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Comparative Analysis of the Reliability of Carbon Dioxide Fire Suppression Systems As Required by 46 CFR, SOLAS II-2, and NFPA 12

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16. Abstract

Coast Guard regulations governing the design and installation of total flooding carbon dioxide fire suppression systems for shipboard machinery spaces are compared to the equivalent standards promulgated by the International Maritime Organization (IMO) and the National Fire Protection Association (NFPA). Differences among the standards that can affect the reliability of a carbon dioxide system involve: 1) the quantity of carbon dioxide required for a machinery space installation; 2) manual versus automatic system actuation; 3) requirements for closure of ventilation systems, doors, vents, duct dampers, etc., and 4) required carbon dioxide discharge rates and piping design guidelines to achieve the required discharge rates.

A Failure Modes and Effects Analysis (FMEA) has been conducted for a prototypical modern high pressure carbon dioxide system for a large cruise ship. The FMEA has identified seven system components with failure modes that could affect the ability of the system to extinguish a machinery space fire. Potential sources of failure rate data for these and other components are identified.

Fire incident reports involving machinery spaces equipped with total flooding carbon dioxide systems have been complied and reviewed. The carbon dioxide system extinguished the fire in 35% of those fires and either temporarily extinguished or controlled the fire in another 23% of the incidents. The primary reason for the limited effectiveness of the carbon dioxide systems seems to be carbon dioxide leakage due to either: 1) unclosed doors, vents, ducts, etc.; 2) fire/explosion damaged closures (particularly in fires with delayed system actuation); and 3) crew or firefighter early re-entry into the machinery space before temperatures have been reduced sufficiently to preclude re-ignition. System failure rate data for land-based carbon dioxide systems indicate that high pressure systems have had failure rates in the range of 4% to 53%, whereas low pressure systems have had failure rates (0.2% to 0.4%) at least an order-of-magnitude lower.

Possible ways to provide improved system reliability and to streamline the Coast Guard standard and make it more compatible with the other two standards are presented in the conclusions to this report.

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METRIC CONVERSION FACTORS

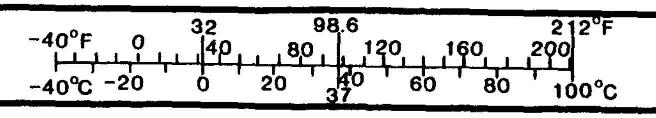
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

Carbon dioxide total flooding fire suppression systems are utilized in engine rooms, generator rooms, paint lockers, cargo holds, and other enclosed areas on commercial ships. Several different regulations and standards govern the design and installation of carbon dioxide suppression systems. The relevant regulations for vessels falling under U.S. Coast Guard jurisdiction are 46 CFR 34.15 (Ref. 1), 46 CFR 76.15, and 46 CFR 95.15, which are prescriptive standards with detailed design specifications. The relevant standard promulgated by the International Maritime Organization (IMO), as described in the most recent SOLAS volume (Ref. 2), is a simple performance based standard with minimal design guidance. Both of these standards differ from the National Fire Protection Association (NFPA) carbon dioxide system standard (Ref. 3) and the equivalent Factory Mutual (FM) standard (Ref. 4).

This report is intended to compare the pertinent carbon dioxide (CO_2) system standards and discuss how the differences may affect system performance and reliability for machinery space installations. Comparisons are discussed in Section 2, with detailed tables and sample pipe flow calculations provided in Appendix A and C respectively. Since most shipboard CO_2 systems are high pressure systems with banks of CO_2 cylinders, the emphasis is on high pressure systems.

One approach to analyzing system reliability and performance is to compile incident reports and statistics on the historical performance of CO_2 systems. Section 3 provides a summary of CO_2 system performance described in Coast Guard incident reports involving engine room fires. Common system failure modes and responsible system components are identified in those reports. Report narrative summaries are provided in Appendix D.

Another approach to assessing system reliability is to conduct a Failure Modes and Effects Analysis in which the consequences of individual component failures are identified. The high pressure CO_2 system FMEA is presented in Appendix B. Key results, including the identification of critical system components that are required for discharge actuation and the delivery of CO_2 to the fire compartment, are summarized in Section 4.1. Potential sources of data on the component failure rates and failure probabilities are listed in Section 4.2.

2. COMPARISON OF CO_2 SYSTEM STANDARDS

Item by item comparisons of the carbon dioxide total flooding system requirements in the Code of Federal Regulations (Ref. 1), the IMO/SOLAS regulations (Ref. 2), and NFPA 12/FM 4-11N (Refs. 3 and 4) are presented in table form in Appendix A. These comparisons are summarized here under the categories Required Quantities/Concentrations (Sec 2.1), Discharge Actuation Controls and Delay Times (Sec 2.2), Piping and Nozzles (Sec 2.3), Enclosure Openings and Ventilation (Sec 2.4), and Miscellaneous Items (Sec 2.5). Differences that could affect system reliability are discussed. System reliability refers here to the ability of the system to extinguish a machinery space fire.

2.1 Required CO_2 Quantities/Concentrations

The amount of carbon dioxide required according to the CFR (Ref. 1) is specified in terms of a flooding factor that is defined as the volume of space protected per pound of CO_2. The amount of CO_2 required in the IMO/SOLAS regulations is specified in terms of a volumetric concentration. The relationship between the these two specifications depends on the assumed specific volume of CO_2, which is taken as 0.56 m^3/kg in Reference 2. The IMO specified volumetric concentration for machinery spaces (40% of the net volume exclusive of machinery casing volume) is independent of volume, whereas the CFR flooding factors increase with increasing machinery space net volume.

Figure 1 is a comparison plot of the required mass of CO_2 versus machinery space net volume, for machinery spaces in which the machinery casing volume is no more than 12% of the space gross volume. When machinery volumes are 2,000 m^3 and larger, the required amounts are virtually identical. At smaller machinery space volumes, the CFR requires more CO_2 than IMO/SOLAS. For example, in a 100 m^3 machinery space, the CFR requires about 22% more CO_2 than does IMO.

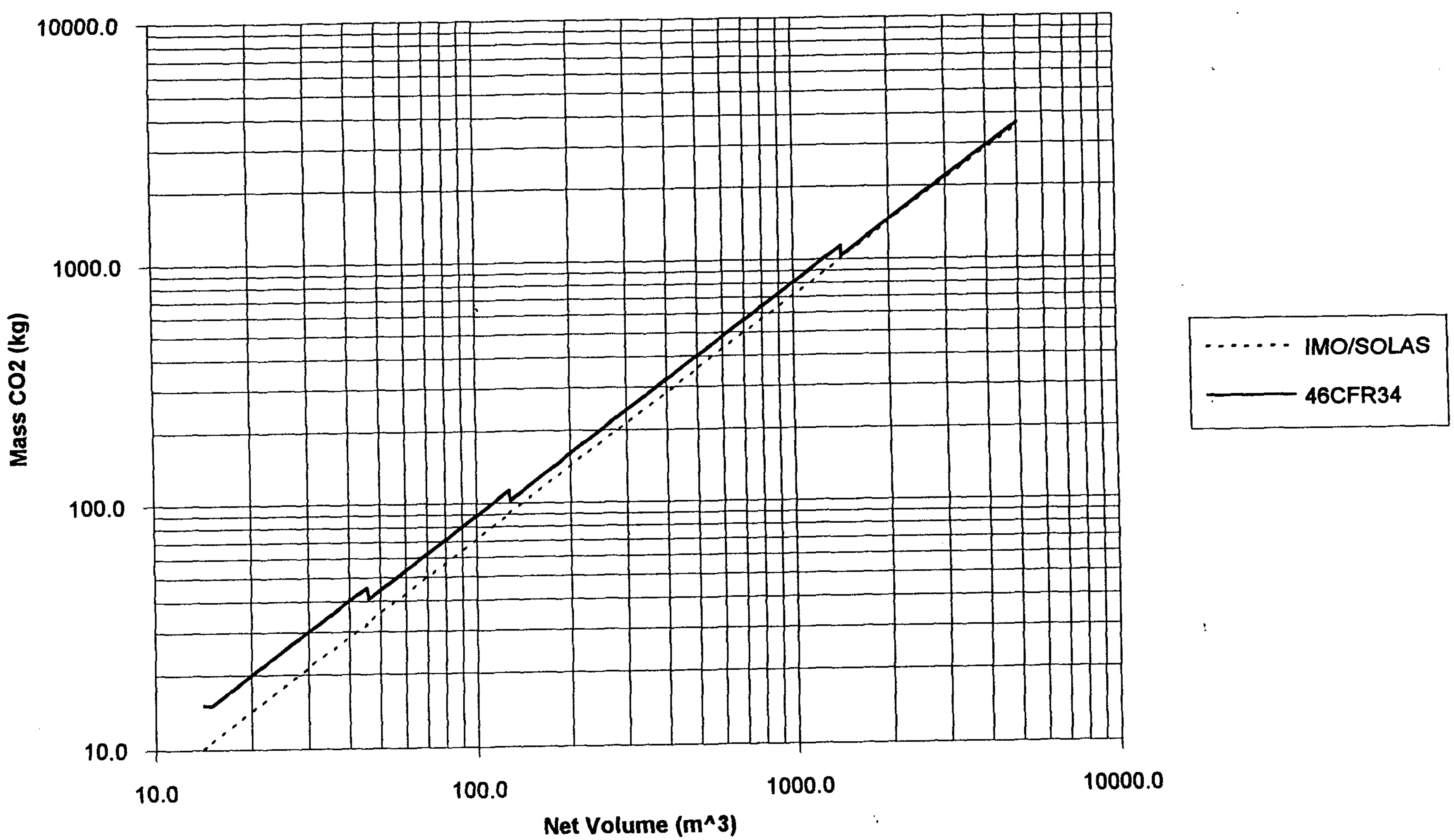

Figure 1. Comparison of CO_2 Quantities Required

Thus, there is no significant difference in required quantities for moderate size and large machinery spaces, but significantly more CO_2 is required by the CFR for small machinery spaces.

The primary difference between the marine (CFR, IMO) and land based (NFPA) required CO_2 quantities is that the land based requirements are fuel specific and dependent on whether the design basis fire is a surface fire or a deep-seated fire. Deep-seated fires and certain flammable liquids and vapors require substantially higher CO_2 concentrations for extinguishment. Most machinery space fires involve either fuel oil or lubricating oil, and the concentration requirements for these fires are identical in the land-based and marine standards. Some machinery space fires involve electrical equipment and cables, which have the potential of becoming deep-seated and thus NFPA requires higher CO_2 concentrations for these fires than called for in the CFR and IMO regulations.

2.2 Actuation Controls and Delay Times

Actuation control requirements are virtually the same in the CFR and IMO regulations. In both cases, two separate control valve actuators are required; one actuator to release the CO_2 and another actuator to open a valve admitting the CO_2 into the desired machinery space. Both regulations also allow two actuation station locations, with at least one location being in the vicinity of the machinery space but safely outside it. Neither shipboard regulation allows automatic release of CO_2 upon detection, whereas the NFPA standard states automatic actuation is required unless the authority having jurisdiction rules that it "could result in an increased risk." Furthermore, NFPA 12 specifies only one control actuation to discharge CO_2 into the enclosure.

The discharge time for both CFR and IMO CO_2 total flooding applications are identical: 85% of required amount within 2 minutes. The delay times do, however, differ. The CFR requires a minimum of 20 seconds while IMO systems must provide a "suitable period before the medium is released" (Ref. 2). In this aspect IMO and NFPA are similar. NFPA indicates that the delay time shall be "of sufficient duration to allow for evacuation under "worst case" conditions........." (Ref. 3). However, the NFPA requires that drills be performed to determine the minimum time required for personnel to remove themselves from the protected area, after identifying the warning signal, while IMO does not.

This is a difficult issue: the sooner the system is activated, the more likely the fire will be controlled. However, because of the asphyxiation hazard discussed in Section 3.3, sufficient time must be provided for evacuation of personnel, the 20 second minimum delay time in the CFR is most likely sufficient, given that manual activation of the CO_2 system is required. On the other hand, the approach implied in the NFPA standard is that automatic actuation be utilized with a conservatively long duration delay to allow evacuation. Presumably, the different approaches to system actuation stem from different perceptions on whether a fire that is large enough to actuate an automatic detector can/should be readily extinguished without system discharge.

2.3 Piping and Nozzles

There are important differences in the pipe size specifications in the three standards. The IMO standard does not provide any pipe size specifications. The CFR standard and the CG guidelines for plan review and inspection (Ref. 5) specify minimum pipe diameters and minimum and maximum nozzle orifice. The NFPA standard provides a method for calculating the pressure drop in pipe segments with known lengths and diameters and design CO_2 flow rates. These calculations are intended to verify that the nozzle pressures will not fall below the NFPA 12 minimum requirements for high pressure systems (300 psig) and low pressure systems (150 psig).

Neither the CFR nor the IMO standards restrict the lengths of CO_2 distribution piping. This is a concern in that there could be excessive pressure drops in long runs of piping. In order to investigate the pressure drop effects in lengthy pipe runs, calculated pressure drops are shown in Appendix C for different quantities of CO_2 at the minimum and maximum allowable orifice areas per the CFR standard. The methodology of NFPA 12 is used for these pressure drop calculations. The results presented in Table C-3 of Appendix C show that under most conditions, when the distribution piping is of typical lengths, the pressure drop through the nozzles meets or exceeds the NFPA 300 psi requirement.

Nozzle location is another important factor affecting CO_2 dispersal. Both the CFR and IMO standards call for uniform spacing of nozzles but give no guidance on allowable distances between nozzles. The CG inspection guidelines (Ref. 5) suggest that nozzles can be located at mid elevation in the machinery space because most machinery space fires occur at low elevations. However, there are at least two fires described in Appendix D that involve electrical cable burning at upper elevations. These upper elevation fires cannot be expected to be extinguished with nozzles situated at mid elevation as suggested by Reference 5.

The CFR specifies that ferrous pipes must have corrosion protection, inside and out, while IMO has no such provision. Given that the systems in question are marine-based, and therefore potentially exposable to a corrosive environment, corrosion protection should be a design specification. The effect of not explicitly requiring (or having) corrosion protection on the reliability of the system is expected to be relatively small.

The CFR specifies the allowable branch line diameters, while IMO does not. Once again the IMO regulations appear to treat this point as a design option; not necessarily within the realm of regulation. Additionally, the CFR specifies the pipe schedule for given sizes of pipe, while IMO appears to treat this as another design specification.

2.4 Enclosure Openings and Ventilation

Machinery space bulkhead openings and ventilation systems must be closed prior to CO_2 discharge in order to allow CO_2 concentrations to reach the levels required for extinguishment. These closings are also necessary to maintain an inert atmosphere long enough to achieve sufficient cooling of fire heated equipment, bulkheads, etc. to prevent re-ignition upon air reentry into the machinery space. Neither the CFR nor the IMO standard specifies a required concentration hold time, but the NFPA standard does specify hold times for surface fires and deep-seated fires. Presumably, a CO_2 discharge test is required to demonstrate these hold times.

The CFR and IMO standards have somewhat different requirements for sealing off enclosure openings and ventilation. The CFR requires the mechanical ventilation to be shut down automatically upon CO_2 system actuation, while the IMO standard stipulates that "means shall be provided to close all openings which may admit air or allow gas to escape from a protected space." The CG/CFR regulations (46 CFR 76.15-35) also specify that "means shall be provided for closing all openings to the space protected from outside such space." Installed closures are required in the lower portion of the machinery space, but canvas or similar porous material is allowed for openings in the upper region.

It would seem that the CFR regulations are more stringent than the IMO regulation in this aspect because of the requirement for automatic shutdown of mechanical ventilation and the provision of closures from outside the machinery space. However, the allowance of flimsy, porous materials for openings situated in the upper portion of the space may be less stringent than a strict interpretation of the IMO regulations. In any event, both the CFR and IMO standards fall far short of the NFPA standard in demonstrating a specified hold time.

2.5 Miscellaneous Items

The CFR requires that the mechanical ventilation system be automatically shut down upon activation of the CO_2 system. IMO stipulates that "Means shall be provided to close all openings which may admit air to or allow gas to escape from a protected space." (Ref. 2, Reg. 5, 1.4). Presumably the means to close all openings includes turning off any mechanical ventilation; however, this is not explicitly stated. Since not shutting down the ventilation system would result in a lower volumetric concentration of CO_2, this item could prove to be significant. The CFR requirement is regarded as being more reliable because it specifically states that the mechanical ventilation system be automatically shut down. While the IMO regulation does not preclude automatic mechanical ventilation system shutdown, not specifying it could result in a less reliable system.

The CFR requires an installation inspection. The CFR provides details of tests to check the leakage from the system after pressurizing the piping, and of blowing down the piping for small systems. SOLAS has no requirement for installation inspections. Presumably an installation inspection and system test is part of the installation procedure for IMO compliant CO_2 systems. However, if it is not, the reliability of IMO compliant CO_2 systems could be significantly jeopardized.

Minor differences which should not affect the reliability of the systems involve the nozzle discharge area, and pressure relief for the compartment, distribution manifold, and storage cylinders. For these items the CFR has a requirement but IMO does not. These items are not expected to affect the reliability of the CO_2 system. The IMO appears to treat the nozzle discharge area as a design specification.

The need for compartment pressure relief arises after the CO_2 has been released. Not having it could result in the CO_2 release causing an overpressure condition and thus forming an opening in the compartment large enough to leak excessive CO_2. Not having a pressure relief valve on the distribution manifold could result in damage to manifold during agent discharge and thus prevent the CO_2 from reaching the fire space. Not having cylinder pressure relief could result in agent leakage before a fire, i.e., the CO_2 would be unavailable to fight a fire. Two points are noted for pressure relief provisions: 1) these overpressurization events are relatively rare when compared to other possible failure events, and 2) IMO seems to treat pressure relief as a specification of every design and therefore something that need not be mandated.

3. CO_2 SYSTEM HISTORICAL PERFORMANCE

3.1 Statistical Summary from Reference 6

Reference 6 provides a discussion of the fire suppression requirements for shipboard machinery spaces. From this reference, the most common machinery space fire involves a fuel oil spray ignited by a hot surface.

A total of 26 fires involved the discharge of a CO_2 system (132 total machinery space fire incidents were considered). Table 1 (Table 2.3.2-5 of Reference 6) provides a breakdown of the machinery space fire incidents involving fixed, total flooding carbon dioxide systems (CO_2 System) and the reported effectiveness of such systems.

Table 1. CO_2 System Effectiveness

CO_2 System Effectiveness	Type & Number of Fires	Percent (%)
Extinguished Fire	Spray (9)	34.6
Temporarily Extinguished Fire	Spray (3), Electrical (1)	15.4
Controlled Fire	Spray (1), Electrical (1)	7.7
Ineffective	Spray (5), Pool (2), Electrical (1), Other (1), Unknown (2)	42.3

A temporarily extinguished fire is a one that was suppressed for a period of at least 20 minutes and then re-ignited. A controlled fire is one that is confined to its ignition area (i.e., small flames). The CO_2 System was ineffective against those fires which continued to burn despite the presence of the CO_2 fire suppression agent.

3.2 Common System Problems in Fire Incidents

Table 2 (based on Table 2.3.2-6 of Reference 6) provides information concerning why CO_2 systems were less than fully effective. Of the reasons listed, the category "activated too late" may seem counter intuitive. It would seem reasonable that the longer a fire burns, the less oxygen would be present and the easier the fire would be to extinguish. The available data does not support this position. There is a correlation between long delays in activating the CO_2 system and its failure to extinguish the fire. A causal relationship between activation delays and failure to extinguish has not been established. It is possible that long delay times permit heat distortion of vents, doors, etc., which precludes the formation of a gas tight enclosure (see Appendix D.1). If this is the case, the category "activated too late" is actually a specific case of the category "excessive agent leakage from space."

Table 2. CO_2 System Limited Effectiveness

Reason for Limited Effectiveness of CO_2 System	No. of Incidents	%
Excessive Agent Leakage from Machinery Space	8	47.1
Activated Too Late	3	17.6
Failure to Discharge When Activated	1	5.9
Other	1	5.9
Unknown	4	23.5

The excessive agent leakage was typically the result of not closing the vents or doors of the space prior to discharging the CO_2. In two cases, the mechanical ventilation was not shut down (one of these cases also involved not closing the vents or doors). In at least one case, the door to the space was opened too soon after the CO_2 was released and thus the CO_2 leaked out before it could extinguish or inert sufficiently to prevent re-ignition. The actual reason for not being able to close the vents and/or doors was not provided in the accident reports.

One other reason for ineffective suppression, cited in two incidents, is the presence of fire in the upper region of the machinery space. The CO_2 concentrations in these regions may be below the required values for extinguishment, especially for electrical cable fires.

3.3 CO_2 System Asphyxiation Hazard

Personnel exposure to carbon dioxide concentrations of 7 to 10 volume percent or higher results in loss of consciousness, with death occurring after 5 minutes at a concentration greater than 10 % (SFPE Handbook, lst edition, p 1-238, 241). Since carbon dioxide system design concentrations far exceed these concentrations, a primary reliability consideration is the prevention of system discharge while personnel remain in the machinery space.

None of the fire incidents reviewed in Reference 6 and Appendix D of this report resulted in any fatalities due to discharge into an occupied machinery space. However, there have been several inadvertent discharge incidents resulting in fatalities in recent years. Although the authors are not privy to written accounts and explanations of the causes of these incidents on commercial and Coast Guard ships, they are more familiar with incidents on Navy ships and land based facilities. One incident involved three fatalities when a system accidentally discharged while three sailors were supposed to be doing preventive maintenance on a CO_2 system in a paint locker. Another incident resulted in a fatality when lethal concentrations of CO_2 propagated into an area outside the enclosure in which a CO_2 system was being discharged during an installation test.

It is ironic that the leading failure mode for CO_2 systems in fire incidents, namely excessive leakage through unclosed openings, is also an important mode of inadvertent exposure of personnel to potentially lethal CO_2 concentrations during CO_2 test discharges. Another failure mode that could lead to accidental discharge of a system into an occupied enclosure is the mislabeling (or incorrect tripping) of the actuators for the directional valves that admit CO_2 to the various compartments. This failure mode can occur either during testing or during an intended discharge, as listed in the Failure Modes and Effects Analysis (Appendix B).

4. SYSTEM RELIABILITY ANALYSES

One of the most widely used systems reliability methods is the Failure Modes and Effects Analysis (FMEA). A FMEA is typically used to identify system component failures that could lead to system failure and/or unacceptable hazards. It has been used in this study to identify critical CO_2 system components whose failure could lead to the inability of the system to extinguish a machinery space fire or to inadvertently discharge CO_2 into an occupied area. Results are summarized in Section 4.1.

After a FMEA or some other type of qualitative systems reliability study indicates that there are indeed single component failures that could lead to unacceptable consequences, there is motivation to go to some type of quantitative study such as a Fault Tree Analysis. Quantitative Fault Tree Analyses require input data on individual component failure rates and system demand rates, i.e. frequency of operation. The scope of this particular study does not include quantitative analysis, but it does include a brief overview of relevant system/component failure rate databases that could eventually be utilized in such an analysis. Results are presented in Section 4.2.

4.1 Failure Modes and Effects Analysis

Appendix B is a FMEA for a prototypical high pressure CO_2 system installed on a modern large European passenger vessel. This particular system/vessel was selected because it was subjected to a Coast Guard initial inspection at a local port (Boston) during the course of this investigation and the system detailed drawings were made available to the authors.

Based on the FMEA tabulation in Appendix B for system discharge in response to manual actuation, the following critical components have been identified in that their failure (failure mode specified in Appendix) could lead to either no CO_2 being delivered to the machinery space on fire, or to a reduced CO_2 concentration that would prevent successful extinguishment. Drawings of the system layout and locations of these components are provided in Appendix B.

Seven critical components are listed in Table 3. Three of those components have failure modes that could prevent any CO_2 from being delivered into the intended machinery space. Two of the three components (directional valves and control panel wiring/switches actuating these valves) could also deliver CO_2 into an unintended, occupied area. In view of the possibility of creating a potential asphyxiation hazard as well as preventing fire extinguishment, these two components warrant special consideration about their reliability. Four other components have failure modes that could result in significantly reduced CO_2 concentrations in the machinery space. Many of the total of 23 components listed in the FMEA for full discharge of the system were considered of secondary importance, because there was a manual way of working around the failure, if a crewmember was properly trained and familiar with the system. However, the manual work around would significantly delay the discharge of CO_2 to the point that serious injuries and damage may be incurred before the fire is extinguished, if indeed it can be extinguished.

Table 3. Critical Components

Component	Failure Mode	Effect
Distribution Piping	Fully obstructed	No CO_2 Delivered
Directional Valves for Distribution Piping	Fails closed	No CO_2 Delivered and/or CO_2 Discharge into occupied area.
Nozzle	Obstructed or Improperly Located	Reduced CO_2 Concentration
CO_2 Cylinders	Leaky or not properly refilled	Reduced CO_2 Concentration
Cylinder Valve	Fails Closed or Obstructed	Reduced CO_2 Concentration
Ventilation Shutdown Circuit and Duct Dampers	Improperly installed or fails open	Reduced CO_2 Concentration
Control Panel (Switch for Directional Valve Actuation)	Wiring/Component Failure	No CO_2 Delivered and/or CO_2 Discharge into occupied area.

4.2 CO_2 System and Component Reliability Data Sources

Several sources of system and component reliability data have been identified. These are discussed in the following sections.

4.2.1 Machinery Space Fire Incident Database

The Machinery Space Fire Incident Database (MSFIdb) developed for Reference 6 is discussed in Sections 3.1 and 3.2. This database is limited in that system level failures are typically considered. If the system failed to activate, no indication of the component that actually failed is given in the database. However, incident reports, which are available for many of the incidents in the database, sometimes contain the details needed to identify the failed component.

4.2.2 Stronach (Alcan Aluminum)

Reference 7 presents CO_2 system failure data gathered from aluminum rolling mills. The CO_2 suppression systems installed in these mills are both high and low pressure, with automatic activation via heat detectors. Stronach distinguished between system failure and system malfunction. System failure was defined as lack of extinguishment with "single or multiple discharges of CO_2 and with portable fire extinguishers [such that repairs to the mill] must not exceed twenty-four hours." System malfunction involved a problem with the system that did not prevent satisfactory extinguishment as defined above.

Two studies were conducted. The first considered data for two low pressure systems between 1972 and 1986. This study found two failures and two malfunctions out of 1,238 activations. The second study considered data for both low and high pressure systems, obtained between 1981 and 1986. In this study, two failures out of 504 low pressure system activations were logged. Six failures out of 145 activations of high pressure CO_2 systems were logged. The results of this reference are summarized in Table 4.

Table 4. Reference 7 Failure Data Summary

System Type	Year	System Failure (%)	System Malfunction (%)
Low Pressure	1972 - 1986	0.16	0.16
Low Pressure	1981 - 1986	0.4	0.8
High Pressure	1981 - 1986	4.1	14.5

These failure rates are dramatically lower than those for shipboard machinery space incidents. Furthermore, the failure rate for low pressure systems is an order-of-magnitude lower than for high pressure systems. As a result of their improved reliability, Stronach recommended that all new CO_2 systems be low pressure, and that ways of improving the reliability of high pressure systems be investigated.

4.2.3 Miller (Navy and FM)

Reference 8 presents data that from the U.S. Navy and from Factory Mutual (FM) loss reports. Few details are provided regarding the type of CO_2 system, the areas protected, the number of demands and failures, and the definition of effective as it pertains to the study.

According to Miller, Navy data for the years 1966 - 1970 indicate that CO_2 systems were 96.1% effective. The corresponding failure rate of 3.9% is remarkably close to the 4.1% failure rate reported by Stronach for high pressure systems.

Data from FM loss reports indicated a CO_2 system failure rate of 53%, or an order-of-magnitude higher than those cited above. Miller points out that many successful system actuations go unreported to FM, so there really is no basis for a direct comparison of Navy and industrial incident failure rates.

4.2.4 Center for Chemical Process Safety

Reference 9 is a wealth of reliability data for selected process systems and equipment used in the chemical process and other industries. Reliability data for flame detectors, pipes, hoses, valves, and various fire protection/suppression systems are included. However, there was nothing for CO_2 suppression systems. Sufficient data for individual CO_2 system components seems to be available to provide the basis for a quantitative risk analysis. Data is presented in either failures per 10^6 hours or in failures per 10^3 demands. Various failure modes are considered for each component, with data presented for several specific failure modes in most cases.

4.2.5 Reliability Analysis Center

Reference 10 is similar to Reference 9 in that many components are considered. While whole systems are not presented (upon a cursory investigation), sufficient component data seems to be available to analyze a simple CO_2 suppression system. The task becomes one of sifting through all of the data to extract the appropriate components and their associated failure data. This data is also presented in terms of failures per hour and failures per demand, depending on the nature of the component. This reference also provides the population of components that form the basis for the failure data presented.

If both References 9 and 10 are used together, most (if not all) of the components of a prototype shipboard CO_2 suppression system could be modeled for a quantitative risk analysis.

4.2.6 Other Sources

One source of land based CO_2 system data that has not been investigated because of time/funding limitations is the Fire Equipment Manufacturers Association. One source originally thought to contain pertinent data, that in fact does not, is the National Fire Reporting System (NFIRS). This reporting system deals with land based fires that involved fire department response; any mention of a CO_2 system activation would be incidental. Additionally, the Naval Safety Center fire incident database was consulted for Reference 6. Of the 310 incidents reported, only 4 involved the release of a CO_2 fire suppression system and there were no failures (i.e., all fires involving a

CO_2 system were extinguished). Because of this, the Naval Safety Center may not be a good source of additional data.

5. CONCLUSIONS and RECOMMENDATIONS

- There are three differences between the CG/CFR regulations and IMO/SOLAS regulations for CO_2 total flooding systems that could affect the reliability of a system to extinguish a machinery space fire. These differences are: 1) significantly less CO_2 required by IMO/SOLAS in small machinery spaces; i.e., smaller than about 200 m^3; 2) the IMO/SOLAS regulations do not provide any specifications, guidance, or verification test for piping designs to achieve the required CO_2 flow rates; and 3) the CG/CFR regulations require automatic shutdown of ventilation systems upon CO_2 system actuations, whereas the IMO/SOLAS regulations merely stipulate that some means be provided to close openings that allow air flow into or out of the machinery space.

- There are some significant differences between the CG/CFR regulations and the NFPA regulations that could render shipboard CO_2 systems more prone to failure (inability to extinguish) than land based systems. These differences include 1) the NFPA 12 allowance of automatic discharge following detection, alarm, and a suitable delay time for personnel evacuation; 2) NFPA 12 description of a calculation method to determine if piping between the CO_2 cylinder and the discharge nozzles is sufficiently short to allow nozzle pressures to be at or above the minimum required pressures for effective dispersal of CO_2; 3) NFPA 12 stipulation that the required CO_2 concentration for surface fires be achieved within 1 minute from start of discharge whereas the CFR and IMO regulations stipulate 85% of design concentration be achieved in two minutes; and 4) NFPA 12 provision of fuel specific required concentrations and flooding factors and more stringent requirements for deep-seated fires in electrical equipment and wiring; and 5) NFPA 12 requirement for a 20 minute concentration hold requirement for deep-seated fires.

- Pressure drop calculations for CFR specified minimum flow rates at different pipe lengths and diameters indicate that nozzle pressures are below the NFPA 12 specified minimum value (300 psig). Calculations also indicate that the length of distribution piping required to produce the minimum flow rate specified in the CFR are very long. In most situations when distribution piping is of typical length, the pressure drop through the nozzles of systems designed to 46 CFR meet or exceed the NFPA 300 psi requirement.

- CO_2 system failure rates from sources in which every discharge is reported are an order-of-magnitude lower than those from sources in which failure rates are based entirely on voluntary submittals of fire incident reports.

- The reported failure rate for low pressure systems (0.2 to 0.4 %) is at least one order-of-magnitude lower than the failure rate for high pressure systems (4% to 53%). Unfortunately, relatively few low pressure systems are used on ships.

- The most prevalent cause of CO_2 system limited effectiveness (failure to extinguish and/or prevent re-ignition) in machinery space fires has been excessive leakage of CO_2 from the machinery space. In some fires the leakage is due to unclosed or improperly closed doors, vents, or ventilation ducts. In other fires, particularly those with delayed CO_2 system actuation, it is due to fire or explosion damaged doors, bulkheads, etc. In still other fires, the leakage occurs when crew or firefighters enter the machinery space before equipment and bulkhead temperatures have been reduced below the auto-ignition temperatures of fuel oil (or other combustible liquid) flammable vapors.

- Excessive leakage can be reduced by requiring 1) enclosure integrity tests (perhaps utilizing door fan pressurization equipment as described in NFPA 12A and 2001), 2) earlier CO_2 system activation (for example, automatic activation 5 minutes after detection unless the system is manually recycled during that 5 minute interval), 3) automatic closing of doors, vents, duct dampers, etc. upon system discharge, and 4) training crew and firefighters to avoid re-entering the machinery space after a discharge until they are confident that temperatures are reduced below auto-ignition values. The latter may require either a few hours wait for fires with extensive burning prior to system activation or the installation of temperature or CO_2 concentration sensors with remote displays.

- System inspections should include verification that operating instructions and controls are posted in the native language of the crew, and that directional valves directing CO_2 to the various enclosures are installed and labeled correctly. Nozzle locations should be situated to provide near-uniform coverage throughout the machinery space and not just at lower elevations.

6. REFERENCES

1) Code of Federal Regulations, Chapter 46, Subpart 34.15, 10-1-93 Edition.

2) SOLAS Consolidated Edition, 1992, Chapter II-2, Part A, International Maritime Organization, London, 1992.

3) Carbon Dioxide Extinguishing Systems, NFPA 12 (93 ed.), National Fire Protection Association, Quincy, MA, 1993.

4) Carbon Dioxide Extinguishing Systems, Factory Mutual Data Sheet 4-11N, Factory Mutual Engineering and Research, Norwood, MA, 1993.

5) Navigation and Inspection Circular 6-72, Guide to Fixed Fire-Fighting Equipment Aboard Merchant Vessels, Department of Transportation, U.S. Coast Guard, 1972.

6) Zalosh, R.G., Finnegan, D.M., and Beller, D.K., Fire Suppression Requirements for Shipboard Machinery Spaces, Draft Final Report: to be published, U.S. Department of Transportation, United States Coast Guard, Washington, D.C., 1995

7) Stronach, R.I., "Reliability of Carbon Dioxide Extinguishing Systems," presented to the Fire Suppression Systems Association, Baltimore, MD at their Annual Meeting, Naples, FL, January 1987.

8) Miller, M.J., "Reliability of Fire Protection Systems," Loss Prevention, Vol. 8, American Institute of Chemical Engineers, New York, 1974.

9) Guidelines for Process Equipment Reliability Data with Data Tables, Center for Chemical Process Safety of the American Institute of Chemical Engineers, New York, 1989.

10) Denson, W., Chandler, G., Crowell, W., and Wanner, R., Nonelectronic Parts Reliability Data, NPRD-91, Reliability Analysis Center, Rome, NY, 1991.

11) Henley, E.J., and Kumamoto, H., Reliability Engineering and Risk Assessment, Prentice-Hall, Englewood Cliffs, NJ, 1981.

APPENDIX A:

Regulation Comparison Table

The total flooding carbon dioxide fire suppression system requirements according to the Code of Federal Regulations (Ref. 1, Chapter 46, Subpart 34.15, 10-1-93 Edition), the International Maritime Organization (Ref. 2, SOLAS, Chapter II-2, Part A), and the National Fire Protection Association (Ref. 3, NFPA 12, 1993 edition) have been compared. Additionally, the Factory Mutual Engineering and Research Data Sheet 4-11N (Ref. 4) has been included via footnoted differences to NFPA 12. These footnotes are listed following the table.

TABLE A-1 Comparison of Regulation Functional Requirements

ITEM	CFR (10-1-93 Edition)	IMO/SOLAS (1992 Edition)	NFPA (1993 Edition)
Quantity of Supply (l)	(GV - MCV) divided by flooding factor (15-25 $ft^3/lb\text{-}CO_2$) of Table A-2 (Ref. 1, 34.15-5(e)) *1	GV (ft^3) / 20.9 ($ft^3/lb\text{-}CO_2$) or (GV - MCV) / 17.6, whichever is larger. *2	Surface fires: Flooding Factor = 14-22 $ft^3/lb\text{-}CO_2$. See Table A-3 Deep-seated fires: Flooding Factor = 6-10 $ft^3/lb\text{-}CO_2$. See Table A-4
% Volume Concentration	30 - 45 vol %: See Table A-2, based on Ref. 1, 34.15-5(e).	40% of (GV - MCV) or 35% of GV, whichever is larger (neglecting leakage). *3 (Ref. 2, Reg. 5, 2.2.1, .2)	Surface fires: 34 -47 vol %. See Table A-3 Deep-seated fires: 50 - 75 vol %. See Table A-4
Discharge Time (sec)	85% of required amount within 2 minutes (Ref. 1, 34.15-5(e)(9))	85% of required amount within 2 minutes (Ref. 2, Reg. 5, 2.4)	Surface fires: design concentration achieved within 1 minute. (Ref. 3, 2-5.2.1) Deep-seated fires: design concentration achieved within 7 minutes *4 (Ref. 3, 2-5.2.3)
Delay Time (sec)	20 second minimum (Ref. 1, 34.15-10(f))	Alarm "shall operate for a suitable period before the medium is released" (Ref. 2, Reg. 5, 1.6)	Shall be "of sufficient duration to allow for evacuation under "worst case" conditions...Dry runs shall be made to determine the minimum time that shall be allowed for persons to remove themselves from the hazard area after allowing time to identify the warning signal." (Ref. 3, 1-5.1.4)
Hold Time (sec)	None stated.	None stated.	Surface fires: none stated. Deep-seated fires: at least 20 minutes after design concentration is reached. *5 (Ref. 3, 2-4.1)

TABLE A-1 Comparison of Regulation Functional Requirements (continued)

ITEM	CFR (10-1-93 Edition)	IMO/SOLAS (1992 Edition)	NFPA (1993 Edition)
Nozzle Discharge Area	"The total area of all discharge outlets shall not exceed 85 percent nor be less than 35 percent of the nominal cylinder outlet area or the area of the supply pipe, whichever is smaller." *6 (Ref. 1, 34.15-5(e)(8))	None stated.	Based on calculations to deliver the required rate of flow at each nozzle. (Ref. 3, 1-9.5)
Nozzle Number, Type, and Location	"The number, type and location of discharge outlets shall be such as to give a uniform distribution throughout the space." (Ref. 1, 34.15-5(e)(7)) "Discharge outlets shall be of an approved type." (Ref. 1, 34.15-25)	"...discharge nozzles so positioned that a uniform distribution of medium is obtained." (Ref. 2, Reg. 5, 1.3)	"Discharge nozzles shall be suitable for the use intended and shall be listed or approved for discharge characteristics." (Ref. 3, 1-9.4)
Auto/Manual Operation	Automatic release not permitted. However, if the CO2 cylinders are stored in the space protected (i.e., not more than 300 pounds of CO_2), then "the system shall be arranged in an approved manner to be automatically operated with a heat actuator within the space in addition to the regular remote and local controls". (Ref. 1, 34.15-20 (b)).	Automatic release not permitted. (Ref. 2, Reg. 5, 1.8)	Automatic release permitted.*7 (Ref. 3, 1-7.1)

TABLE A-1 Comparison of Regulation Functional Requirements (continued)

ITEM	CFR (10-1-93 Edition)	IMO/SOLAS (1992 Edition)	NFPA (1993 Edition)
Local/Remote Operation	"Distribution piping ... shall be controlled from not more than two stations. One of the stations controlling the system for the main machinery space shall be located as convenient as practicable to one of the main-escapes from the space." (Ref. 1, 34.15-10 (c)).	"The means of control...shall be grouped together in as few locations as possible at positions not likely to be cut off by a fire in a protected space." (Ref. 2, Reg.5, 1.7)	Local operation only: i.e., "manual control... located so as to be conveniently and easily accessible at all times..." (Ref. 3,1-7.3.4)
Controls	Machinery space systems "shall be actuated at each station by one control operating the valve to the space and a separate control releasing at least the required amount of carbon dioxide...Systems installed without a stop valve shall be operated by one control releasing at least the required amount of carbon dioxide." (Ref. 1, 34.15-10 (d)).	CO2 systems installed after 1OCT94 shall comply with: "Two separate controls shall be provided for releasing carbon dioxide into a protected space and to ensure the activities of the alarm. One control shall be used to discharge the gas from its storage containers. A second control shall be used for opening the valve of the piping which conveys the gas to the protected space." (Ref. 2, Reg. 5, 2.5)	"(Manual) Operation of one control shall be all that is required to bring about the full operation of the system." (Ref. 3, 1-7.1(b))
Storage Conditions	Storage is outside the protected space (except for machinery space systems containing less than 300 pounds CO_2). (Ref. 1, 34.15-20(a)) Properly vented and maintain temperature below 130°F. (Ref. 1, 34.15-20(c))	"Containers for the storage of fire-extinguishing medium ...shall be designed to pressure codes of practice to the satisfaction of the Administration having regard to their locations and maximum ambient temperatures expected in service." (Ref. 2, Reg. 5, 1.13)	Temperature range: 0°F - 130°F (Ref. 3, 1-8.5.5)

TABLE A-1 Comparison of Regulation Functional Requirements (continued)

ITEM	CFR (10-1-93 Edition)	IMO/SOLAS (1992 Edition)	NFPA (1993 Edition)
Alarms	Automatic, audible predischarge alarm depending on no source of power other than the carbon dioxide. (Ref. 1, 34.15-30(a))	Automatic, audible predischarge alarm. (Ref. 2, Reg. 5, 1.6)	Audible predischarge signal with a visual signal if the ambient noise level is high. Discharge alarm required for automatic system operation. (Ref. 3, 1-5.1.4) *8
Enclosure Leakage Paths	automatically shut down mechanical ventilation system (Ref. 1, 34.15-35 (a)) "(b) ...provision shall be made for easily and effectively closing off the (natural) ventilation. (c) Means shall be provided for closing all other openings to the space protected from outside such space." (Ref. 1, 34.15-35)	"Means shall be provided to close all openings which may admit air to or allow gas to escape from a protected space." (Ref. 2, Reg. 5, 1.4)	shut down power/fuel sources of equipment associated with the hazard (Ref. 3, 1-7.3.8); shut down and/or close mechanical ventilation systems (Ref. 3, 2-2.2.2); close doors, windows, and other openings (Ref. 3, 2-2.2.1).
Enclosure Pressure Relief	Relatively tight compartments "shall be provided with suitable means for relieving excessive pressure ..." upon CO_2 discharge. (Ref. 1, 34.15-40(a))	None specified.	"For very tight enclosures, the area necessary for free venting shall be calculated..." (Ref. 3, 2-6.2.1) *9
Pipe, Material	None specified. However, ferrous materials must have corrosion protection, inside and out. (Ref. 1, 34.15-15(c))	None specified.	Black or galvanized steel is acceptable (ASTM A-120 and ordinary cast-iron pipe is not permitted). Standard does not preclude the use of other materials provided it can withstand the expected system pressure and is noncombustible. (Ref. 3, 1-9.1)

TABLE A-1 Comparison of Regulation Functional Requirements (continued)

ITEM	CFR (10-1-93 Edition)	IMO/SOLAS (1992 Edition)	NFPA (1993 Edition)
Pipe, Schedule/Size	For branch lines sizes, see Table A-5. (Ref. 1, 34.15-5(e)(5)) Nominal sizes ≤ ¾-inch, use Schedule 40: over ¾-inch, use Schedule 80 (Ref. 1, 34.15-15(b))	None specified.	Nominal sizes ≤ ¾-inch, use Schedule 40 Over ¾-inch, use Schedule 80 (Ref. 3, 1-9.1)
Pressure Relief Valve	Installed on distribution manifold and set to relieve between 2,400 and 2,800 psi (Ref. 1, 34.15-15(d))	None specified.	"In systems where valve arrangement introduces sections of closed piping, such sections shall be equipped with pressure relief devices or the valves shall be designed to prevent entrapment of liquid carbon dioxide. The pressure relief devices shall operate between 2400 and 3000 psi..." (Ref. 3, 1-9.2.2)
Cylinder Pressure Relief	None specified in Ref. 1: however, Ref. 5 (Section A.10) indicates that the cylinders have a rupture disk to prevent cylinder overpressurization.	None specified.	"Each cylinder shall be provided with a safety device to relive excess pressures...frangible safety disks shall be fitted accordingly." (Ref. 3, 1-8.5.2)

TABLE A-1 Comparison of Regulation Functional Requirements (continued)

ITEM	CFR (10-1-93 Edition)	IMO/SOLAS (1992 Edition)	NFPA (1993 Edition)
Instructions	"Complete but simple instructions" must be located in a conspicuous place near all pull boxes, stop valve controls and in the CO_2 storage room. (Ref. 1, 34.15-10(h))	At each control station "there shall be clear instructions relating to the operation of the system having regard to the safety of personnel." (Ref. 2, Reg. 5, 1.7).	"...may include...(g) Provision of warning and instruction signs at entrances to and inside such (protected) areas." (Ref. 3, A-1-5) "All persons who may be expected to inspect, test, maintain, or operate carbon dioxide fire extinguishing systems shall be thoroughly trained and kept thoroughly trained in the functions they are expected to perform." (Ref. 3, 1-10.4)

TABLE A-1 Comparison of Regulation Functional Requirements (continued)

ITEM	CFR (10-1-93 Edition)	IMO/SOLAS (1992 Edition)	NFPA (1993 Edition)
Installation Inspection	After piping installation and before cylinders are connected: 1) pressure test piping from the cylinders and to stop valves to 1,000 psi - leakage from the system shall not permit a pressure drop of 150 psi/min for 2 minutes. 2) Branch lines tested similarly to above but to 600 psi. 3) Small independent systems may be tested "by blowing out the piping with the air at a pressure of at least 100 pounds psi." (Ref. 1, 34.15-15(j)(4)).	None specified.	"The completed system shall be inspected and tested by qualified personnel to meet the approval of the authority having jurisdiction... (a) A thorough visual inspection of the installed system and hazard area. The piping, operational equipment and discharge nozzles shall be inspected for proper size and location. The locations of alarms and emergency releases shall be confirmed... (b) A check of labeling devices for proper designation and instructions... (c) Nondestructive operational tests on all devices necessary for proper functioning of the system, including detection and activation devices. (d) A full discharge test shall be performed on all systems except when specifically waived by the authority having jurisdiction..." (Ref. 3, 1-6.3) *10

*1 GV = absolute gross volume of the machinery space (ft^3). MCV = volume of the normal machinery casing (ft^3). "By "normal machinery casing" shall be meant a casing the area of which is not more than 40 percent of the maximum area of the machinery space." Ref. 1, 34.15-5 (e) (2) (I).

*2 For cargo ships of less than 2,000 tons gross tonnage, GV / 20.9 or (GV - MCV) / 25.2, whichever is larger .

*3 Values reduced to 35% and 30% for cargo ships of less than 2,000 tons gross tonnage.

*4 The discharge rate should be great enough to develop a concentration of 30% in two minutes.

Table A-1: Notes (continued)

*[5] Factory Mutual Data Sheet 4-11N states a holding time of 30 minutes for fur and record vaults and closely packed combustible materials that will tend to smolder.

*[6] Nominal cylinder area (in^2) = 0.0022 * lbs CO_2 required

*[7] Factory Mutual Data Sheet 4-11N states that carbon dioxide systems should be designed for automatic operation but also have manual means of operation.

*[8] Factory Mutual Data Sheet 4-11N states that predischarge and discharge, and trouble signals should be both audible and visual (Ref. 3, 1-8.5.4).

*[9] "Record storage rooms, refrigerated spaces, and ductwork have also been found to need no additional venting when tested in their average system conditions." (2-6.2)

*[10] Factory Mutual Data Sheet 4-11N states that "In high pressure systems, sufficient carbon dioxide should be discharged to insure proper operation of all system components."

Table A-2 USCG CO_2 Factors

GROSS VOLUME [*1] (ft^3) OVER:	BUT NOT OVER:	FLOODING FACTOR (ft^3/lb CO_2)	CALCULATED % VOLUME CONC. [*2]
0	500	15	45.1
500	1,600	16	43.0
1,600	4,500	18	39.3
4,500	50,000	20	36.2
50,000		22	33.5
Tankships contracted on/after 26MAY65; use whichever is larger: above or...	GV	25	30.2

*1 Actually, GV - MCV, as discussed in footnote 1 of Table A-1.

*2 Assuming one pound of CO_2 expands to 9 cubic feet when released, the % volume concentration of CO_2 (%CO_2) is calculated from:

volume of CO_2 added per volume of space = $\{\log_{10}[100/(100\text{-}\%CO_2)]/0.434\}$

Table A-3 NFPA/FM CO_2 Factors: Surface Fires
(NFPA/FM Table 2-3.3)

GROSS VOLUME (ft^3) OVER:	BUT NOT OVER:	FLOODING FACTOR ($ft^3/lb\ CO_2$)	CALCULATED % VOLUME CONCENTRATION*
0	140	14	47.4
141	500	15	45.1
501	1,600	16	43.0
1,601	4,500	18	39.3
4,501	50,000	20	36.2
50,000		22	33.5

* Assuming one pound of CO_2 expands to 9 cubic feet when released, the % volume concentration of CO_2 is calculated from:

volume of CO_2 added per volume of space = $\{\log_{10}[100/(100-\%CO_2)]/0.434\}$

Table A-4 NFPA/FM CO_2 Factors: Deep-seated Fires (NFPA/FM Table 2-4.2.1)

DESIGN CONC.	FLOODING FACTOR (ft^3/lb CO_2)	HAZARD	CALCULATED % VOLUME CONCENTRATION*
50	10	Dry electrical hazards in general. (Spaces 0-2,000 ft^3).	59.3
50	12	(Spaces greater than 2,000 ft^3).	52.7
65	8	Record (bulk paper) storage, ducts and covered trenches.	67.5
75	6	Fur storage vaults, dust collectors.	77.7

* Assuming one pound of CO_2 expands to 9 cubic feet when released, the % volume concentration of CO_2 is calculated from:

$$\text{volume of } CO_2 \text{ added per volume of space} = \{\log_{10}[100/(100-\%CO_2)]/0.434\}$$

Table A-5 CFR Branch Line Sizes (Reference 1, Table 34.15(e)(5))

Max. Quantity of Carbon Dioxide Required (lbs)	Minimum Pipe Size (in)	Max. Quantity of Carbon Dioxide Required (lbs)	Minimum Pipe Size (in)
100	½	2,500	2 ½
225	3/4	4,450	3
300	1	7,100	3 ½
600	1 ¼	10,450	4
1,000	1 ½	15,000	4 ½
2,450	2		

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APPENDIX B:

CO_2 System Failure Modes and Effects Analysis

A FMEA is a tabulation of failure modes of equipment and the resulting effects on a system or plant. It generates a qualitative, systematic reference list of system components, failure modes, and their effects. A detailed Failure Modes and Effects Analysis (FMEA) was performed for a high pressure CO_2 system in three modes of operation; full discharge, standby, and installation test. The full FMEA tables for each of these modes are listed at the end of this appendix.

A high pressure CO_2 system from a large modern cruise ship was utilized for the FMEA. A diagram of the system is shown in Figure B-1. The principal dimensions of the ship are 218 meters length overall, 31 m in beam, and a height above the keel of over 40 m (13 decks). There are eight engine room compartments protected by the main CO_2 system. As indicated in Table B-1, these eight compartments are served by various combinations of six banks of 100-lb CO_2 cylinders. Activation alarms are sent to the bridge, engineering control, and the compartments affected. The eight actuation valves for the various compartments are contained in an enclosed control panel.

Table B-1. Zones of Operation

Zone	Bank(s)	Total Number of 40 Kg. $C0_2$ Cylinders
A. Aft Engine Room	1-2-3-4-5-6	91
B. Fore Engine Room	1-3-4-5	61
C. Engine Casing	1-3-6	59
D. P.E.M. Room	1-4-5	53
E. A.C. Compressor Room	1-3	36
F. Stabilizer Separator Room	2-4	27
G. Engine Control Room	3	8
H. E. G. Control Room	5	5

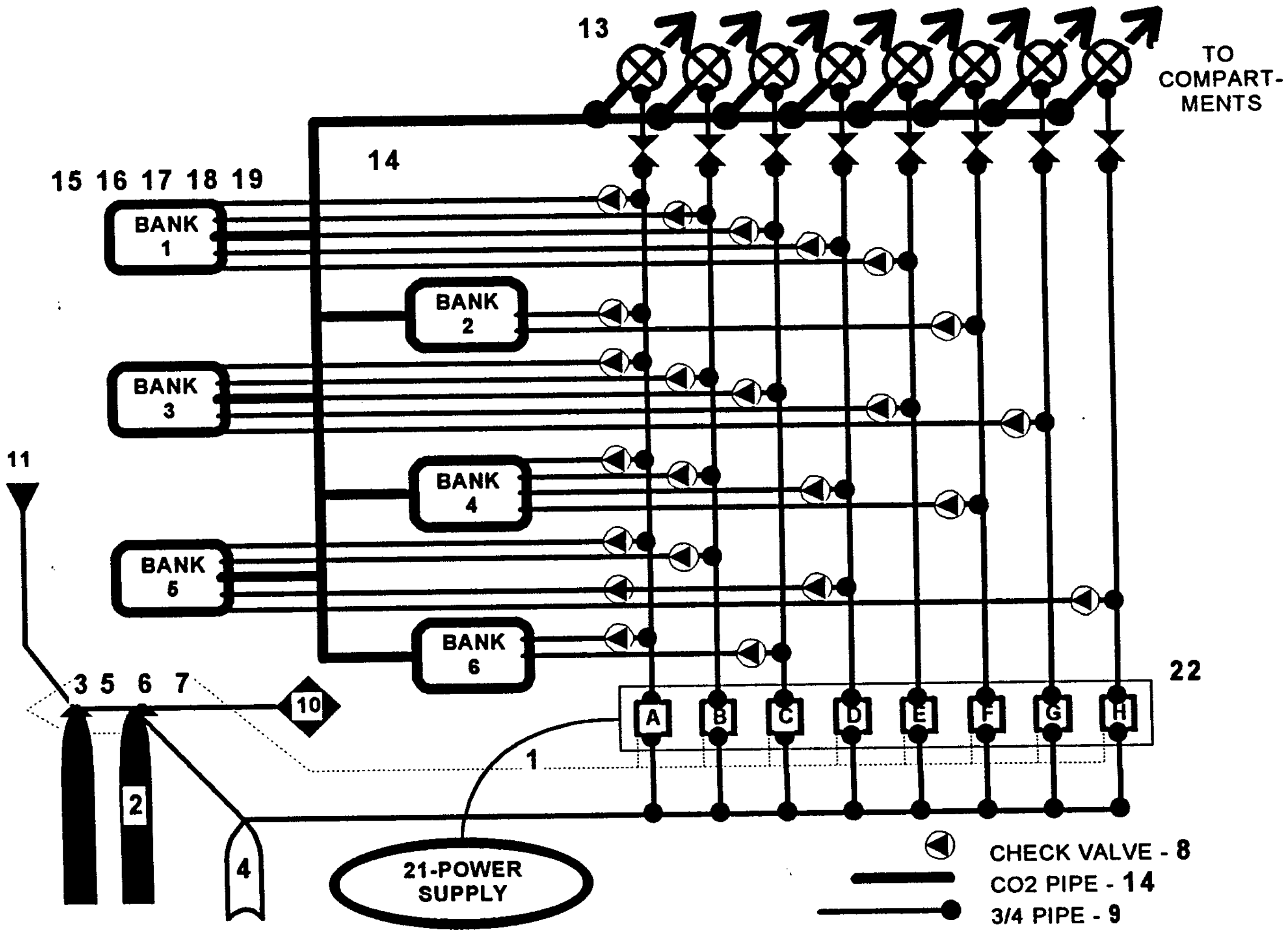


Figure B–1 Large Scale CO_2 System

Operating Mode

Operation of the CO_2 system in response to a detected fire is described in Table B-2.

Table B-2. Procedure for Normal System Activation

1	Opening of the door on the actuation panel closes contacts on a limit switch that signals visual alarms in engineering control, the bridge and the spaces affected by that particular actuation panel.
2	Rotation of the gas release handle (Item 22 in Fig. B-1) for a given compartment on the actuation panel trips a limit switch that drives the relays for the pilot cylinder solenoid valve, ventilation stop, and automatic door closing.
3	Pilot Cylinders (Item 2) are actuated by a solenoid valve (Item 6), and horns are activated to warn occupants of the effected compartments.
4	CO_2 from the pilot cylinders pressurizes the time delay cylinder (Item 4) over a preselected period of time (usually 35 seconds) to allow for the evacuation of the effected compartments.
5	After the time delay, the discharge hose (Item 9) becomes pressurized, and actuates the Automatic/Manual directions valves (Item 13) opening the large diameter piping from the main CO_2 banks to the compartment to be flooded. In addition, the cylinder valves (Item 17) are actuated for the banks to be exhausted, allowing the necessary quantity of CO_2 to flood the compartment.

All the components are listed by part number within the FMEA for System Actuation, located in the tables at the end of this appendix.

Standby Mode

Standby mode is the mode that the system is in for the majority of its operating life. It is the mode in which the system is basically "asleep", waiting to be used.

Testing

In order to perform this test, the system was modified by disconnecting the bank of CO_2 cylinders and connecting temporary cylinders, as well as three valves. This is shown in Figure B-2. These cylinder typically contain much less CO_2 than the banks do. These tests are just used to "blow the pipes down", and insure that the multiple actuation valves are working properly. The test procedure is described as follows

Preparation for the Test

As the ship studied called on U.S. ports, a Coast Guard procedure was prescribed, and is shown below in Table B-3.

Table B-3	
Preparation for Test	
1	A, B and C temporary valves to be closed.
2	Pilot cylinders (Item 2) electronically disconnected.
3	Disconnection of the existing flexible hose of the pilot cylinders (Item 3).
4	Connection by 10mm alloy pipe, between the temporary CO_2 test cylinders, the pilot cylinders and the main CO_2 cylinder banks line.
5	For safety reasons, the flexible hoses (items 3 and 16) of the CO_2 copilot cylinders and banks are to be disconnected.
Phase 1 of Testing	
1	Opening of temporary CO_2 test cylinders.
2	Opening of the valve in the actuation station (Items 1 and 22) relevant to the chosen room.
3	Opening of the A temporary valve to simulate release of CO_2 from the pilot cylinders.
4	Checking the pneumatic time delay (Item 4) of the relevant copilot pistons and of the relevant direction valve (Item 13).
Phase 2 of Testing	
1	After the phase 1 checking, opening the B temporary valve.
2	Checking the CO_2 discharge in the chosen room
3	Closing the A and B valves at the end of testing.
Phase 3 of Testing	
1	After the conclusion of phase 2, opening of the C temporary valve to discharge the residual CO_2 from the pipes
2	Reset the open pistons of the copilot cylinders
3	Connection of all the released pipes and valves.

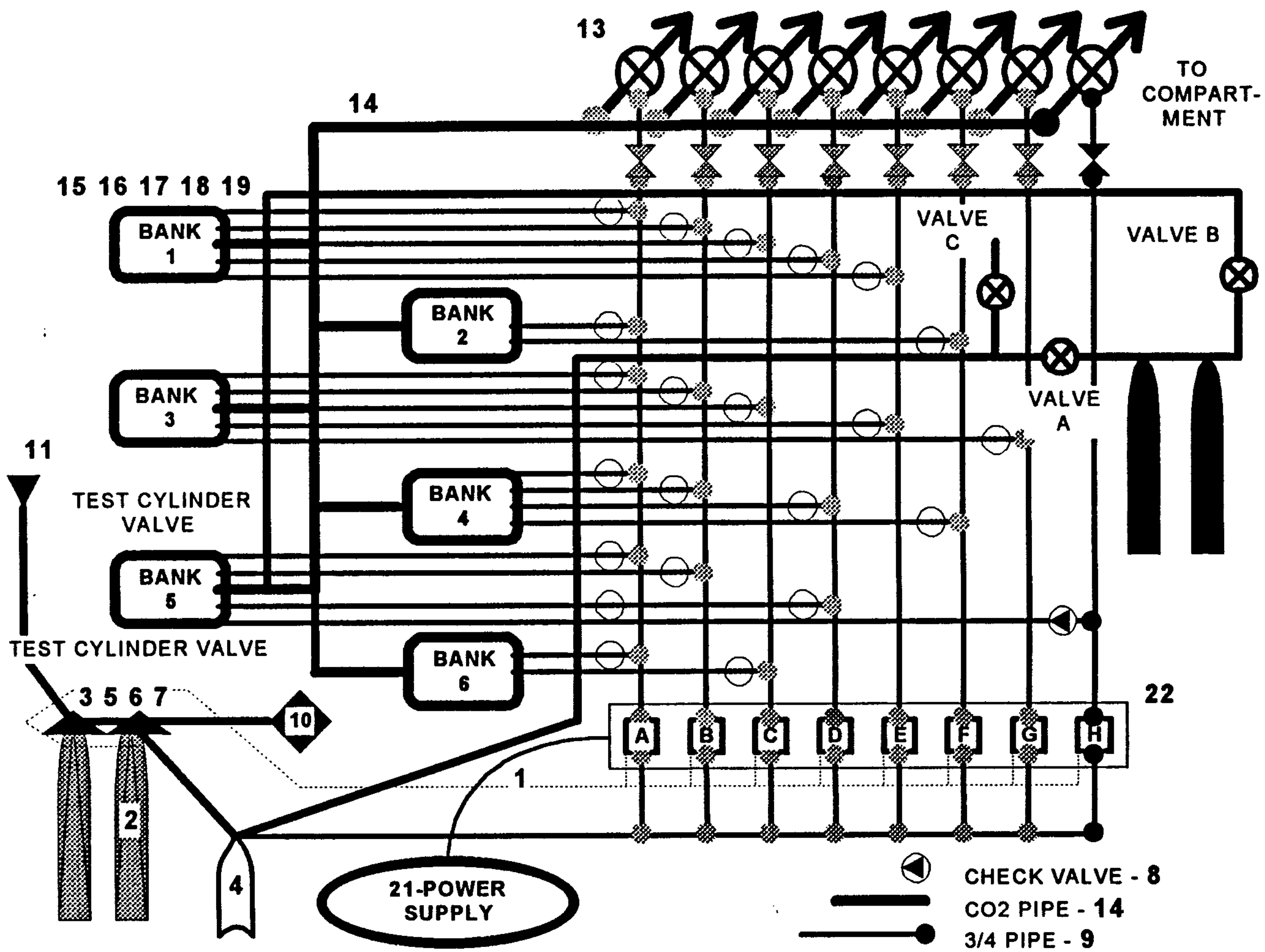


Figure B–2 Large Scale CO_2 System Testing

The FMEA Procedure

The columns of the full FMEA tables included the following information:

Table B-4	
1	Item number and name
2	Operating condition of item in given operating scenario Is the item normally open or closed? On or off? This is only for the condition in which the system is operating.
3	Failure modes. This is a description of how the equipment fails (open, closed, on, off, leaks, etc.).
4	The cause of failure.
5	The possible effects of failure on the system.
6	Criticality of the failure. How important is it?
7	Possible action to reduce failure rate or effect.

A diagram of the system studied is shown in Figure B-1. An example is given to explain how the various columns listed above were developed. This is a description of the FMEA for Item 13, the automatic/manual directions valves, is shown below in Table B-5.

Table B-5		
Operating condition of item in given operating scenario:		Normally open when the system is actuated.
Failure modes:		
	Partially obstructed	
	Fully obstructed	
	Cracking (housing)	
	Packing failure	
	Manually open to wrong compartment	
Cause of failure		
	Partially obstructed	
		Improper manufacture
		Improper installation
	Fully obstructed	
		Improper manufacture
		Improper installation
	Cracking (housing)	
		Improper manufacture
		Improper installation
	Packing failure	
		Improper manufacture
		Improper installation
	Manually open to wrong compartment	
		Failure to reset after a test
		Operator opens wrong valve
Possible effects of failure on system		
		Reduced flow rate
		No CO_2 delivered
		Reduced flow quantity/No flow
		Reduced flow rate/ No flow
Criticality		
	All of these types of failure were deemed to be primary, due to the potential for either no flow of CO_2 or the potential for exposure of the crew to CO_2 and the resulting danger that this imposes.	
Possible Action to Reduce Failure Rate or Effect.		
	For most of these problems, regular inspection, proper operating procedure or regular flow testing will result in a minimization of risk.	

A component was considered of primary concern if its failure in operation led to a complete failure of the system to extinguish the fire, with no possibility of the component being bypassed so that its failure would be of less consequence. A component was also considered to be of primary concern if its failure threatened the life of the crew or passengers. A component was considered of secondary importance if its failure in operation might result in a change in standard operating procedure of the system, but whose failure could be bypassed in some way.

Conclusions

It appears that many of the mishaps listed above can be remedied by following regular inspection and testing procedures. There seems to be a very real potential for incorrectly opening a manual valve which will admit CO_2 into an occupied, unwarned compartment full of CO_2, and in fact situations like this do occur. For the primary concern, failure in full discharge mode, two of those components have failure modes that could prevent any CO_2 from being delivered into the intended machinery space. It is apparent that these failure modes occur directly from obstructions in the CO_2 delivery system. Four other components have failure modes that could result in significantly reduced CO_2 concentrations in the machinery space. Two other components (directional valves and control panel switches actuating these valves) have failure modes that could prevent CO_2 from being discharged and/or could allow discharge into an unintended, occupied area.

APPENDIX C

CO_2 System Pipe Length Limitations

The effectiveness of fixed CO_2 fire extinguishing systems in combating fires is a function of numerous variables. Some of the more important ones include: design CO_2 concentration, discharge time, distribution of the CO_2 within the protected space, and hold time. Fire codes and bodies of regulation attempt to address these variables in different ways. This appendix considers whether Coast Guard Regulations (46 CFR) are sufficient (when compared to NFPA 12) to ensure uniform distribution of the CO_2 within the protected space, especially when faced with distribution piping of varying lengths.

Coast Guard regulations for fixed CO_2 systems (46 CFR 34.15-5(e)) specify that "The number, type and location of discharge outlets shall be such as to give a uniform distribution throughout the space." NFPA 12 specifies that discharge nozzles must be located to "achieve the best results" (NFPA 12 2-5.5). The reader must assume that "achieving the best results includes ensuring a uniform distribution of CO_2 within the space.

To achieve uniform distribution of CO_2 within the protected space, the CO_2 must be uniformly distributed both vertically and laterally. Lateral distribution is primarily affected by the number and location of nozzles. Vertical distribution is affected by the number and location of nozzles, and the degree to which the CO_2 mixes with the ambient air. In cases where there is poor mixing, the cold CO_2 forms a discrete mass of gas which is heavier than the ambient air. Under these conditions, settling of the CO_2 to the bottom of the compartment may be expected. In instances where the mixing in the vicinity of the nozzle is good, the density difference between the incoming (mixed) gas and the ambient air is low and stratification within the space is minimized.

Neither 46 CFR nor NFPA 12 offer any more concrete guidance concerning the lateral distribution of the CO_2 than the above, general, uniform distribution requirement; determining the number and spacing of nozzles is left to the designer. NFPA 12 does provide some guidance toward achieving vertical distribution where 46 CFR does not. NFPA 12 requires that the pressure drop across the distribution nozzles be at least 300 psi (2068 kPa) for high pressure systems, and 150 psi (1034 kPa) for low pressure systems. Pressure drops of these magnitudes are assumed to be sufficient to ensure significant turbulent mixing in the area of the nozzle.

It is, at this point, worthwhile to consider whether the pressure drop requirement in NFPA 12 actually results in more uniform vertical distribution of CO_2 when compared to 46 CFR systems. Criteria for high pressure systems are used because high pressure systems are much more common than low pressure systems in marine use. To make this comparison, two issues must be considered. First, the 300 psi specified in NFPA 12 does not represent a mixing "cutoff" (i.e., mixing at higher pressures, no mixing at lower pressures). 300 psi is that pressure deemed by the NFPA to produce sufficient mixing. Second, pressure drop across the nozzle is not a variable which can be controlled independently. The pressure drop is a function of initial storage pressure (assumed to be 750 psi (5170 kPa) which is the vapor pressure of liquid CO_2 at 70°F (21°C)), the piping geometry (length and diameter) and the orifice diameter.

While it is the intent of this analysis to compare the abilities of 46 CFR and NFPA 12 to ensure uniform CO_2 distribution, in fact it is only comparing pressure drops through the nozzles. These pressure drops may only be considered an indicator of CO_2 distribution. Ensuring uniform CO_2 distribution within a space would require either a fully validated 3D mathematical model or 3D post installation CO_2 concentration testing. Neither 46 CFR nor NFPA 12 requires these steps.

The analysis is conducted using system sizing information contained in 46 CFR 34.15-5 (Table C-1) and pressure drop calculations contained in NFPA 12. The NFPA required pressure drop of 300 psi will be used to determine equivalence. The analysis will be conducted in two sections. The first section will consider whether systems which discharge as slowly as permitted by Coast Guard Regulations (85% of the required CO_2 within 2 minutes) meet the NFPA pressure drop requirement. The second section will consider the maximum length of distribution piping that will produce a pressure drop at the nozzle of at least 300 psi. English units will be used throughout the analysis in keeping with the units used in the CFR. The subscripts min and max will be used throughout the following calculations. In all cases the subscript min is associated with values derived from the minimum permissible orifice area. The subscript max is associated with values derived from the maximum permissible orifice area.

Table C-1

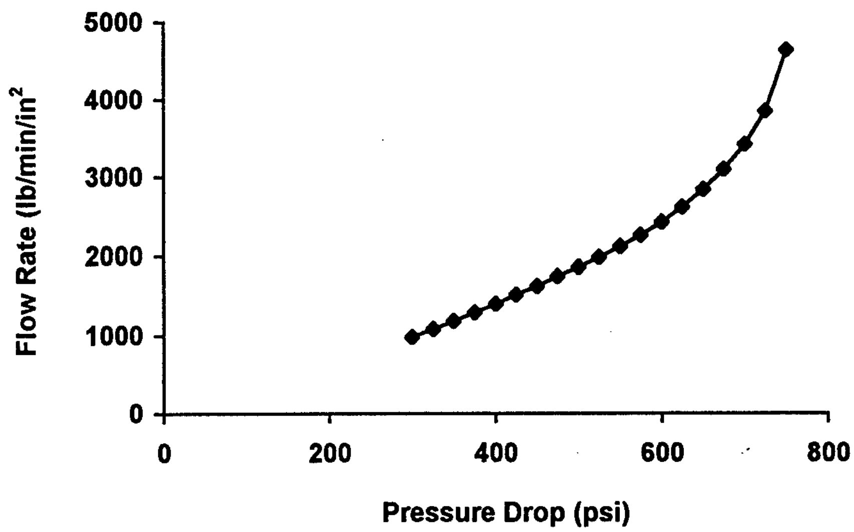
System Size (W) (lb)	300		2500		10450	
Orifice Size	min	max	min	max	min	max
Nominal Pipe Dia. (in)	1		2.5		4	
Inside Dia. (ID) (in)	.957		2.32		3.83	
$ID^{1.25}$	.946		2.86		5.34	
ID^2	.916		5.40		14.6	
Flow Rate (Q) (lb/min)*	128		1063		6375	
Orifice Area (in^2)	.23	.56	1.93	4.68	8.05	19.5
Spec Flow Rate (q) (lb/min/in^2)**	554	228	550	227	552	227

* $Q = W * 85\% / 2_{min}$
** $q_{min} = Q$ / min orifice area
** $q_{max} = Q$ / max orifice area

Graph C-1 was derived from the pressure drop/flow information for high pressure systems contained in NFPA 12 table 1-10.4.4. From the graph it can be seen that a specific flow rate (q) of 980 lb/min/in^2 is necessary to create the 300 psi pressure drop required by NFPA 12. Since q_{min} (approx 552 lb/min/in^2) and q_{max} (227 lb/min/in^2) from Table C-1 are significantly less than

980 lb/min/in^2, it should be apparent that a CO_2 system operating at the minimum delivery rate required by 46 CFR can never meet the NFPA pressure drop requirement.

Graph C-1



The basis for the second part of this analysis is that the actual discharge rate for a system is a function of both orifice size and pipe geometry and, as a result, the actual discharge time may be significantly less than the maximum permitted by regulation. It can be seen from Graph C-1 that if the discharge rate increases (discharge time decreases) that the pressure drop across the nozzle increases. It is therefore possible for a system designed to 46 CFR specifications to meet the NFPA 300 psi pressure drop requirement.

Determining the conditions under which a system will discharge at a sufficient rate to meet the pressure drop requirement requires that two conditions be simultaneously satisfied. The first condition is that the total pressure drop in the system (P_t) is 750 psi. This pressure drop is produced by two components, the pressure drop through the orifice (P_o) and the frictional pressure drop of the fluid flowing through the distribution piping (P_f) as shown in Equation 1.

$$P_o + P_f = P_t = 750 \text{ psi} \qquad \text{Equation 1}$$

The second condition which must be satisfied is that the flow rate (Q) through the nozzle and the pipe must be equal. This flow rate is an implicit function of P_o and P_f as shown in Equations 2 and 3.

$$P_o = f(Q, \text{orifice area}) \qquad \text{Equation 2}$$

$P_f = f(Q, \text{pipe length, pipe diameter})$ Equation 3

Ideally, the discharge characteristics of a system could be fixed by the simultaneous solution of these three equations. In practice, the complexities of these functions requires the employment of Graphs C-1 and C-2 to solve for P_o, P_f and Q.

Just as in the first section of this analysis, if 300 psi is selected as the critical pressure drop across the nozzle, Graph C-1 indicates that the specific flow rate will be equal to 980 $lb/min/in^2$. Prior to entering Graph C-2, the specific flow rate must be converted to an actual flow rate (Q) (lb/min) (Table C-2) through the use of the minimum and maximum orifice areas. The calculated Q values along with the pipe diameter information contained in Table C-1 and a terminal pressure of 300 psi may be used to enter Graph C-2. The terminal pressure is the pressure at the end of the piping system. It is equal to the pressure drop through the orifice since the pressure of the gas after passing through the orifice is 0 psig.

Table C-2. INPUT FOR GRAPH C-2

System Size (W) (lb)	300		2500		10450	
Orifice Size	Min	Max	Min	Max	Min	Max
Nominal Pipe Dia. (in)	1		2.5		4	
Inside Dia (ID) (in)	.957		2.32		3.83	
ID^2	.916		5.40		14.6	
Orifice Area (in^2)	.23	.56	1.93	4.68	8.05	19.5
Spec Flow Rate (q)	554	228	550	227	552	227
Q_{actual} (lb/min)*	225	548	1891	4586	7889	19149
Q_{actual} (ID^2)	246	599	350	849	539	1307
Terminal Pressure (psi)	300		300		300	

* Q_{actual} = 980 $lb/min/in^2$ * orifice area (max or min)

The output from Graph C-2 is the equivalent length of pipe required to cause the pressure in the piping system to drop from the storage pressure (750 psi) to the terminal pressure (300 psi). Table C-3 contains two sets of equivalent pipe length information. These lengths correspond to the minimum allowable orifice area ($L_{e(min)}$) and the maximum allowable orifice area ($L_{e(max)}$). The equivalent length of pipe consists of the actual length of straight pipe plus additional lengths for tees, elbows, and other fittings. Pipe lengths shorter than those listed in Table C-3 will yield higher flow rates, higher pressure drops through the nozzles, and shorter actual discharge times. Conversely, longer pipe runs will result in lower flow rates, lower pressure drops through the nozzle, and longer discharge times.

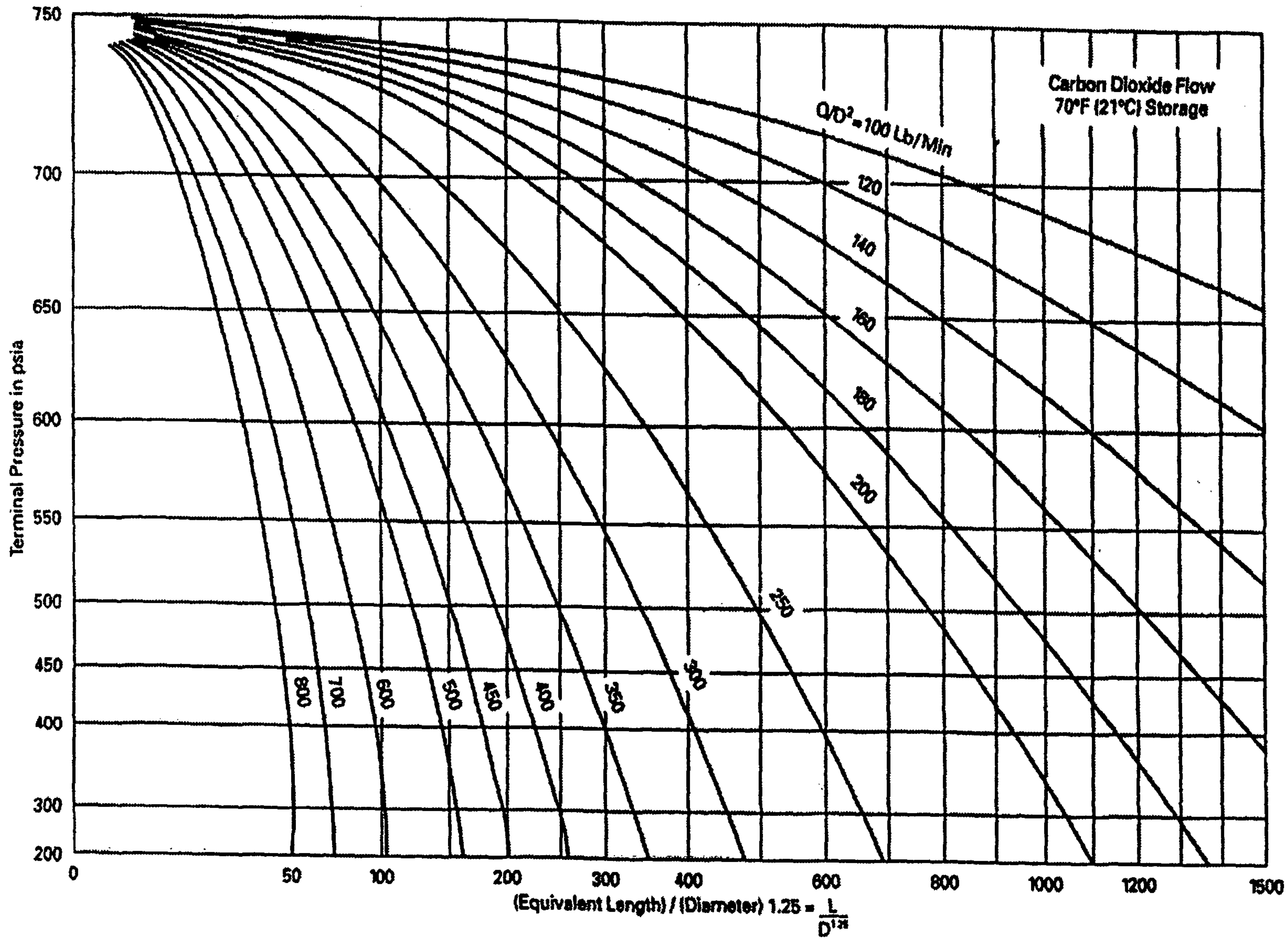


Figure C–1. Pressure Drop in Pipeline for High Pressure Systems (Figure A–1–10.5B of NFPA 12)

Table C-3. OUTPUT FROM GRAPH C-2

System Size (W) (lb)	300		2500		10450	
Orifice size	min	max	min	max	min	max
Nominal pipe dia (in)	1		2.5		4	
Inside Dia (ID) (in)	.957		2.32		3.83	
$ID^{1.25}$	.946		2.86		5.34	
$L_e/ID^{1.25}$*	675	105	330	45@	140	#
L_e (ft)	639	99	945	129@	747	#
Discharge time (min)	1.33	.55	1.32	.55	1.32	.55

* Obtained from Graph C-2
@ Extrapolated from Graph C-2
# Extrapolation not possible

Conclusions

1. Neither 46 CFR nor NFPA 12 provide quantitative means to assure uniform distribution of CO_2 within the protected space. Both 46 CFR and NFPA 12 state that nozzles must be placed to yield a uniform distribution but neither provide a design or test method to accomplish this goal.

2. NFPA 12 includes a pressure drop across the nozzle requirement to ensure through mixing in the area of the nozzle. 46 CFR does not. The value of this requirement will be further discussed in subsequent conclusions.

3. CO_2 systems which require the entire period allowed by 46 CFR to discharge cannot meet the NFPA requirement for a 300 psi pressure drop through the nozzles.

4. The actual discharge time for CO_2 systems is a function of, among other things, pipe length. While the length of pipe required to make a system discharge as slowly as permitted by 46 CFR cannot be readily calculated using the NFPA methods, the length is "very long".

5. For 5 of the 6 cases considered, CO_2 systems designed to 46 CFR and having reasonable lengths of distribution piping will meet the NFPA requirement for a 300 psi pressure drop through the nozzle. If it is determined that it is desirable to meet the NFPA requirement in all cases, for large volume systems consideration should be given to: reducing the maximum allowable orifice size, increasing the diameter of the distribution piping, or requiring the submission of pressure drop calculations as part of the system approval process.

6. Pressure drop calculations, in and of themselves, are not sufficient to ensure the uniformity of CO_2 distribution within a space. This situation could be improved through the development and validation (at both small and full scale) of a computer model. This model could be used either as a design tool for performance based regualtions or by the Coast Guard to develop perscriptive

codes. Alternatively, a post installation discharge test which measures the CO_2 concentration in three dimensions could be imposed.

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APPENDIX D

Summaries of Representative CO_2 System Problems in Selected Incidents

Machinery space fire incidents which involved a CO_2 suppression systems discharge that resulted in extinguishing the fire are not discussed. Only those CO_2 discharge incidents which resulted in the fire being temporarily extinguished, controlled, or not extinguished are summarized below. All quotes are taken from the accident reports and are not referenced. Authors' comments are provided for each incident described.

D.1 Enerchem Asphalt

An explosion in the engine room blew open an engine room door. Upon locating the resulting fire, the chief engineer ordered the dampers in the funnel, the ventilation system, and all the doors into the engine room closed down. The chief engineer then discharged the CO_2 extinguishing system, approximately ten minutes after the fire started. However, a small amount of smoke was observed escaping through air vents and around the funnel. Thus, the engine room was not completely sealed. When shore-based fire fighters entered the engine room, they observed that the fire had re-ignited with "great" intensity.

Authors' Comment: Most likely the reason for not being able to seal the engine room is due to the initial explosion deforming the door jamb, and possibly any other closed vent at the time. When an attempt was made to close the door after the explosion, it did not completely seal. Therefore, after activation of the CO_2 system some CO_2 leaked out. This leakage together with the dilution associated with the fire fighter's entry into the engine room resulted in an insufficient concentration to suppress the fire.

D.2 Protector Alpha

Fuel oil overflowed a diesel tank and was ignited by contact with the exhaust manifold of a ship's service generator. A subsequent explosion blew open the centerline door. A period of 45 to 55 minutes after the fire started was required for search and rescue efforts before the CO_2 system was activated. Additionally, this vessel was manned by Filipinos and had Greek owner's representatives onboard at the time of the fire. The instructions for the CO_2 system were written in German. No one onboard at the time of the fire could read the CO_2 instructions.

Authors' Comment: This incident has two points. The first is that the instructions for the CO_2 suppression system must be written in a language all crew members can understand. The second point is that even if the engine room had been sealed, the effectiveness of the CO_2 would probably have been limited since the fire was allowed to grow for at least 45 minutes after ignition. This size fire presents a high challenge to a CO_2 system.

D.3 Mara Hope

This fire started in the engine room bilge at approximately 1850 while the vessel was moored at a repair facility. A shore-based fire department responded and firefighters were told upon their arrival, at 1909, that people were trapped in the engine room. Search and rescue efforts resulted in no persons being found in the engine room. At 1930 the fire department was notified that all personnel were accounted for and they began pumping foam into the engine room. Since the foam was not effective, the vessel's fixed CO_2 system was activated. The CO_2 system was not effective due to the engine room not being sealed. The fire burned for about 41 hours before being extinguished with high expansion foam.

Authors' Comment: Like the previous case, if the engine room had been properly sealed prior to discharge, the CO_2 most likely would not have had limited effectiveness due to the length of time between ignition and activation of the CO_2 system; more than 40 minutes in this case.

D.4 Saratoga

Apparently, a hydraulic pump hose ruptured and sprayed hydraulic fluid onto the casing of a diesel engine thus igniting a large spray fire. The chief engineer pulled the releasing gear for the fixed CO_2 fire extinguishing system. No crew members saw any CO_2 escaping from the engine room or heard the audible CO_2 alarm. Therefore, "the CO_2 fire extinguishing system either malfunctioned or failed to activate."

Authors' Comment: This is the only incident (out of 17 incidents described in this appendix) in which the CO_2 system failed to discharge upon an activation attempt.

D.5 Maersk Oakland

The fire was discovered at 2336. After fighting the fire with portable extinguishers, the fire was declared out of control at 2343. At 0010 "All but one of the ventilation sources to the space were then secured. The mechanical means of securing the ventilation ducts near the top of the main stack did not function properly. Tarpaulins were used to partially block this ventilation source into the engine room." The fixed CO_2 system was activated at 0120 under the supervision of a shore-based fire department. "The CO_2 system did not completely extinguish the blaze..."

Authors' Comment: Since this fire burned for one hour and 40 minutes before the CO_2 system was activated, there may have been fire damage to various closures including tarpaulins.

D.6 Princess Tamara

"About 0600 a fire broke out on the main electrical switchboard in the engineroom. The fixed CO_2 fire extinguishing system which protected the engineroom was activated, but it did not extinguish the fire because the crew opened hatches to the engineroom shortly after the CO_2 was released." The report states that this allowed fresh air to enter the engine room and thus supplied the fire with oxygen.

Authors' Comments: This is an obvious case of improper training or negligence since the CG regulations require closure of all ventilation onpenings.

D.7 Curlew

A fire was discovered about 0600 that engulfed "the entire port side of the engineroom". A crewmember "notified the master who operated the remote release for the fixed CO_2 system in the engineroom. The engineroom vents were left open." The CURLEW burned and sank.

Authors' Comments: Ostensibly, the ventilation was not secured. The question is whether this was due to improper training or due to somebody panicking and forgetting to secure the engine room ventilation.

D.8 Madelyn G.

About 1530 a fire was discovered in the engine room and "there were flames throughout the bilges." The chief engineer said, "after waiting a few minutes to allow everyone to "get clear", he released the CO_2". "...the ventilation blowers were probably turned off by the release of the CO_2. However, a hatch in the upper level of the engineroom had been left open,..."

Authors' Comment: Another case of not securing the ventilation before discharging the CO_2.

D.9 American Queen

Fire was discovered about 1730. "About 1750, the chief engineer released the CO_2 into the engineroom and secured the engineroom door." No flames were seen when the engine room door was opened at 1830. Flames were observed at 1900 when the engine room was again checked. At this point the vessel was abandoned and subsequently sank.

Authors' Comment: This is an example of a possible re-ignition due to the opening of a door allowing air entry and CO_2 dilution.

D.10 Charleston

A lube oil leak occurred during unsupervised and unscheduled work on lube oil pressure gauges. The lube oil spray contacted the steam turbine casing and ignited. "The fire quickly spread from the turbogenerator to the upper level of the engineroom. Initial firefighting attempts with portable CO_2 extinguishers were unsuccessful and the intensity of the fire increased. After evacuating the engineroom and accounting for crewmembers, the fixed CO_2 system was activated. The fire was extinguished by the exhaustion of the lube oil supply."

Authors' Comment: Besides the delayed actuation time, another important factor in this fire may have been an insufficient CO_2 concetration in the upper region of the engine room.

D.11 Lujua

A lube oil spray fire resulted from negligence of a crew member. This incident has both a letter report and a Coast Guard vessel accident report (CG-2692). The letter report states: "The fire was extinguished by shutting down the main engine and flooding the engineroom with carbon dioxide." The vessel accident report states: "The engine room was then evacuated and the CO_2 system was then put into use to try and put the fire under control. CO_2 fire extinguishers were also used to bring the fire under control."

Authors' Comments: The description of this incident is too cursory to determine the true effectiveness of the CO_2 system. It appears that the fixed CO_2 system controlled the fire sufficiently to allow the crew to fully extinguish the fire with portable extinguishers.

D.12 Fidelity

Fire discovered at approximately 1945. When the fire was declared out of control, the main engine, the generator, and the engine room mechanical ventilation were shut down. Prior to 2009, all personnel were evacuated from the engine room and all ventilation dampers and entrances to the machinery space were closed. The master then activated the fixed CO_2 system. At 2200 the machinery space was checked for flames. Small pockets were found and the space was "immediately vacated and again sealed." "At 2400 the fire was found to be completely extinguished..."

Authors' Comment: Difficult to assess this scenario. It appears that all the proper steps were taken prior to the release of the fixed CO_2. This case is listed as a "controlled" fire due to the time between when the CO_2 was released and when the space was checked, about two hours. The CO_2 did not fully extinguish the fire after two hours, but it decreased the size of the fire so that it was no longer a threat to personnel or equipment.

D.13 Boheme

Fire in the machinery space reported at 1307 onboard this cruise ship while moored and embarking passengers. Passengers were ordered to disembark and by 1315 had done so. Also at that time the master remotely closed the engine room door and ordered the manual fire dampers closed. Shore-based fire department arrived at 1320. At 1345 "...CO_2 cylinders specified for the auxiliary engineroom and control room were released ...". "The initial application of CO_2 did not extinguish the fire. At 1355, the CO_2 cylinders specified for the main engine room were diverted to the auxiliary engine room. While the second application temporarily reduced the flames it did not totally extinguish the fire."

Authors' Comment: It is not clear why the CO_2 discharge did not extinguish the fire, but an earlier actuation would probably have been more effective.

D.14 Neoga

Straight forward; from the accident report: "The CO_2 system had little effect in containing or extinguishing the fire because the crew had failed to close engineroom accesses and vents in order to seal off oxygen to the fire." This fire also involved a fuel tank that had no external shut off valve. Thus, the fire burned for almost five days before consuming all the fuel.

Authors' Comment: From the accident report, this appears to have been a fast moving fire, with a CO_2 system discharge into an engine room with open vents and doors.

D.15 Weiho Career

Fire started about 0350 while the vessel was moored. Fire department arrived at 0403 and ordered all personnel off the vessel. Subsequent to the evacuation, "the engineroom CO_2 fire extinguishing system was activated, but it failed to extinguish the fire." "At 0700, additional CO_2 supplied by trucks on shore was applied to the engineroom. About 20 minutes later, foremen entered the deckhouse and extinguished the fire."

Authors' Comment: No mention is made of the status of the ventilation openings, etc., so it is not clear why the CO_2 wasn't more effective.

D.16 Jack D. Wofford

Heavy black smoke was observed coming from the engineroom. The engineer "stopped both main engines, exited and closed the engineroom door and discharged one bank of CO_2 bottles into the engineroom." Ten minutes later he checked the engineroom and found heavy black smoke. He left the engine room and "discharged the last bank of CO_2 bottles into the space. The fire was still not completely extinguished and had traveled up the bulkhead and through the electrical cable runs...".

Authors' Comment: Factors contributing to the limited effectiveness of the CO_2 system in this fire appear to be: 1) premature opening of the engine room to see if the fire was out; 2) flame propagation into the upper region of the engine room where CO_2 concentrations may be reduced; and 3) ineffective cable penetration stops.

D.17 Scandanavian Sun

As this cruise ship was preparing to disembark passengers after docking, a fire started in the auxiliary machinery space at about 2300. The report notes "the failure of the crew...to keep closed the watertight door and the self-closing fire door...". However, the master had ordered closed all automatic fire doors and stopped all ventilation fans at 2312. After 2324 the chief engineer released CO_2 "into what he thought was the [auxiliary machinery space]. Five days later Coast Guard investigators determined that the CO_2 had been released into a room not involved in the fire.

Authors' Comment: According to the CG report, the most likely reason the CO_2 was released into the wrong space is because the release mechanisms for the CO_2 systems were not adequately labeled.

D.18 Zorra

This was an engine room diesel fuel fire on the U.S.-flagged integrated tug-barge Zorra moored at a berth in Guanica Bay, Puerto Rico. According to the account in the August 1995 issue of Professional Mariner, crew "responded quickly to the fire by sealing off the engine room and activating the CO_2 system." Puerto Rican firefighters, assisted by the crew, attempted extinguishment for more than 12 hours before declaring the fire unmanageable. At that point, the Coast Guard was concerned about the fire igniting dockside tanks, and decided to tow the vessel away from the dock and ground it outside the shipping channel. The vessel was a total loss.

Author's Comments: Although the report said the engine room was sealed, it also describes a thick, black smoke plume engulfing a nearby school. It is not clear how long the engine room was sealed before the plume was observed. It is also not clear if there was any confirmation of the CO_2 system discharging, and how long firefighters waited before entering the engine room for manual firefighting.