must be present to warn personnel to vacate the area when the alarm sounds.[3]

(D) Complete inspections of the system and the hazard area to ensure that the system meets the specifications and that it is appropriate for the type of fire hazard.

Use Controls

Despite the use of carbon dioxide in fire-fighting applications above its lethal concentration, NFPA 12 does not limit its use in occupied areas. The standard calls for safeguards such as pre-discharge alarms and time delays to ensure prompt evacuation prior to discharge, prevent entry into areas where carbon dioxide has been discharged, and provide means for prompt rescue of any trapped personnel.

The standard also requires that personnel be warned of the hazards involved as well as be provided with training regarding the alarm signal and safe evacuation procedures. In addition, NFPA 12 requires that a supervised "lock-out" be provided to prevent accidental or deliberate discharge of a system when persons not familiar with the system and its operation are present in a protected space (NFPA 12).[4] The Appendix to NFPA 12 lists the following steps and safeguards that may be used to prevent injury or death to personnel in areas where carbon dioxide is discharged:[5,6]

(A) Provision of adequate aisle ways and routes of exit. These areas should be kept clear at all times.

(B) Provision of the necessary additional or emergency lighting, or both, and directional signs to ensure quick, safe evacuation.

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[3] No foreign language requirements (e.g., Spanish) for signage are specified by U.S. AHJs. Ideally all labels and warning signs should be printed both in English and in the predominant language of non-English-reading workers (NIOSH 1976).

[4] A definition of a "lock-out" has been included in the 2000 edition of the NFPA 12 Standard (Willms 1999).

[5] The degree of compliance with the suggestions provided in NFPA 12 varies across different facilities.

[6] The 2000 edition of NFPA 12 will include an additional provision for mandatory evacuation of the protected area prior to conducting any testing, servicing, or maintenance on the carbon dioxide system (Willms 1999).

(C) Provision of alarms within such areas that will operate immediately upon activation of the system on detection of the fire, with the discharge of carbon dioxide and the activation of automatic door closures delayed for sufficient time to evacuate the area before discharge begins.[7]

(D) Provision of only outward swinging, self-closing doors at exits from hazardous areas, and, where such doors are latched, provision of panic hardware.

(E) Provision of continuous alarms at entrances to such areas until atmosphere has been restored to normal.

(F) Provision for adding an odor to the carbon dioxide so that hazardous atmospheres in such areas may be recognized.

(G) Provision of warning and instruction signs at entrances to and inside such areas.

(H) Provision for prompt discovery and rescue of personnel that may be rendered unconscious or physically impaired in such areas. This may be accomplished by having such areas searched immediately after carbon dioxide discharge stops by trained personnel equipped with proper breathing equipment. Those rendered unconscious by carbon dioxide can be restored without permanent injury by artificial respiration, if removed quickly from the hazardous atmosphere. Self-contained breathing equipment and personnel trained in its use, and in rescue practices including artificial respiration, should be readily available.

(I) Provision of instructions and drills of all personnel in the vicinity of such areas, including maintenance or construction people who may be brought into the area to ensure their correct action when carbon dioxide protective equipment operates.

(J) Provision of means for prompt ventilation of such areas. Forced ventilation will often be necessary. Care should be taken to really dissipate hazardous atmospheres and not merely move them to another location. Carbon dioxide is heavier than air.

(K) Provision of such other steps and safeguards necessary to prevent injury or death as indicated by a careful study of each particular situation.

(L) Provision for mandatory evacuation of the protected area prior to conducting any testing, service, or maintenance on the CO_2 system.

Industrial Risk Insurers (IRI), one of the insurance companies that provides property and business interruption insurance to large Fortune 500 companies such as Ford, General Motors, and Chrysler (IRI 1994), uses NFPA 12 as a basis for their insurance process and has prepared an interpretative guideline to the NFPA 12 Standard (IM 13.3.1). IM 13.3.1 interprets NFPA 12 and also specifies the use of a "system lock-out." A system lock-out is a device that either

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[7] In the next edition of the NFPA 12 Standard this provision will be revised to state that time delays and predischarge alarms that operate prior to discharge should be used (Willms 1999).

mechanically or electrically prevents the system from discharging. Examples of system lock-outs include manually operated valves that block the flow of an agent through downstream pipe work. Similarly, IRI also suggests that for normally unoccupied areas where fast growth fires may occur, a "supervised intermittent time delay" may be desired. Such devices function only when personnel are in the protected area and allow the system to discharge gas only after an extended time delay, thus allowing personnel to egress the area prior to discharge.

International maritime use of carbon dioxide extinguishing systems is extensive. Fire protection in these applications is covered under the regulations and requirements set forth in the International Maritime Organization's SOLAS (IMO 1992). As with NFPA 12, SOLAS does not prevent the use of carbon dioxide in normally occupied areas. Also similar to NFPA, SOLAS requires that "means be provided for automatically giving audible warning of the release of fire-extinguishing medium into a space in which personnel normally work or to which they have access." The alarm must operate for a suitable amount of time prior to the gas being released. Similar to NFPA 12, SOLAS requires that access doors to the areas where fire-extinguishing medium is stored shall have doors that open outwards. These requirements are not differentiated for carbon dioxide or halogenated hydrocarbon or inert gas agent systems. Unlike NFPA, SOLAS mandates that "automatic release of gaseous fire-extinguishing medium shall not be permitted" except with respect to local application systems.

USCG regulations for carbon dioxide systems in passenger vessels are documented in 46 CFR Part 76.15. Separate subparts describe different types of vessels. Similar to SOLAS, 46 CFR Part 76.15 stipulates manual control of cylinder activation.[8] 46 CFR Part 76.15 also requires that systems using more than 300 lb of carbon dioxide must be fitted with an "approved delayed discharge" arranged in such a way that when the alarm sounds the carbon dioxide is not released for at least 20 seconds. This requirement also may pertain to systems of less than 300 lb depending on the number of protected levels and the egress pathway configurations. To minimize the possibility of inadvertent actuations, USCG specifies that two separate manual controls be operated for release of carbon dioxide, thereby requiring two independent actuations to occur before carbon dioxide discharges into the protected space. In addition, all personnel must be evacuated from the protected space prior to performing any testing or maintenance on the carbon dioxide system (Willms 1999).[9]

In land-based workplace environments, OSHA regulates the use of carbon dioxide. These regulations are provided in 29 CFR Parts 1910.160 and 1910.162, which outline the requirements for general and gaseous fixed extinguishing systems, respectively. Despite the fact that the concentration of carbon dioxide needed to extinguish fires is above the lethal level, OSHA does not prevent the use of carbon dioxide in normally occupied areas. (However, OSHA does

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[8] It should be noted that 46 CFR Part 76.15-20 stipulates that "Systems...consisting of not more than 300 lb of carbon dioxide, may have the cylinders located within the space protected. If the cylinder stowage is within the space protected, the system shall be arranged in an approved manner to be automatically operated by a heat actuator within the space in addition to the regular remote and local controls."

[9] The 2000 edition of the NFPA 12 Standard includes a chapter on marine applications mandating evacuation of a space prior to testing and other activities (Willms 1999).

explicitly limit the use of chlorobromomethane and carbon tetrachloride as extinguishing agents where employees may be exposed (29 CFR Part 1910.160 (b) (11).) For carbon dioxide systems, OSHA requires a predischarge alarm for alerting employees of the impending release of carbon dioxide when the design concentration is greater than 4 percent (which is essentially true for all carbon dioxide systems, see Table 1). This predischarge alarm must allow sufficient time delay for personnel to safely exit the area prior to discharge. Although it is speculative, it is likely that these regulations would confer adequate protection only in the event of planned discharge, not accidental discharge. Accidental discharges have occurred, however, in which adherence to regulations has provided personnel protection, whereas some planned discharges have resulted in injury to personnel.

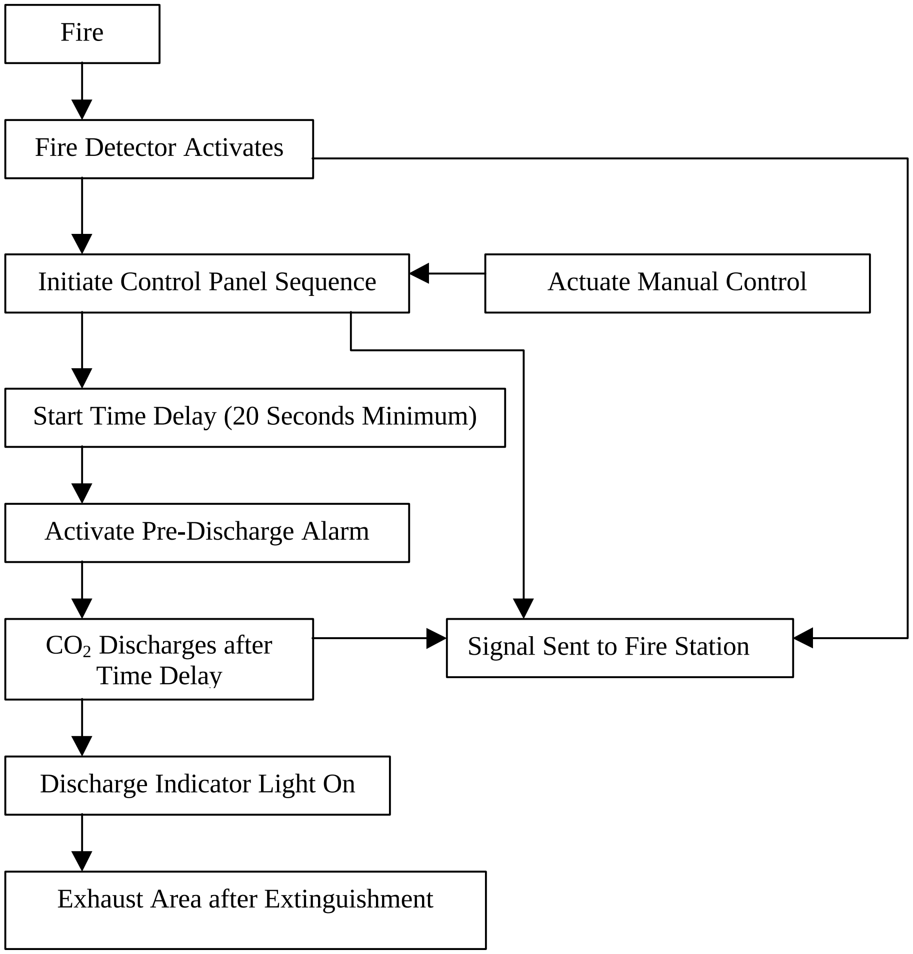
The purpose of the predischarge alarm required by OSHA, NFPA, and SOLAS is to allow occupants time to evacuate an area into which carbon dioxide will be discharged. However, ensuring egress from spaces that are either very large or that have obstacles or complicated passageways has proven to be difficult. Evacuation is particularly difficult once discharge begins because of reduced visibility, the loud noise of discharge, and the disorientation resulting from the physiological effects of carbon dioxide.

In a number of the regulations, concern is given to the possibility of carbon dioxide leaking or flowing into adjacent, low-lying spaces such as pits, tunnels, and passageways. In these cases, carbon dioxide can inadvertently create suffocating atmospheres that are neither visible nor detectable.

Two examples of the ideal fire scenario and how the carbon dioxide systems/safeguards are expected to work are described below for two applications (car parks in Japan and a marine engine room). Carbon dioxide systems are used in Japan in car parks (known in the United States as parking garages) such as tower parking or floor machinery parking, but not in normally occupied car parking facilities, where clean agents are generally used. The enclosed volume of the typical garage facility ranges from 1,000 m^3 to 1,500 m^3 [roughly 35,000 ft^3 to 53,000 ft^3], where 800 kg to 1,125 kg [1,764 lb to 2,480 lb] of carbon dioxide are used. The system operates through automatic discharge with a manual override option. The typical fire scenario for a carbon dioxide system in a tower parking or floor machinery parking facility is shown in Figure 1 (Ishiyama 1998).

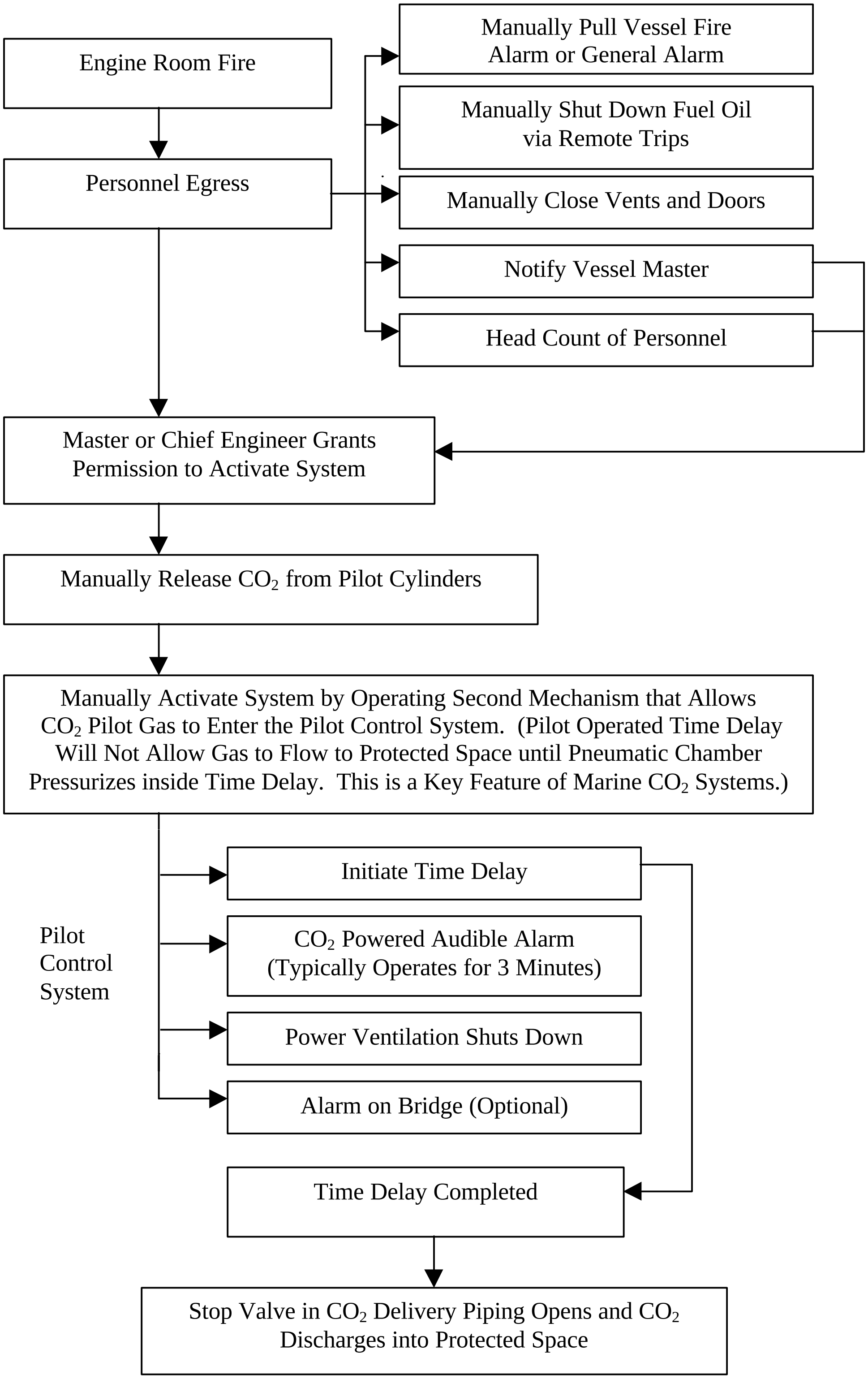
Marine applications, such as engine rooms, are areas where carbon dioxide systems are often used. The typical fire scenario for a carbon dioxide system in a large marine engine room is shown in Figure 2. Most of these systems function through manual activation (except systems containing less than 300 lb [136 kg] of carbon dioxide, which correspond to enclosure volumes less than 6,000 ft^3 [170 m^3]). A typical engine room will be on the order of 250,000 ft^3 [7,079 m^3] and use 10,000 lb [4,536 kg] of carbon dioxide (Gustafson 1998). Despite the safeguards that are required by regulation and meant to guard against injuries associated with carbon dioxide fire extinguishing systems, accidents resulting in injuries and deaths have occurred, primarily caused by not following established safety procedures.

Figure 1. Typical Fire Scenario for a Carbon Dioxide System in a Tower Parking or Floor Machinery Parking Facility



Source: Ishiyama 1998.

Figure 2. Typical Fire Scenario for a Carbon Dioxide System in a Large Marine Engine Room



Source: Gustafson 1998.

Review of Incidents (Accidents/Deaths) Involving Carbon Dioxide as a Fire Extinguishing Agent

A comprehensive review of carbon dioxide incidents in fire protection was undertaken by searching governmental, military, public, and private document archives. The variability in record-keeping practices of various organizations has impacted the success of the data collection effort.

Incident Record Search

Library/Internet Searches Completed

Literature Searches

Two literature searches were conducted. The first literature search (1975-present) was conducted to collect information on incident reports on injuries/deaths associated with carbon dioxide as a fire protection agent. Key words used in the searches included: death(s), incident(s), injury(ies), accident(s), carbon dioxide (or CO_2), fire extinguishing agent(s), fire suppressant(s), maritime, marine, shipping industry, military, civilian, industry(ies), company(ies), firm(s), human, men, worker(s), employee(s), laborer(s). All relevant articles were retrieved. The following databases were searched:

- OSHA 1973-1997
- MEDLINE 1966-1997
- Toxline 1965-1997
- Energy SciTec 1974-1997
- NTIS 1964-1997
- GPO Publications Reference File
- IAC Trade and Industry Database 1976-1997
- Life Sciences Collection 1982-1997
- Ei Compendex 1970-1977
- Wilson Applied Science and Technology Abstracts 1983-1997
- Chemical Safety NewsBase 1981-1997
- GPO Monthly Catalog 1997

A second literature search (1970-1998) was conducted using the DIALOG OneSearch database and general key words (e.g., CO_2, carbon dioxide, and fire suppression) to determine how and where carbon dioxide systems are being used.

National Institute for Occupational Safety and Health (NIOSH) Library Search

A search of the NIOSH database at their library in Cincinnati, Ohio, was conducted.

Internet Search

An Internet search using the same key words used in the library search also was conducted within the following electronic databases:

- Government Printing Office
- FireDoc
- NFPA Online Database

Nuclear Regulatory Commission (NRC)

The NRC public document room was visited to obtain more detailed information on incidents involving commercial nuclear power reactors.

Professional Contacts

Contacts were asked to provide information on incidents concerning human deaths and/or injuries associated with the accidental or intentional discharge of carbon dioxide fire protection systems.[10] Details of the incident (e.g., date, site name, and location of the incident) were requested, as well as a description of the cause of the incident and the number of people injured or killed. Although this information was requested, the amount of information available varied by incident.

Associations/Private Companies/Government Organizations/Research Laboratories

All relevant information was retrieved directly from the following sites and/or from contacts that were identified therein:

- The Society of Fire Protection Engineers
- National Association of Fire Equipment Distributors
- Fire Suppression Systems Association
- Hughes Associates, Inc.
- Kidde International
- Ansul Fire Protection
- Fike Corporation
- Insurance companies that specialize in high-performance risk protection
- National Defense Canada
- U.S. Department of the Navy
- U.S. Department of Energy (DOE)
- USCG
- NIOSH - Division of Safety Research

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[10] Accidental discharges include those occurring during maintenance operations on or near the carbon dioxide system, testing exercises, or those resulting from operator error or a faulty system component. Intentional discharges are generally those occurring in fire situations; however, they also include some discharges during testing exercises or due to a false alarm.

- Center for Global Environmental Technologies, New Mexico Engineering Research Institute (NMERI)
- National Fire Laboratory, Canadian Research Council
- Ship Support Agency, United Kingdom Ministry of Defense
- German Contacts:
    - Association of German Safety Engineers
    - Bavarian Land Institute for Labor Protection
    - Bavarian Land Institute for Medicine
    - Coordinating Office for Labor Protection
    - Directorate of Fire Brigade Affairs
    - Environmental Department (Umweltbundesamt)
    - Federal Labor Association
    - Federal Union of Fire Extinguishers and Installation
    - Federal Union of Professional Safety Engineers
    - Federal Institute for Occupational Safety and Health
    - Fire Shelter Industries
    - German Society of Occupational Health and Hazard
    - German Fire Union
    - Home Office of the Federal State of Baden Württemberg
    - Hygiene Institute
    - Institute of Research for Fire Safety (Universitaet Karlsruhe)
    - Labor Protection and Technical Safety
    - Ministry of Internal Affairs
    - Office of Damage Prevention
    - Union of Safety (Insurance)

- Australian Maritime Safety Authority
- Richard Bromberg, HTOC representative from Brazil[11]
- Matsuo Ishiyama, HTOC representative from Japan
- Syncrude Canada Ltd.
- Loss Prevention Council, U.K.

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[11] A more detailed library search was performed to collect corroborating information on the incident provided by this source.

Search Results

The results of this comprehensive data review are presented in Appendix A. From 1975 to the present, a total of 51 carbon dioxide incident records were located that reported a total of 72 deaths and 145 injuries resulting from accidents involving the discharge of carbon dioxide fire extinguishing systems.[12] All the deaths that were attributed to carbon dioxide were the result of asphyxiation. Details about the injuries were generally not provided in the incident reports, although some OSHA inspections listed asphyxia as the nature of the injury.

Prior to 1975, a total of 11 incident records were located that reported a total of 47 deaths and 7 injuries involving carbon dioxide. Twenty of the 47 deaths occurred in England prior to 1963; however, the cause of these deaths is unknown. Table 2 presents a categorical breakdown of the carbon dioxide incident reports and the deaths/injuries identified.

Although a comprehensive review was performed, it should be noted that data developed through this process may be incomplete because: 1) additional sources of data may be difficult to uncover (e.g., international incidents), 2) records are incomplete, 3) agencies are not required to report, 4) anecdotal information is sketchy and difficult to verify, and 5) fire-related deaths due to CO_2 are generally not well documented.

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[12] Information was requested on any incidents of death or injury resulting from the use of carbon dioxide fire extinguishing systems. Data were requested on both fire- and nonfire-related incidents; however, it was significantly more difficult to gather information on fire-related incidents. Injuries and fatalities from fire situations are generally classified only as fire-related and are not broken down by the fire suppression agent that was used. Therefore, carbon dioxide deaths and injuries from fire-related situations may not be adequately represented. In addition, it should be noted that any discharge of carbon dioxide which resulted in no injuries and/or deaths was not included in the analysis.

Table 2. Search Results

Use Category		Number of Incidents	Deaths	Injuries
United States and Canada				
1975-Present	Military	9	10	15
	Nonmilitary	20	19	73
Before 1975	Military	3	11	0
	Nonmilitary	5	3	3
Total		37	43	91
International				
1975-Present	Military	1	4	5
	Nonmilitary	21	39	52
Before 1975	Military	0	0	0
	Nonmilitary[a]	3	33	4
Total		25	76	61
Total		**62**	**119**	**152**

[a] Included in the total international nonmilitary incidents, deaths, and injuries before 1975 are the 20 deaths resulting from the use of carbon dioxide as a fire suppressant in England from 1945 to the mid 1960s, for which the cause is unknown.

All of the 13 military incidents reported since around 1948 were marine-related. Only 11 of the 49 civilian (commercial, industrial, or state) incidents reported during the same time period were marine-related. The remaining incidents occurred in data processing centers, nuclear power plants, pilot training centers, airplanes, bus garages, emergency unit communication centers, waste storage facilities, underground parking garages, steel rolling mills, motor vehicle assembly lines, and other facilities.

Results presented in Appendix A show that accidental exposure to carbon dioxide during maintenance or testing was found to be the largest cause of death or injury. In some cases, personnel did not follow required safety procedures that may have prevented the injury or death and perhaps even the exposure itself. In several instances, new procedures have been introduced as a result of the incident. The causes of the injuries and/or deaths are summarized in Table 3.

In some cases, maintenance on items other than the fire extinguishing system itself was the cause of the accidental discharge. The most recent reported case occurred at the Test Reactor Area, Idaho National Engineering and Environment Lab (a major DOE site) where carbon dioxide was accidentally released into an electrical switchgear building during routine preventative maintenance on electrical breakers. In another recent incident on a Brazilian oil tanker docked in harbor, a cleaning crew accidentally discharged the carbon dioxide system while working below deck. Similarly, at the Murray Ohio Manufacturing Company, workers discharged the carbon dioxide system while performing an installation near a detector that actuated the system. On the Navy Replenishment Oiler, a maintenance worker lost his footing and stepped on the activation valve while performing maintenance on an overhead light. In these incidents, it was not noted whether preliminary precautionary measures were followed as stated in OSHA, SOLAS, or NFPA guidance. However, in certain other instances, the required precautionary measures were not followed. For example, in the USS Sumter incident, sailors were performing planned maintenance on a carbon dioxide system in a paint locker when the system discharged. Later it was determined that these personnel skipped three of the four preliminary steps on the Maintenance Requirement Card.

In testing and training situations, discharges causing death and injuries were not always accidental. In two reported incidents, the carbon dioxide system was intentionally discharged for testing purposes and the gas escaped into an adjacent area (University of Iowa Hazardous Waste Storage Facility, A.O. Smith Automotive Products Company). In a 1993 incident in Japan, CO_2 was intentionally discharged into an outdoor pit as part of a training exercise. Personnel subsequently entered the pit, unaware of the discharge. Two deaths occurred during a "puff" test of the carbon dioxide system onboard the Cape Diamond cargo vessel. Subsequent investigations indicated that shipboard personnel were not evacuated from the engine room during the test, as should have occurred in accordance with established safety procedures. Furthermore, the main discharge valve was not closed completely, releasing more carbon dioxide than anticipated.

Table 3. Causes of Injuries and/or Death Associated with Carbon Dioxide Discharges After 1975.[a]

Cause of Injuries/Death	Incident	Reference[b]
Accidental Discharge During Maintenance/Repairs to the Carbon Dioxide System	Navy Aircraft Carrier (1993) USS Sumter Turbo Generator Little Creek Naval Navy Aircraft Carrier (1980) Cartercliffe Hall Cargo Vessel Carolina Fire Protection Automated Fire Suppression Systems Autoridad Energia Electrica-Planta Daguao	Darwin 1997 Heath 1993 Allen 1997 Heath 1993 Darwin 1997 Warner 1991 Allen 1997 OSHA 1999 OSHA 1999
Accidental Discharge During Maintenance in the Vicinity of Carbon Dioxide System	Brazilian Oil Tanker Murray Manufacturing Co. Navy Replenishment Oiler Oiler Kalamazoo Navy Submarine Tender SS Lash Atlantico Stevens Technical Services Inc. Test Reactor Area, Idaho National Engineering and Environment Lab	Bromberg 1998 McDonald 1996 Darwin 1997 Heath 1993 Darwin 1997 Hager 1981 OSHA 1999 Caves 1998
Accidental Discharge During Testing	Cape Diamond	Marine Casualty Investigation Report 1996
Accidental Discharge During Fire Situation	LNG Carrier Surry Nuclear Power Station	Paci 1996 Warnick 1986
Accidental Discharge from Faulty Installation or System Component	Dresden Sempergalerie Hope Creek	Drescher and Beez 1993 Caves 1998
Accidental Discharge from Operator Error	French Data Center Car Park (Japan)	Gros et al. 1987 Ishiyama 1998
Accidental Discharge - False Alarm	Consolidated Edison Co. Barge Meredith/Burda Corporation	OSHA 1998 OSHA 1999
Intentional Discharge During Testing/Training	U. of Iowa Hazardous Waste Storage Facility Japanese Outdoor Pit A.O. Smith Automotive Products Company	Bullard 1994 Ishiyama 1998 OSHA 1999
Intentional Discharge During Fire Situation	Navy Aircraft Carrier (1966) Australian Naval Ship Westralia Airline Constellation Ravenswood Aluminum Corporation Muscle Shoals Construction Site	Darwin 1997 Webb 1998 Gibbons 1997 OSHA 1999 OSHA 1999
Intentional Discharge - False Alarm	Japan	Ishiyama 1998

[a] Incidents where the cause of discharge was uncertain are not included in the table.

[b] References from Table 3 are listed in Appendix A.

Examining the Risks Associated with Carbon Dioxide Extinguishing Systems

The risk involved with the use of carbon dioxide systems is based on the fact that the level of carbon dioxide needed to extinguish fires (and, thus, to protect an enclosure) is many times greater than the lethal concentration. For instance, the minimum design concentration to suppress a propane fire is 36 percent. This concentration of carbon dioxide can produce convulsions, unconsciousness, and death within several seconds. Since carbon dioxide cylinder store rooms are often relatively small compared to the protected areas, inadvertent discharges into these store rooms will also produce levels much higher than the lethal level. Because the consequences of exposure happen quickly and without warning, there is little or no margin for error.

It is intended that total flooding carbon dioxide systems be designed such that human exposure does not occur during fire-fighting scenarios. Predischarge alarms and time delays are prescribed in NFPA 12, OSHA, and SOLAS guidelines to prevent such exposure. Hence, relatively few accidents involving carbon dioxide systems occur during fire events; rather, accidents most often occur during maintenance of the carbon dioxide system itself, during maintenance around the carbon dioxide system, or to a more limited extent, during testing of the fire suppression system. Of the accidental discharges that occurred during maintenance, results of the survey indicated that the deaths and/or injuries from carbon dioxide exposure were caused by: 1) inadvertently actuating the system because there was a lack of adequate safety procedures to prevent such discharges, 2) failure to adhere to safety procedures, or 3) low technical proficiency of personnel in the vicinity of the carbon dioxide system.

Although the risk associated with the use of carbon dioxide for fire protection in protected enclosures is fairly well understood by regulators, standard-setting bodies, and insurers, the risk of carbon dioxide may not be well understood by the maintenance workers who perform functions on or around carbon dioxide systems. The failure to adhere to prescribed safety measures is a demonstration of this lack of understanding and appreciation of the dangers associated with carbon dioxide. Precautionary measures must be mandated to ensure that personnel follow strict guidelines, even if those personnel are simply entering the storage areas where the carbon dioxide system cylinders and components are being housed.

This point is exemplified by the German experience with the use of carbon dioxide in fire protection. In Germany, a large number of carbon dioxide systems are used to protect facilities and installations. Most of these are equipped with automatic release of carbon dioxide, even in occupied spaces. Despite the relative abundance of carbon dioxide systems in Germany and an exhaustive search of German records for accidents involving carbon dioxide, only one reported nonfire event was found. Personal communication with a number of sources (Brunner 1998, Schlosser 1997, Lechtenberg-Autfarth 1998) supports the finding that relatively few accidents during nonfire events have occurred with carbon dioxide in Germany. (It should be noted, however, that accidents during fire events were more difficult to locate because German data sources did not distinguish between fatalities and injuries caused by the fire and fatalities and injuries caused by the use of carbon dioxide.) The good safety record of the German experience may be attributed to their approach in installing and operating carbon dioxide systems.

In Germany (and much of Europe), unlike in the United States, only certified carbon dioxide-specialized installers are allowed to install the carbon dioxide systems. Once the system is installed, it is checked and approved by VdS Schadenverhütung (VdS), an approval body much like Factory Mutual. Regulations on system operations are strictly enforced and ensure that time delays are adequate to allow egress, that the alarms are functioning properly, and that rules and warnings are posted in the vicinity of the carbon dioxide system. Approval is granted to use the system only if it meets all the standards and requirements. In addition, according to the Comité Européen des Assurances (CEA),[13] the carbon dioxide installation and protected risk are required to be inspected at least once a year by an expert of the AHJ (CEA 1997).

In addition to the system of double and triple checks imposed by the German authorities, the prevalence of carbon dioxide use in Germany may have provided increased awareness and education of the agent's risks and dangers.

Because of the widespread use of Halon 1301 in the United States, which is safer than carbon dioxide at fire-fighting concentrations, there may be a lower awareness of the hazards surrounding carbon dioxide use. Experience has shown that a relatively higher margin of safety has been experienced with the use of Halon 1301 compared to carbon dioxide. This high safety margin may add to the lack of awareness of the dangers involved with using carbon dioxide systems.

Conclusion and Recommendations

A review of accidental deaths or injuries related to carbon dioxide use in fire protection indicates that the majority of reported incidents occurred during maintenance on or around the carbon dioxide fire protection system. In many of the situations where carbon dioxide exposure led to death or injury during maintenance operations, the discharge resulted from personnel inadvertently touching, hitting, or depressing a component of the system. In some cases, personnel did not adhere to the precautionary measures prescribed. In other cases, the safety measures were followed, but other accidental discharge mechanisms occurred.

Examination of the accident records shows that a disproportionately large number of accidents involving carbon dioxide have occurred on marine vessels. A number of factors may play a part in these occurrences. First, a limited number of personnel on the ship's crew have training and authority to activate the carbon dioxide system (Gustafson 1998). These few crew members are very well trained regarding the system's operation, however, the remaining personnel would not have the same level of sophisticated knowledge. In particular, new crew members and contracted maintenance workers may be unfamiliar with a ship's particular installation, even if they are aware of the potential dangers of carbon dioxide systems in general. This unfamiliarity could result in an inadvertent actuation, and it is therefore important that ship operators provide instruction on and require adherence to ship-specific procedures (Hansen 1999). The lack of training may cause certain personnel to touch, tamper, or hit system components, which then trigger activation. In addition, untrained personnel may disregard warning signs or alarms because they have not been adequately informed of the hazards. In addition, because of the design of many shipboard systems, the manual activation mechanism is sometimes a cable connected from a lever to the actuation

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[13] The CEA is the federation of national insurance company associations in European market economy countries (CEA 1997).

device. In some designs the cable is not enclosed in a protective casing where it attaches to the pilot cylinders. The exposed nature of this device makes accidental deployment easier. In most system designs, however, the cable runs in conduit with pulleys to provide for turns and bends in the cable run. Furthermore, two separate controls are necessary to activate USCG-approved shipboard systems over 300 lb, thereby reducing the risk of accidental discharge resulting from exposed cables (Wysocki 1999).

Another factor influencing the safety record of marine applications is the nature of the regulatory requirements governing use of carbon dioxide systems. Maritime regulations (46 CFR Part 76.15 and SOLAS) do not provide detailed requirements to ensure safety of personnel. These maritime regulations can be contrasted with the NFPA standard that has more specific suggestions to protect personnel against the adverse effect of carbon dioxide. Improvement of maritime regulations would at least provide specific requirements that would presumably help reduce the accidental exposures that occur in marine applications.

Additionally, in certain instances language barriers may present a source of additional risk. For example, if signage and training manuals are available only in English, non-English-reading personnel may not receive adequate or timely warning. Hence, making these materials available in the predominant language of non-English-reading workers may help to educate personnel and thereby reduce risks.

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APPENDIX A

Death and Injury Incidence Report

DEATH AND INJURY INCIDENCE REPORTS ASSOCIATED WITH CARBON DIOXIDE TOTAL FLOODING FIRE EXTINGUISHING SYSTEMS

	Name/Site	Date	Location	Use Category	Number Killed	Number Injured	Summary of Cause	Sources
UNITED STATES AND CANADA[14]								
1	Test Reactor Area, Idaho National Engineering and Environment Lab	July 28, 1998	Idaho	Government-Owned Test Facility	1	13	The CO_2 system in an electrical switchgear building of the Engineering Test Reactor Building complex unexpectedly actuated during routine preventative maintenance on an electrical system.	Caves 1998 The Idaho Statesman 1998
2	Consolidated Edison Co.	February 15, 1996	New York	Commercial	1	0	A false fire trip of the system occurred on a barge used to generate electricity. The victim was probably overcome while working to reset a CO_2 distribution valve and a plunger controlling the switch for the ventilation system.	OSHA 1998
3	University of Iowa Hazardous Waste Storage Facility	June 16, 1994	Iowa City, IA	State	0	2	A fire suppression system test released too much CO_2. During the release, a door was blown open and CO_2 escaped into an adjacent area.	Bullard 1994
4	Murray Ohio Manufacturing Company	December 31, 1993	Lawrenceburg, TN	Commercial	0	2	A total flooding CO_2 system accidentally discharged during installation of a new piece of duct work on a flammable liquid paint spray booth (located near the CO_2 detector).	McDonald 1996
5	M/V Cape Diamond/Norshipco	March 3, 1993	Norfolk, VA	Military	2	6	The injuries and fatalities occurred during a “puff” test of the ship’s low pressure CO_2 fire suppression system. Reports indicated that personnel had not been evacuated from the engine room during the test, and that the main discharge valve was not closed completely, releasing more carbon dioxide than anticipated.	Hurley 1996 Marine Casualty Investigation Report 1996 Willms 1999
6	Navy Aircraft Carrier	January 16, 1993	In Port, U.S.	Military	0	3	A CO_2 fire suppression system was accidentally tripped during routine maintenance.	Darwin 1997
7	Navy Ship USS Sumter/Little Creek Naval Amphibious Base	July 30, 1992	Norfolk, VA	Military	2	1	Three sailors were performing planned maintenance on a CO_2 system in a paint locker when the system discharged. They were asphyxiated and two died. The sailors skipped three of the four preliminary steps on the Maintenance Requirement Card.	Heath 1993

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[14] North American incidents are listed in reverse chronological order.

	Name/Site	Date	Location	Use Category	Number Killed	Number Injured	Summary of Cause	Sources
8	Muscle Shoals Construction Site	September 26, 1991	Muscle Shoals, Alabama	Commercial	1	2	An employee was performing construction work in an oil filtration building when the CO_2 fire suppression system was activated in response to a fire. The employee was trapped and died from asphyxia. The CO_2 seeped into the basement of another building where two other employees were working. The two employees regained consciousness.	OSHA 1999
9	Autoridad Energia Electrica-Planta Daguao	April 3, 1991	San Juan, PR	State Government	0	2	A fixed extinguishing system was accidentally activated during installation of CO_2 cylinders. The employees were untrained and failed to follow procedures regarding connection of the control head on the cylinder valve.	OSHA 1999
10	Preserver Warship	January 14, 1991	Quebec City, Canada	Commercial	1	5	The fatality was due to an accidental discharge of the CO_2 fire extinguishing system.	Sinclair 1997 Warner 1991
11	Ravenswood Aluminum Corporation	June 18, 1990	Ravenswood, WV	Commercial	2	0	The CO_2 system was triggered by a small fire on the cold rolling mill. Two security guards attempted to enter the basement underneath the mill to reset the system 6 hours later. There was a known concentration of CO_2 in the basement but the self-contained breathing apparatus (SCBA) units were left in the guards' vehicle. The guards collapsed when they reached the bottom of the stairwell leading to the basement, where they died.	OSHA 1999
12	Lukens Steel Company	July 14, 1988	Conshohocken, PA	Commercial	1	0	The fire suppression system for the rolling mill was manually released, allowing CO_2 into the oil cellar. The safety doors on the cellar did not close and permitted CO_2 into the hallway, where the employee was found.	OSHA 1999
13	Oiler Kalamazoo	1987	Kalamazoo, MI	Military	1	0	Sailors changing a light bulb in a paint locker hit the CO_2 switch by accident.	Heath 1993
14	Meredith/Burda Corporation	December 3, 1987	Casa Grande, AZ	Commercial	0	15	A false alarm resulted in the release of a CO_2 fixed extinguishing system in a press room. The overhead door was opened to ventilate the room because of a malfunction of the manual shut-off valve. The CO_2 spread into the fire brigade room across the hall from the open door, exposing personnel to the gas.	OSHA 1999
15	Navy Replenishment Oiler	January, 1987	At Sea, U.S.	Military	1	0	During maintenance on the overhead lighting system, a worker lost his footing and accidentally stepped on the activation valve.	Darwin 1997
16	Surry Nuclear Power Station	December 9, 1986	Richmond, VA	Commercial	4	4	An accidental discharge of both the CO_2 and Halon extinguishing systems was caused by water damage to the extinguishing system control panels. The water came from a pipe break in the feedwater system. Four died and four were injured in a fire associated with the accident. However, it is not clear if the release of the gases from fire extinguishing systems were responsible for these injuries and deaths.	Sinclair 1997 Warnick 1986

	Name/Site	Date	Location	Use Category	Number Killed	Number Injured	Summary of Cause	Sources
17	Stevens Technical Services Inc.	March 5, 1986	Bronx, NY	Commercial	1	0	The CO_2 cylinders for a fire suppression system accidentally discharged into the chamber in which they were stored. Upon entering the chamber, the employee was asphyxiated.	OSHA 1999
18	A.O. Smith Automotive Products Company	November 29, 1985	Milwaukee, WI	Commercial	1	0	During a test discharge of the CO_2 fire suppression system, the gas entered a larger space than anticipated by personnel, resulting in the death of one employee. Only one of the three employees conducting the test discharge was wearing a respirator.	OSHA 1999
19	Hope Creek Generating Station	September 4, 1985	Hancocks Bridge, NJ	Commercial Nuclear Power Reactor	0	23	Carbon dioxide (10 tons) was inadvertently discharged into a diesel generator fuel storage area. The warning bell and beacon light did not operate and workers who were cleaning the corridor walls outside of the fuel storage room with air/water guns under pressure were not alerted. The cause of the discharge was determined to be moisture (that entered the CO_2 control panel through openings at the top of an inadequately installed protective panel) that shorted the CO_2 control panel circuitry. The moisture was believed to have originated from the workers cleaning the corridor walls.	U.S. NRC 1985 Caves 1998 OSHA 1999
20	Automated Fire Suppression Systems Ford Motor Company	October 13, 1984	Hapevilles, GA	Commercial	1	1	During work on the CO_2 suppression system protecting the pit under the gas fill at the end of the chassis line, 18 50-lb bottles and 6 75-lb bottles of the gas were accidentally discharged. One employee was trapped in the pit and a second employee passed out in an attempt to rescue him.	OSHA 1999
21	Navy Repair Ship	April 29, 1982	At Sea, U.S.	Military	0	1	A CO_2 fire suppression system was accidentally tripped during routine maintenance.	Darwin 1997
22	Turbo Generator	1981	U.S.	Commercial	0	1	An employee was checking an extended-discharge system protecting a turbo-generator (under the acoustical hood) when the system accidentally discharged. A transformer vault was total-flood protected by the same system, employing a total of 1,800 lb of CO_2.	Allen 1997
23	Dry-Docked SS Lash Atlantico at the Sun Ship, Inc. Yard	June 9, 1981	Chester, PA	Commercial	3	2	The CO_2 fire suppression system was tripped accidentally during welding work in the engine room. The system discharged CO_2 and automatically shut the compartment doors, trapping the workers in the engine room.	Hager 1981
24	Little Creek Naval Amphibious Base	1980	Norfolk, VA	Military	2	0	Similar to the USS Sumter incident described above (reference #7), the victims ignored preliminary steps on the Maintenance Requirement Card.	Heath 1993
25	Carolina Fire Protection	1980	North or South Carolina	Commercial	1	0	An employee of Carolina Fire Protection was checking a CO_2 system in a bus garage when the system accidentally discharged.	Allen 1997
26	Navy Aircraft Carrier	June 20, 1980	At Sea, U.S.	Military	1	2	During routine maintenance on the system, heavy seas caused a worker to fall and accidentally grab the conduit through which the CO_2 system activation cord ran.	Darwin 1997

	Name/Site	Date	Location	Use Category	Number Killed	Number Injured	Summary of Cause	Sources
27	Bulk Cargo Vessel Cartercliffe Hall	May, 1980	Quebec City, Canada	Commercial	1	0	Accidental discharge during repairs resulted in a fatality.	Sinclair 1997 Warner 1991
28	Navy Submarine Tender	March 26, 1979	In port under construction at a private shipyard, U.S.	Military	1	2	The ship was not in commission and was undergoing construction. Civilian shipyard workers were painting the space behind the cage containing the CO_2 cylinders when one worker accidentally pulled the release cable.	Darwin 1997
29	Airline Constellation	1977	U.S.	Commercial	0	1 or more	Crew members responded to a fire alarm in the plane's cargo compartment by releasing CO_2. The CO_2 also entered the cockpit and partially incapacitated one or more of the crew.	Gibbons 1977 CAB 1948
30	Navy Yard Oil Barge	March 22, 1972	In Port, U.S.	Military	2	0	Maintenance workers were replacing the CO_2 cylinders and accidentally discharged old cylinders during removal.	Darwin 1997
31	Ship (Name Unknown)	1970s	Anchorage, AK	Commercial	0	1	The automatic features of the CO_2 system had been disabled on the ship during repairs. A painter aboard the ship accidentally hit the trip lever and the system discharged.	Vining 1997
32	Navy Fleet Oiler	March 21, 1969	At Sea, U.S.	Military	1	0	A CO_2 fire suppression system was accidentally tripped during routine maintenance.	Darwin 1997
33	Navy Aircraft Carrier	November 4, 1966	At Sea, U.S.	Military	8	0	The CO_2 system tripped in response to a fire. The victims were in a compartment separate from the fire, and did not realize that the CO_2 would be released into their location.	Darwin 1997
34	Pan American Pilot Training Center	Late 1960s	Miami, FL	Commercial	0	2	A CO_2 system was being tested in a shop at the Pilot Training Center. Two pilots were working on a radio in the shop, unbeknownst to the testers. When the discharge sequence started, they ignored the flashing red lights, horn, and illuminated sign.	Vining 1997
35	Columbia Geneva Steel Rolling Mill (now USS Posco Industries)	Before 1954	Pittsburg, CA	Industrial	2	0	Two workers were killed by a CO_2 fire extinguishing system.	Vining 1997
36	DC-6 Airplane	1948	U.S.	Commercial	43[15]	0	A DC-6 crashed killing all the passengers. The last transmission indicated that the CO_2 fire extinguishers had been released in the forward cargo pit moments before the crash. It is not clear if any of the deaths can be directly attributed to CO_2 exposure.	CAB 1948 Gibbons 1977
37	Biscayne Fire	N/A	Miami, FL	Commercial	1	0	An employee of Biscayne Fire died while servicing a CO_2 system in the engine compartment of a large cruiser boat.	Allen 1997

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[15] These deaths are attributed to the plane crash and are not included in the calculations of the total number of deaths from CO_2 exposure.

	Name/Site	Date	Location	Use Category	Number Killed	Number Injured	Summary of Cause	Sources
1975 - PRESENT INCIDENT TOTALS		29 Incidents		9 Military 20 Nonmilitary	29 Deaths	88 Injuries		
BEFORE 1975 INCIDENT TOTALS		8 Incidents[16]		3 Military 5 Nonmilitary	14 Deaths	3 Injuries		
TOTAL DOMESTIC		37 Incidents		12 Military 25 Nonmilitary	43 Deaths	91 Injuries		

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[16] This number includes two incidents for which the date is not specified (references #35 and #37).

	Name/Site	Date	Location	Use Category	Number Killed	Number Injured	Summary of Cause	Sources
INTERNATIONAL[17]								
38	Australian Naval Ship Westralia	April, 1998	Indian Ocean off the coast of Fremantle, Australia	Military	4	5	Four sailors were repairing a fuel leak in the engine room when the fuel ignited and started a fire. The room was sealed and flooded with CO_2.	Webb 1998
39	Oil Tanker	1994/95?	Angra dos Reis, Brazil	Commercial	11	0	A cleaning team working below deck accidentally tripped the CO_2 system.	Bromberg 1998
40	Unknown	Before 1963	England	Unknown	20	Unknown	A total of 20 deaths occurred in England prior to 1963 due to the use of CO_2.	Young 1998
41	French Data Processing Center	December 25, 1986	France	Commercial	1	0	A fatal accident occurred in a data processing center in its developmental stages. The operator activated the CO_2 extinguishing manual trigger switch instead of an automatic-manual rocker switch.	Gros et al. 1987
42	Dresden Sempergalerie	January 14, 1993	Dresden, Germany	Commercial	2	10	A faulty installation allowed a climate technician at the gallery to choose the CO_2 release button. In 11 minutes 3700 kg of gas was released in public areas and 12 people began to suffer from asphyxiation, 2 later died. The installers of the fire suppressant system were held accountable.	Drescher and Beez 1993 Paech 1995
43	LNG Carrier SNAM Portovenere	October 2, 1996	Genoa, Italy	Commercial	6	3	A technician aboard the carrier accidentally activated the CO_2 extinguisher during a fire. The discharge saturated 85% of the engine room within 2 minutes. Six men who were fighting the fire with hand extinguishers were killed.	Paci 1996
44	Car Park Building	October 19, 1996	Japan	Commercial	0	4	An inadvertent discharge occurred during maintenance activities.	Ishiyama 1998
45	Power Station	May 18, 1996	Japan	Commercial	0	4	An inadvertent discharge occurred during repair work.	Ishiyama 1998
46	Car park Building	December 1, 1995	Japan	Commercial	2	1	A child locked in the space pushed the discharge button. Guards entered the space in response.	Ishiyama 1998
47	Building	October 18, 1995	Japan	Commercial	0	3	An inadvertent discharge occurred during maintenance activities.	Ishiyama 1998
48	Outdoor pit	November 5, 1993	Japan	Commercial	1	0	CO_2 was discharged during a training session in an outdoor pit. Personnel entered the pit unaware of the discharge.	Ishiyama 1998
49	Underground Power Station	October 12, 1993	Japan	Commercial	1	0	A repair worker accidentally cut a system wire causing a discharge of CO_2. Personnel entered the space after the discharge.	Ishiyama 1998
50	Building	February 5, 1991	Japan	Commercial	0	2	An inadvertent discharge occurred during maintenance activities.	Ishiyama 1998

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[17] International incidents are listed in alphabetical order by country.

	Name/Site	Date	Location	Use Category	Number Killed	Number Injured	Summary of Cause	Sources
51	Building	November 9, 1987	Japan	Commercial	0	4	A false alarm resulted in a manual discharge of the system.	Ishiyama 1998
52	Building	August 9, 1987	Japan	Commercial	3	0	An inadvertent discharge occurred during maintenance activities.	Ishiyama 1998
53	Underground Car Park	June 9, 1987	Japan	Commercial	2	3	An inadvertent discharge occurred during maintenance activities.	Ishiyama 1998
54	Building	September 5, 1986	Japan	Commercial	1	0	An inadvertent discharge occurred during maintenance activities.	Ishiyama 1998
55	Cargo Ship	June 24, 1986	Japan	Commercial	8	5	An inadvertent discharge occurred during maintenance activities.	Ishiyama 1998
56	Underground Car Park	September 5, 1985	Japan	Commercial	0	3	An inadvertent discharge occurred during maintenance activities.	Ishiyama 1998
57	Building	January 8, 1982	Japan	Commercial	0	3	Personnel entered the building following discharge.	Ishiyama 1998
58	Building	January 25, 1978	Japan	Commercial	0	3	An inadvertent discharge occurred during maintenance activities.	Ishiyama 1998
59	Building	June 16, 1977	Japan	Commercial	1	1	An inadvertent discharge occurred during repair work.	Ishiyama 1998
60	Building	November 19, 1975	Japan	Commercial	0	3	An inadvertent discharge occurred during maintenance activities.	Ishiyama 1998
61	Car Park Building	October 29, 1971	Japan	Commercial	1	1	Caused by operator.	Ishiyama 1998
62	Norwegian shipyard	1970	Norway	Commercial	12	3	Twelve crew members died in the ship's engine room (while conducting routine assembly and repair work) when they were exposed to an undetected CO_2 leak from a fire-extinguishing system.	Jorde 1973
1975 - PRESENT INCIDENT TOTALS		22 Incidents		1 Military 21 Nonmilitary	43 Deaths	57 Injuries		
BEFORE 1975 INCIDENT TOTALS		3 Incidents		0 Military 2 Non-military 1 Unknown	33 Deaths	4 Injuries		
TOTAL INTERNATIONAL		25 Incidents		1 Military 23 Nonmilitary 1 Unknown	76 Deaths	61 Injuries		

	Name/Site	Date	Location	Use Category	Number Killed	Number Injured	Summary of Cause	Sources
INCIDENT FINAL TOTALS		62 Incidents	37 Domestic 25 International	13 Military 48 Nonmilitary 1 Unknown	119 Deaths	152 Injuries		

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APPENDIX B

Overview of Acute Health Effects

APPENDIX B – Overview of Acute Health Effects

Appendix B presents an overview of the acute health effects associated with carbon dioxide. Part I discusses the dangerous, lethal effects of carbon dioxide at high exposure concentrations. The minimum design concentration of carbon dioxide for a total flooding system is 34 percent (340,000 ppm). When used at this design concentration, carbon dioxide is lethal. Part II discusses the potentially beneficial effects of carbon dioxide at low exposure concentrations and the use of added carbon dioxide in specialized flooding systems using inert gases.

PART I: Acute Health Effects of Carbon Dioxide

Carbon dioxide acts as both a stimulant and depressant on the central nervous system (OSHA 1989, Wong 1992). Table B-1 summarizes the acute health effects that are seen following exposure to high concentrations of carbon dioxide. Exposure of humans to carbon dioxide concentrations ranging from 17 percent to 30 percent quickly (within 1 minute) leads to loss of controlled and purposeful activity, unconsciousness, coma, convulsions, and death (OSHA 1989, CCOHS 1990, Dalgaard et al. 1972, CATAMA 1953, Lambertsen 1971). Exposure to concentrations from greater than 10 percent to 15 percent carbon dioxide leads to dizziness, drowsiness, severe muscle twitching, and unconsciousness within a minute to several minutes (Wong 1992, CATAMA 1953, Sechzer et al. 1960).

Exposure to 7 to 10 percent carbon dioxide can produce unconsciousness or near unconsciousness within a few minutes (Schulte 1964, CATAMA 1953, Dripps and Comroe 1947). Other symptoms associated with the inhalation of carbon dioxide in this range include headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing, mental depression, shaking, and visual and hearing dysfunction that were seen following exposure periods of 1.5 minutes to 1 hour (Wong 1992, Sechzer et al. 1960, OSHA 1989). In a study of 42 human volunteers, following inhalation of 7.6 and 10.4 percent carbon dioxide for short periods of time (2.5 to 10 minutes), it was reported that only about 30 percent of the subjects complained of difficult breathing (dyspnea), although respiration was vigorously stimulated (Lambertsen 1971, Dripps and Comroe 1947). In this study, the most common symptoms were headache and dizziness (Lambertsen 1971, Dripps and Comroe 1947). Other symptoms described included mental clouding or depression, muscle tremors or twitching, tingling or cold extremities, and exhaustion (Lambertsen 1971, Dripps and Comroe 1947). Confusion to the point of unconsciousness was reported in several subjects at both concentrations (Lambertsen 1971). Increasing concentrations of carbon dioxide up to 7.5 percent for a period of 20 minutes had no significant effects on accuracy of reasoning and short-term memory, although speed of performance of reasoning tasks was significantly slowed at the higher levels (Sayers et al. 1987).

Exposure to a concentration of 6 percent carbon dioxide can produce hearing and visual disturbances within 1 to 2 minutes (Gellhorn 1936, Gellhorn and Spiesman 1935). Acute exposures (minutes) to 6 percent carbon dioxide affected vision by decreasing visual intensity discrimination in 1 to 2 minutes (Gellhorn 1936) and resulted in a 3 to 8 percent decrease in hearing.

Table B-1. Acute Health Effects of High Concentrations of Carbon Dioxide

Carbon Dioxide Concentration (Percent)	Time	Effects
17 - 30	Within 1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death
>10 – 15	1 minute to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness
7 – 10	Few minutes	Unconsciousness, near unconsciousness
	1.5 minutes to 1 hour	Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing
6	1 – 2 minutes	Hearing and visual disturbances
	≤16 minutes	Headache, dyspnea
	Several hours	Tremors
4 – 5	Within a few minutes	Headache, dizziness, increased blood pressure, uncomfortable dyspnea
3	1 hour	Mild headache, sweating, and dyspnea at rest
2	Several hours	Headache, dyspnea upon mild exertion

threshold in six human subjects (Gellhorn and Spiesman 1935). Headache and dyspnea were also seen during a 16-minute exposure to 6 percent carbon dioxide in air or oxygen (White et al. 1952, Wong 1992). Tremors were produced in human subjects exposed to 6 percent carbon dioxide for several hours (Schulte 1964). Mental depression occurred following exposures (several hours) to 5 percent carbon dioxide (Schulte 1964, Consolazio et al. 1947). Exposure to 4 to 5 percent carbon dioxide for 15 to 32 minutes can produce headache and dizziness, increased blood pressure, and can produce uncomfortable dyspnea within a few minutes (Schulte 1964, Schneider and Truesdale 1922, Patterson et al. 1955).

A concentration of 3 percent carbon dioxide produced headache, diffuse sweating, and dyspnea at complete rest after an exposure period of several hours (Schulte 1964). Sinclair et al. (1971) showed that 1-hour exposures of 4 human volunteers to 2.8 percent carbon dioxide resulted in occasional mild headaches during strenuous, steady-state exercise. Menn et al. (1970) found that in 30-minute exposures to 2.8 percent carbon dioxide, dyspnea was detected in 3 out of 8 human volunteers during maximal exercise, but not during half-maximal or two-thirds maximal exercise. After several hours exposure to atmospheres containing 2 percent carbon dioxide, headache and dyspnea can occur with mild exertion (Schulte 1964). Table B-2 shows the physiological tolerance time for various carbon dioxide concentrations in healthy males under exercising conditions. Short-term exposures (5 to 22 minutes) to carbon dioxide-air mixtures (2 percent to 8.4 percent carbon dioxide) also caused a distinct hearing loss at ≥3 percent carbon dioxide (Gellhorn and Spiesman 1934, 1935). No effect on the hearing threshold was observed at 2.5 percent (Gellhorn and Spiesman 1935).

Table B-2. Physiological Tolerance Time for Various Carbon Dioxide Concentrations

Concentration of Carbon Dioxide in Air (percent by Volume)	**Maximum Exposure Limit (Minutes)**
0.5	*indefinite*
1.0	*indefinite*
1.5	*480*
2.0	*60*
3.0	*20*
4.0	*10*
5.0	*7*
6.0	*5*
7.0	*Less than 3*

Source: Compressed Gas Association 1990.

Carbon dioxide is normally present in the atmosphere at a concentration of 0.03 percent (NFPA 12, Wong 1992). It is also a natural end product of human and animal metabolism. As a result, carbon dioxide dramatically influences the function of major vital processes, including control of breathing, vascular dilation or constriction (particularly in certain brain tissues), and body fluid pH.

The most familiar effect of inhaled carbon dioxide is its stimulant action upon respiration (Lambertsen 1971). The respiratory system acts as a physiologic buffer system (Jensen 1980). It is controlled by a typical feedback mechanism where the respiratory center responds directly to alterations in blood pH (i.e., changes in blood H^+ concentrations), and the alveolar ventilation rate in turn can regulate H^+ concentration. When blood H^+ concentrations rise above normal levels, alveolar ventilation is stimulated, and the concentration of carbon dioxide in the blood is reduced. The H^+ concentration falls toward normal level, eliminating the stimulus to an increased ventilatory rate. Greatly elevated carbon dioxide concentrations can lead to respiratory acidosis if the capacity of the blood buffering system is exceeded. In response, respiratory excretion of carbon dioxide occurs rapidly through an increase in the ventilation rate.

Immediately after exposure to elevated carbon dioxide levels, the minute ventilation, tidal volume (total volume of air inhaled and exhaled during quiet breathing), alveolar carbon dioxide, and acidity of the blood are elevated (Glatte et al. 1967). Acute exposure to 1 percent and 1.5 percent carbon dioxide is tolerated quite comfortably. Very little noticeable respiratory stimulation occurs until the inspired carbon dioxide concentration exceeds about 2 percent (Glatte et al. 1967, Lambertsen 1971). At 3 percent carbon dioxide, measurable increases in pulmonary ventilation, tidal volume, and arterial P_{CO_2} occur (Glatte et al. 1967). Respiratory stimulation then increases sharply until inspired carbon dioxide concentrations of about 10 percent are reached (Lambertsen 1971). Between 10 and 30 percent inspired carbon dioxide, the increase in respiratory minute volume (the product of tidal volume and respiratory rate) is less per unit of rise in inspired carbon dioxide than with the lower concentrations (Lambertsen 1971). Within 1.5 minutes of inhalation of 30 percent carbon dioxide in oxygen, ventilation suddenly declines, and convulsions occur (Lambertsen 1971).

Carbon dioxide also affects the circulatory system. If the concentration of carbon dioxide in the inspired air increases, the body will compensate by increasing the respiratory depth and rate with an accompanying increase in cardiac output (Schulte 1964). If the carbon dioxide in the breathing atmosphere continues to increase, the increases in cardiac and respiratory rates cannot effectively compensate (i.e., eliminate carbon dioxide) and carbon dioxide will accumulate in the blood and other body tissues (Schulte 1964). A short-term exposure of 17 to 32 minutes in humans to 1 or 2 percent carbon dioxide has been shown to cause a slight increase in systolic and diastolic pressure (Schneider and Truesdale 1922). A 15 to 30 minute exposure to 5 or 7 percent carbon dioxide caused increases in blood pressure and cerebral blood flow and a decrease in cerebrovascular resistance but no change in cardiac output (Kety and Schmidt 1948). However, in another study, exposure to 7.5 percent carbon dioxide for 4 to 25 minutes showed an increase in cardiac output and blood pressure (Grollman 1930). Dripps and Comroe (1947) studied the respiratory and circulatory responses of 42 normal young men to inhalation of 7.6 and 10.4 percent carbon dioxide for 2.5 to 10 minutes. Inhalation of both 7.6 and 10.4 percent carbon dioxide increased the average minute volume of respiration, pulse rate, and blood pressure. Acute exposures to higher concentrations of carbon dioxide (30 to 70 percent carbon dioxide for 38 seconds) may result in electrocardiogram changes (Wong 1992).

PART II: Effects of Added Carbon Dioxide at Low Concentrations

Carbon dioxide is useful for counteracting the effects of oxygen deficiency (Gibbs et al. 1943). In the presence of low oxygen, carbon dioxide is beneficial because it exerts a vasodilator effect on cerebral blood vessels (Patterson et al. 1955, Gibbs et al. 1943). Patterson et al. (1955) studied the threshold of response of the cerebral vessels in humans following exposure to 2.5 and 3.5 percent carbon dioxide for up to 30 minutes. The results showed that the threshold for cerebral vasodilator effects was greater than 2.5 percent, based on the absence of changes in cerebral blood flow, vascular resistance, and arteriovenous oxygen difference seen at this exposure concentration (Patterson et al. 1955). In the same study, inhalation of 3.5 percent carbon dioxide produced a 10 percent mean increase in cerebral blood flow, but little change in blood pressure in most subjects. Dilation of cerebral blood vessels may account for the severe headache also produced by carbon dioxide inhalation (Lambertsen 1971).

Other beneficial effects of carbon dioxide in the presence of low oxygen include the fact that it increases the ventilation of the lungs, and it shifts the hemoglobin dissociation curve so that with a given oxygen saturation more oxygen is delivered to the tissues. A study of arterial and internal jugular blood oxygen, carbon dioxide content, and brain function in eight healthy young men who breathed mixtures containing low percentages of oxygen and varying ratios of carbon dioxide indicated that normal brain function can be maintained for very short periods of time in spite of low percentages of oxygen in the inspired air (as low as 2 percent oxygen). This study can be summarized as follows: in four experiments, the subjects breathed 6 percent oxygen plus 5 percent carbon dioxide for 3 minutes and then 4 percent oxygen plus 5 percent carbon dioxide for three minutes. None of the subjects lost consciousness, response to commands and memory remained normal, and the electroencephalograms were unchanged. Two subjects were given 2 percent oxygen plus 5 percent carbon dioxide. For over 2 minutes, both were able to subtract and obey commands, and the electroencephalograms remained unchanged. Then the deep rapid breathing was interrupted by a single shallow respiration, the arterial oxygen saturation dropped, and consciousness was lost (Gibbs et al. 1943).

Lambertsen and Gelfand (1995) conducted an experiment with human volunteers to study the physiological effects of abrupt exposures to 10 percent oxygen with 4 percent carbon dioxide. Their results showed that for 3 minute exposures at 10 percent oxygen with 4 percent carbon dioxide and for 3 minute exposures at 10 percent oxygen without carbon dioxide, there were several advantages that resulted from breathing carbon dioxide in the presence of low oxygen. These included a higher end tidal oxygen partial pressure, increased ventilation, slightly lower heart rate, stable hemoglobin saturation (above 90 percent), higher middle cerebral artery blood velocity, and increased (above normal) brain oxygenation flow.

In instances where carbon dioxide is added in specialized flooding systems using inert gases, different regulatory agencies treat these agents differently. For example, in the United States, EPA does not distinguish between inert gas blends with and without added carbon dioxide. However, in the UK, inert gas blends containing added carbon dioxide are granted longer “safe exposure” times (HAG 1995).

In conclusion, uptake of oxygen into the bloodstream in low oxygen environments can be enhanced by the presence of carbon dioxide within a narrow concentration range.

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