REPORT NO: CG-D-09-83

AD A127977

EXTINGUISHING DEEP-SEATED CARGO HOLD FIRES WITH CARBON DIOXIDE

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Avery Point Groton, Connecticut 06340

MARCH 1983

FINAL REPORT

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PREPARED FOR
U. S. DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD

OFFICE OF RESEARCH AND DEVELOPMENT
WASHINGTON D.C. 20593

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Technical Report Documentation Page

1. Report No. CG-D-09-83	2. Government Accession No. AD-A127 977	3. Recipient's Catalog No.
4. Title and Subtitle EXTINGUISHING DEEP-SEATED CARGO HOLD FIRES WITH CARBON DIOXIDE		5. Report Date March 1983
		6. Performing Organization Code
7. Author(s) DAVID E. BEENE, JR., and ROBERT C. RICHARDS		8. Performing Organization Report No. CGR&DC 20/81
9. Performing Organization Name and Address United States Coast Guard Research and Development Center Avery Point Groton, Connecticut 06340		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Department of Transportation United States Coast Guard Office of Research and Development Washington, DC 20593		13. Type of Report and Period Covered FINAL REPORT
		14. Sponsoring Agency Code

15. Supplementary Notes
Performed at the U.S. Coast Guard Fire and Safety Test Detachment under the technical supervision of the U.S. Coast Guard Research and Development Center, Avery Point, Groton, Connecticut.

16. Abstract

This test program evaluated the effectiveness of carbon dioxide in extinguishing, controlling, and containing deep-seated Class A cargo fires. Tests were conducted to: (1) identify a Class A test fuel closely simulating cotton without its high cost; (2) determine an ignition source for creating and reproducing standard deep-seated fires; (3) create deep-seated fire scenarios in single bales of cardboard test fuel for comparison with, and modeling of, full-scale cargo hold tests; and (4) determine extinguishment, control, and confinement concentrations of carbon dioxide for Class A cargo hold fires. All testing was conducted at the U.S. Coast Guard Fire and Safety Test Detachment in Mobile, Alabama. The small-scale tests were conducted in a two hundred cubic foot (5.7 cu m) test chamber while the full- scale tests were conducted in a 37,000-cubic foot (1,048 cu m) cargo hold area aboard the test vessel SS MAYO LYKES.

The results indicated that: (1) corrugated cardboard with its low cost and rapid, sustained fire buildup represented the best Class A fuel substitute for cotton, (2) electric (charcoal) ignitors (120V, 525W) were found to maintain high, reproducible test temperatures inside the bales, (3) the single-bale chamber tests created model fire scenarios comparable to the full-scale tests for comparing time temperature curves and investigating the effects of different agent concentrations, (4) the extinguishment of a deep-seated Class A cargo hold fire at sea is highly unlikely using the quantity of carbon dioxide which a vessel can economically carry, (5) a carbon dioxide concentration of twenty-five percent or greater will, however, extinguish the superficial flames created by a deep-seated fire, and (6) this concentration will also contain and control the smoldering combustion to a rate which will not endanger the structural integrity of the vessel.

17. Key Words carbon dioxide, deep-seated cargo hold fires, ignition sources	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

METRIC CONVERSION FACTORS

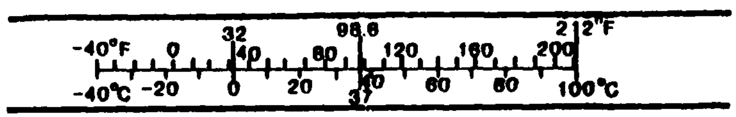
Approximate Conversions to Metric Measures

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). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.

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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1.0 INTRODUCTION

1.1 Problem Statement

Recent developments of new classes of fire extinguishing agents have prompted a reevaluation of fixed fire extinguishing systems used for the protection of cargo holds. At present, a fixed carbon dioxide or other approved system shall be installed in all cargo compartments and tanks for combustible cargo.[1] This rationale is based on the reliability of carbon dioxide systems in suppressing actual fires in cargo holds. Approval of alternate systems using Halon 1301 is made on an individual basis. An exemption from these requirements is given to bulk carriers exclusively engaged in carrying coal and grain.

The effectiveness of Halon or foam agents has been demonstrated by Factory Mutual Research Corporation, Underwriters Laboratories, the U.S. Navy, and other fire research organizations for use against Class A and B fires in buildings, aircraft, and engine compartments.[2,3,4] However, Coast Guard regulations do not recognize Halon or foam for cargo hold fire protection requirements. Testing is needed to determine if the application of carbon dioxide or the alternate extinguishing agents is effective against a deep-seated Class A fire.[2,5-10] Determination of the safety factor in existing carbon dioxide systems and establishment of criteria for concentration and soaking time requirements are important points and are areas in which the National Fire Protection Association (NFPA) standards are deficient. Test results are needed to determine:

a. What concentrations are effective in controlling and extinguishing Class A fires?

b. What concentrations are effective in containing and confining deep-seated fires to their point of origin?

c. How critical is soaking time and the time between agent discharges?

No large-scale testing within cargo holds had previously been undertaken to determine equivalency between existing carbon dioxide and alternate protection systems. Standard installation practices for cargo vessels have not been established by regulatory agencies. Small-scale testing does provide some data on agent performance, but due to the uncertainty of variables in fire testing, controlled full-scale experiments provide the most reliable results.

The carbon dioxide extinguishment tests were part of a full-scale test series designed to evaluate the relative effectiveness of carbon dioxide, Halon 1301, Halon 1211, and high expansion foam. At this time the Halon tests have been indefinitely postponed since the need for Coast Guard regulations governing the use of these agents in cargo hold fire situations has been withdrawn. This is attributed to the lack of industry interest and participation resulting from their concern for the effects of Halon on the environment. All test data from these carbon dioxide tests will be maintained to provide a head start in the event that the Halon testing is conducted in the future. High expansion foam tests would be conducted subsequent to the Halon tests.

1.2 Objective of Test Series

The carbon dioxide cargo hold extinguishment test series was intended to reevaluate carbon dioxide systems used on board cargo vessels and to serve as a data base for the evaluation of newer agents. To pursue this goal, the following objectives were established:

1.2.1 Primary Objectives

a. Create a deep-seated Class A fire with a fuel that simulates fire scenarios typically found in break-bulk cargo vessels. The choice of the fuel would be made by comparison with cotton in small-scale testing.

b. Reproduce this "standard" fire to allow the same thermal buildup to be used for each test. This required fixing all the independent variables in the test except agent concentration.

c. Determine extinguishment, control, and containment concentrations of carbon dioxide and provide the quantitative information needed to evaluate and compare other agent performances.

1.2.2 Secondary Objectives

a. Compare time-temperature traces and control times from test fires in a small 200 cubic foot (5.7 cu m) chamber to those of full-scale cargo hold tests.

b. Measure agent concentration as a function of height in the hold.

1.3 Background

Each year explosions and fires take place within the cargo holds of vessels. In the fiscal years 1972 through 1976, 78 fires were recorded for inspected U.S. cargo vessels. Of these fires, 36 percent were in cargo holds, 42 percent in machinery or boiler spaces, and the remaining 22 percent in miscellaneous ship spaces. Estimated monetary losses totaled $2.4 million for damage to the vessels and over $3.0 million for damage to cargo.[11] An examination of the combustible material involved in these cargo fires revealed that one quarter involved fibrous materials, such as cotton, hemp, or jute; one quarter involved consumable commodities, such as rice, corn, flour, or dry milk; one quarter involved chemicals or autos; and one quarter involved unspecified items or were termed general.

Deep-seated fires result from the ability of a fire to penetrate into the bulk of a material. They represent a worst-case cargo fire. National Fire Code 12A defines a deep-seated fire as one in which a 5 percent concentration of Halon 1301 will not provide extinguishment within ten minutes of application. Extinguishment of these fires often presents an especially difficult problem to a fire protection system. Cargo within a hold is generally close-packed and when a fire erupts, it is often the deep-seated variety with the characteristic burrowing of the fire into the cargo and the generation of dense smoke. The arrangement of cargo and its thermal insulation characteristics can hinder the penetration of an extinguishing agent into the affected areas and flashback can occur.

The present requirement for using carbon dioxide in the protection of cargo vessels has evolved as a result of testing done on board the U.S. Liberty Ship PHOBOS in 1946.[10] The cargo was made up of 1300 standard bales of low-grade cotton loaded in the hold. Concentrations of up to 90 percent carbon dioxide and soaking times of several days were required to extinguish this stubborn fire. It was concluded that while carbon dioxide may not be completely successful in extinguishing a fire, a judicious application of agent and tight closure of the affected hold would allow a vessel to return to port safely. Actual experience has verified this, with carbon dioxide suppression systems being successful in controlling fires in numerous instances. This has resulted in the savings of thousands of dollars worth of cargo and improved safety of life at sea.

A cargo vessel is now required to carry a sufficient quantity of carbon dioxide to control a fire in its largest hold.[12] The number of pounds of carbon dioxide required is equal to the gross volume of the space in cubic feet divided by 30. The carbon dioxide can be stored under high or low pressure. When released to the atmosphere, it boils and becomes a mixture of dry ice and vapor, appearing as a dense white fog. It suppresses a deep-seated fire primarily by oxygen dilution. Cooling from the agent is probably insignificant in suppressing a cargo fire.

Carbon dioxide is inert, noncorrosive, electrically nonconductive, and leaves no residue to remove after a fire. It is only mildly toxic but can cause suffocation due to oxygen dilution in confined spaces. As a gas, it can penetrate and spread into open areas and has a density 50 percent greater than air. It has no effect on ship stability whereas a sprinkler system would add a water load which could damage the cargo and create stability problems for the ship.

To predict chances of cargo damage within a hold, a probability tree for assessing fire loss can be constructed. Various scenarios are possible and, by assigning weighting factors to each occurrence on the tree, an assessment of probable fire situations and the resultant losses can be determined. A worst-case scenario of a fire aboard a cargo vessel at sea might be as follows. Class A combustibles such as cotton, jute, paper, or cardboard are tightly packed in a hold without a functional smoke detector. The hatch covers are closed and the bulk of the cargo eliminates most of the free space, resulting in poor ventilation. Ignition of the cargo could occur by a lit cigarette inadvertently dropped during loading. This worst-case scenario is indicated by the heavy line in figure 1.

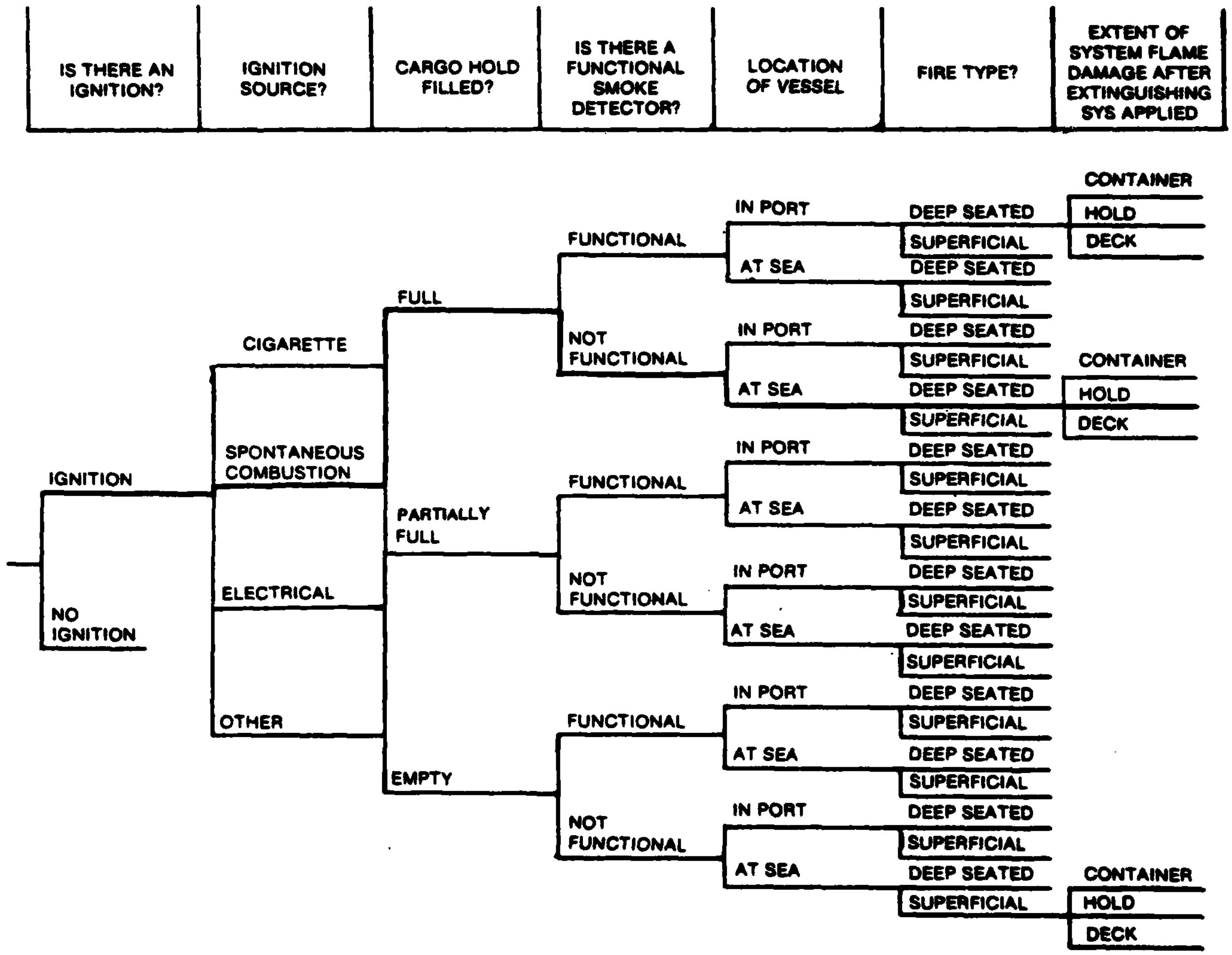


FIGURE 1

Probability Tree for Assessing Class A Cargo Fire Losses

Initially, the cargo would smolder, producing large quantities of smoke. After a period of time, the temperature at the fire source would increase until rapid burning begins. In a cotton fire, this may result in a flashover between bales. Smoke detectors should respond, alerting the crew of the danger. Extinguishment procedure calls for the quick and tight sealing of all openings leading into the affected cargo hold. An initial charge of carbon dioxide is discharged within a few minutes, in a predetermined quantity calculated to provide control of the fire. No specific discharge rate is required for this system.[12] Additional quantities of carbon dioxide are then released as needed to maintain control. In the event of a shipboard power failure, discharge of the carbon dioxide system would be unaffected. Generally the hold is sealed until the vessel reaches port, at which time the hold is opened and the affected cargo is off-loaded and cooled with water or overhauled as necessary to achieve final extinguishment.

2.0 APPROACH

The primary objective of this testing was to determine the concentration of carbon dioxide required to control and extinguish a cargo hold fire as a function of time. If similar relationships for other fire suppression agents can be determined, then comparisons and trade-offs can be made. Inherent to the relationships is the definition of control time. Control may be defined from an engineering/scientific viewpoint or from a ship's master's viewpoint. From the engineering/scientific point of view, control of a deep-seated Class A cargo fire is achieved when some representative temperature in the cargo is caused to be irreversibly decreasing. To pick an exact time which may be called the control time, it is customary to choose a temperature at which the fire is assumed under control (e.g., the autoignition temperature of the fuel). Then the associated time is the control time as shown in figure 2.

For these tests, the control temperature will correspond to the auto-ignition temperature of cardboard (450°F (232°C)). At this temperature, flaming combustion will occur. The representative temperature history in the cargo was based on the average temperature of thermocouples implanted in the bales. By determining the control times for various agent concentrations, the required function can be developed and the objective met. Typical control time curves for a corrugated cardboard fire are shown in figure 3 research performed by Williamson.[8] In these tests, he used a fuel configuration of 6 one-foot (0.3 m) square panels separated by 2-inch (2.5 cm) cardboard spacers.

Control from the shipmaster's point of view is actually a containment of the deep-seated fire in its area of origin. That is, the flaming combustion on the bale is extinguished but the deep-seated fire neither increases nor decreases in intensity. From a practical point of view, containment is verified when the steel decks, hatches, and bulkheads are no longer hot to the crew's touch. For these tests, control will be determined by direct observation and by thermocouples located in the hold.

2.1 Independent Variables

The multi-level hold configuration aboard the cargo vessel SS MAYO LYKES, a victory ship, allows full-scale fire testing to be conducted which will closely approximate the types of cargo hold fires which do occur. There is, however, no "typical" cargo fire and in large-scale fire testing a multitude of parameters can influence the fire.[13] Within a confined structure these include: (1) Average amount of combustible material present, or fire load. (2) Amount of free oxygen and vent openings present. (3) Packaging of the combustible material and its arrangement. (4) Dimensions of the interior space and insulating capability of the walls. (5) Type and place of ignition.

Within a hold, these parameters can be grouped under the major topics of:

(1) Fuel composition and arrangement

(2) Ignition source and application

(3) Ventilation and fire area

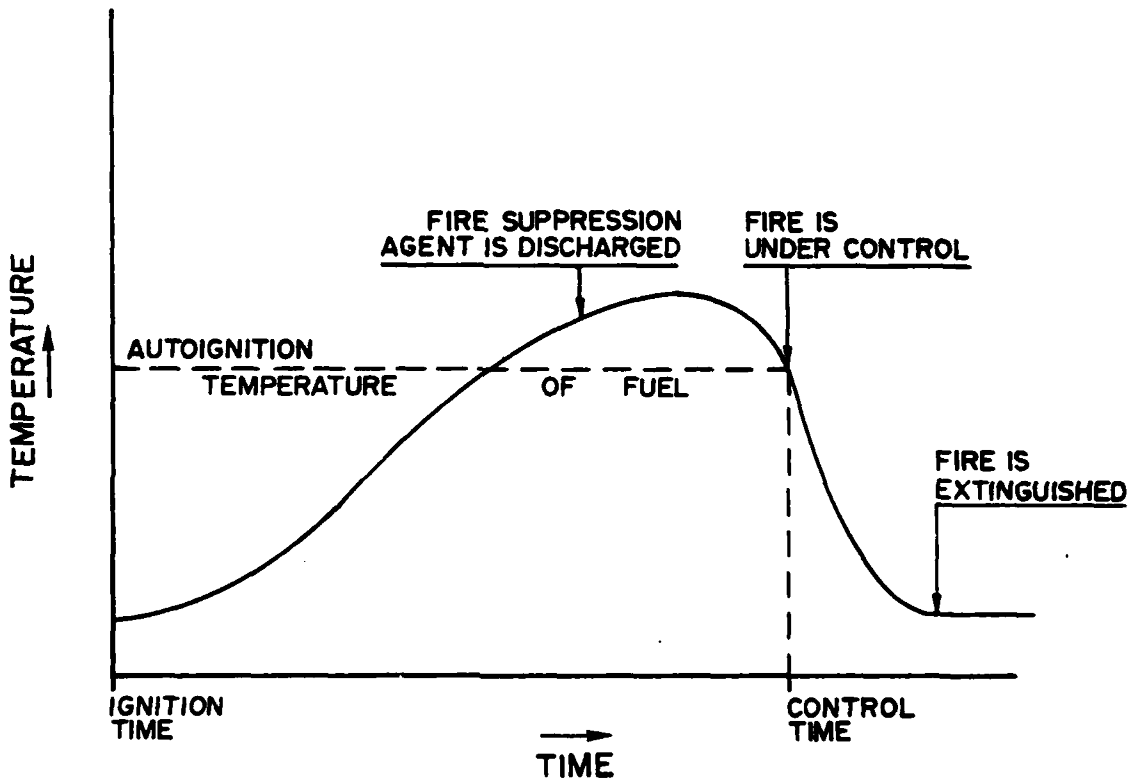


FIGURE 2

Generalized Control/Extinguishment Relationship for Deep-Seated Fires

The period of time to effect extinguishment is based on thermal buildup and agent concentration. The independent variables will determine the severity of the fire or thermal buildup, which should be the same for all tests to allow repeatability. Specific variables for this series are shown in figure 4. Within physical limitations, all the independent variables will be held constant except agent concentration. Furthermore, these variables will be set to provide a worst-case fire. Thus, the fire control data which results will apply to all real fires that are expected to develop.

2.2 Outline of Test Series

The carbon dioxide tests series involved several phases. The beginning phase was to determine a Class A fuel which would produce a worst-case deep-seated fire.

The next phase of testing was to determine an ignition source which would produce consistent, high temperatures inside the Class A fuel. These temperatures needed to be high enough to cause a rapid flame breakout and lead to superficial burning on the bale's surface. They also needed to be reproducible from one test to another.

Two full-scale cargo extinguishment tests were conducted utilizing data from the Class A fuel tests and the ignition source tests. Each full-scale test actually became two or more tests in one by using several core areas each containing its own ignition source. This provided greater confidence in the cargo hold results. The results indicated a need to conduct small chamber tests in order to narrow down and identify the specific concentrations and soaking time requirements for successful extinguishment. The smaller tests were less expensive and required less time and labor. Twenty chamber tests were conducted. The results of the chamber tests and the two full-scale tests shifted the major emphasis of the project from extinguishment and control to control and confinement. Two more full-scale cargo hold tests were conducted to verify the results of the chamber testing.

2.3 Agent Concentrations

The carbon dioxide extinguishing agent was discharged into a cargo hold having a gross volume of 37,000 cubic feet (1,048 cu m). If the volume of the cargo (315 bales (per Dalton Steamship Corp. Loading Manifest) x 50 cubic feet (1.4 cu m) per bale = 15,750 cubic feet (446 cu m)) is subtracted, the free volume of the hold results (21,250 cubic feet (602 cu m)). National Fire Code 12 defines the volume of carbon dioxide required to develop a given concentration in an atmosphere as:

$$V = 2.303 \text{ Log } 10 \left(\frac{100}{100 - \% \, CO_2} \right) \quad \text{(NFPA 12. pg, 12-75)}$$

where V = volume of carbon dioxide added per unit volume of the cargo hold. At 50°F (10°C), carbon dioxide occupies 8.35 cubic feet per pound (0.24 cu m per 0.45 kg). This equation accounts for agent which escapes the hold and is lost to the atmosphere.

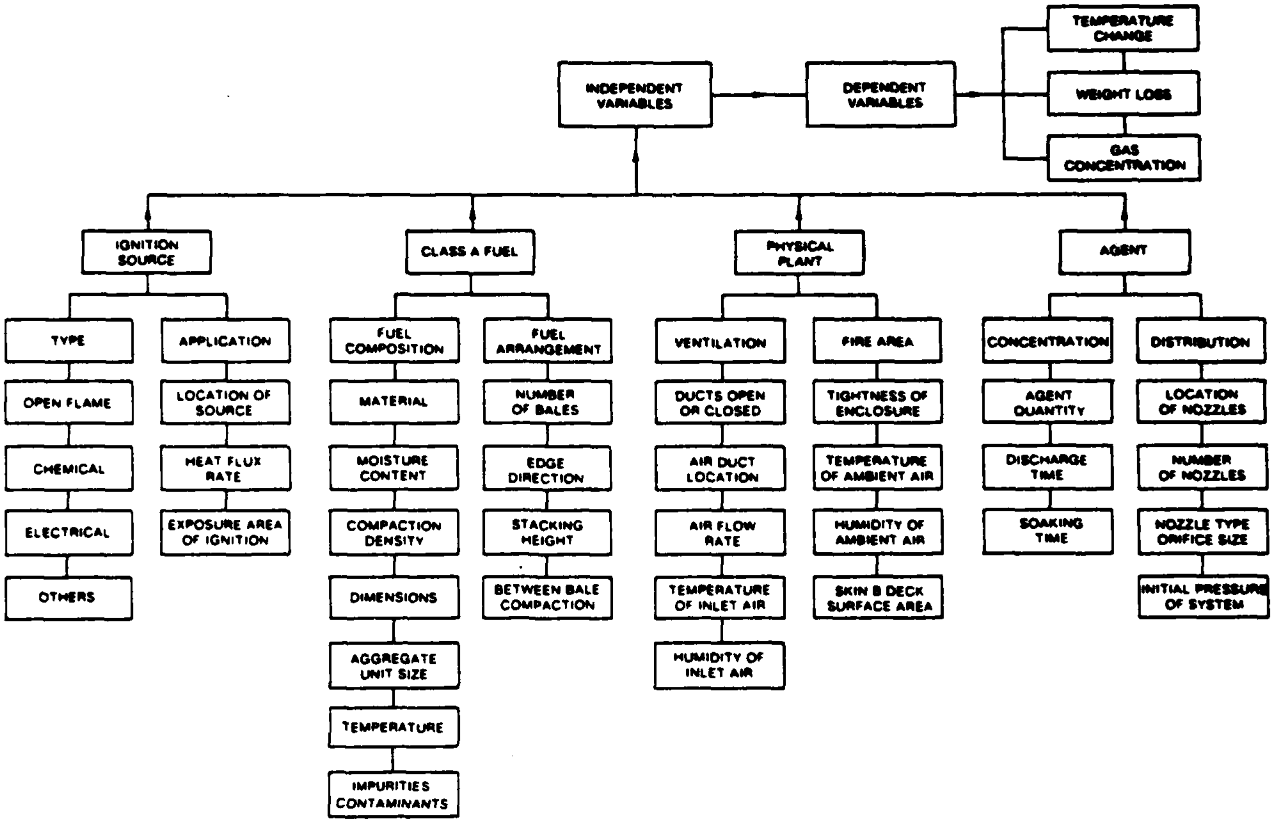


FIGURE 4

Testing Variables for Cargo Hold Extinguishment with Carbon Dioxide

The concentration levels for the carbon dioxide tests were chosen as follows:

Low Concentration of 38.4 percent carbon dioxide based on free volume. The Coast Guard requirements for carbon dioxide fire extinguishing systems in cargo vessels are found in the Code of Federal Regulations, Title 46, Part 95.15-5. These state that "The number of pounds of carbon dioxide required for each space shall be equal to the gross volume of the space in cubic feed divided by 30", and that "No specific discharge rate need be applied to such systems". Based on these requirements, the quantity of carbon dioxide needed for the test hold on the SS MAYO LYKES would be 1,233 pounds (559 kg). The concentration resulting from applying this quantity was chosen as the low test concentration because of its proven record of success. Based on the gross volume of the hold, this quantity will develop a concentration of 24.2 percent carbon dioxide but based on the free volume in the hold it will develop a concentration of 38.4 percent carbon dioxide.

Medium Concentration of 54.3 percent carbon dioxide based on free volume. Recent international developments in cargo hold fire protection have led to Requirement 18(B) (i) in IMCO Resolution A327 which states "The quantity of gas (carbon dioxide) available shall be at least sufficient to give a minimum volume of free gas equal to 45 percent of the gross volume of the largest such cargo space which is capable of being sealed." This would result in 16,650 cubic feet (472 cu m) of gas or 1,994 pounds (904 kg) of carbon dioxide required for these tests. Based on the gross volume of the hold and accounting for escaped agent, this quantity will develop a concentration of 36.2 percent carbon dioxide but based on the free volume in the hold, it will develop a concentration of 54.3 percent carbon dioxide.

High Concentration of 70.0 percent carbon dioxide based on free volume. The low and medium concentrations for carbon dioxide in the free volume of the hold are 38 and 54 percent respectively. To be consistent with a bold experimental approach, the high concentration is chosen to be 70.0 percent concentration under the same conditions. This will require that 3,065 pounds (1,390 kg) of carbon dioxide be initially discharged into the hold and would result in a 49.9 percent concentration of carbon dioxide based on the gross volume of the hold.

3.0 PROCEDURE

All testing was carried out at the U.S. Coast Guard Fire and Safety Test Detachment (F&STD) in Mobile, Alabama. The fuel tests and chamber tests were conducted at the F&STD's concrete test pad while the ignition source tests and the full-scale cargo hold tests were conducted aboard the cargo vessel MAYO LYKES.

3.1 Determination of Class A Fuel

The combustible material used as the test fuel for the deep-seated fires had to be porous enough to allow oxygen to be present in the interior of its bulk. The fuel configuration, area/volume ratios, and length of preburn determine how deep the fire will seat in a particular material. The fuel used in the PHOBOS tests was low-grade cotton in bales approximately 56" x 30" x 20" (142.2 cm x 76.2 cm x 50.8 cm) with an average weight of 472 pounds (214 kg). Cotton fibers consist of 90 percent cellulose, 6 percent moisture, and 5 percent impurities, and decompose primarily into carbon, water, and carbon dioxide. When baled, a great deal of free oxygen remains trapped with a typical bale which contains only 40 percent cotton by volume. Unfortunately, the cost and seasonal availability made cotton unsuitable for the series of test fires planned. An alternate fuel had to be wood or a wood-based product whose composition was basically cellulosic and which could be obtained at any time.

Final choice of the test fuel was made after a series of test fires at F&STD in the small-scale setup shown in figure 5. This small-scale setup was used to determine which Class A material would provide a worst-case fire load. Fuels evaluated were baled newspaper, cotton, and shredded and unshredded corrugated cardboard, each with a volume of approximately 50 cubic feet (1.4 cu m). The testing procedure was to discharge air down the duct through a diffuser and into the chamber for 90 minutes. A controlled discharge of agent was then introduced to provide the desired concentration and the chamber was sealed for 60 minutes. At that time, the bale was removed and examined for deep-seated burning.

In comparing the fuels, the corrugated cardboard recorded a maximum weight loss of 66 pounds (29.9 kg) and temperatures at a 13-inch (33 cm) depth in the bale in excess of 1652°F (900°C). Cotton burned at a much slower rate with a weight loss of 14 pounds (6.4 kg) and temperatures in excess of 666°F (352°C). Newspaper failed to establish sustained interior burning which was in contrast to cotton and corrugated cardboard where, after a 60-minute carbon dioxide soaking, smoldering was still evident (table 1). The rapid fire buildup of corrugated cardboard and the inability to extinguish it by high concentrations of carbon dioxide in the small-scale setup demonstrated that this fuel represents a worst-case fire. In addition, a comparison of Class A test fuels (table 2) indicated that this fuel would be cost effective. This test cost was based on current price per unit commodity delivered to the F&STD, Mobile, Alabama. A unit, such as a bale, is the usual shipping method of these commodities.

Test Cost = Cost Per Unit x Number of Units Per 37,000 Cubic Feet (1,048 cu m) Test

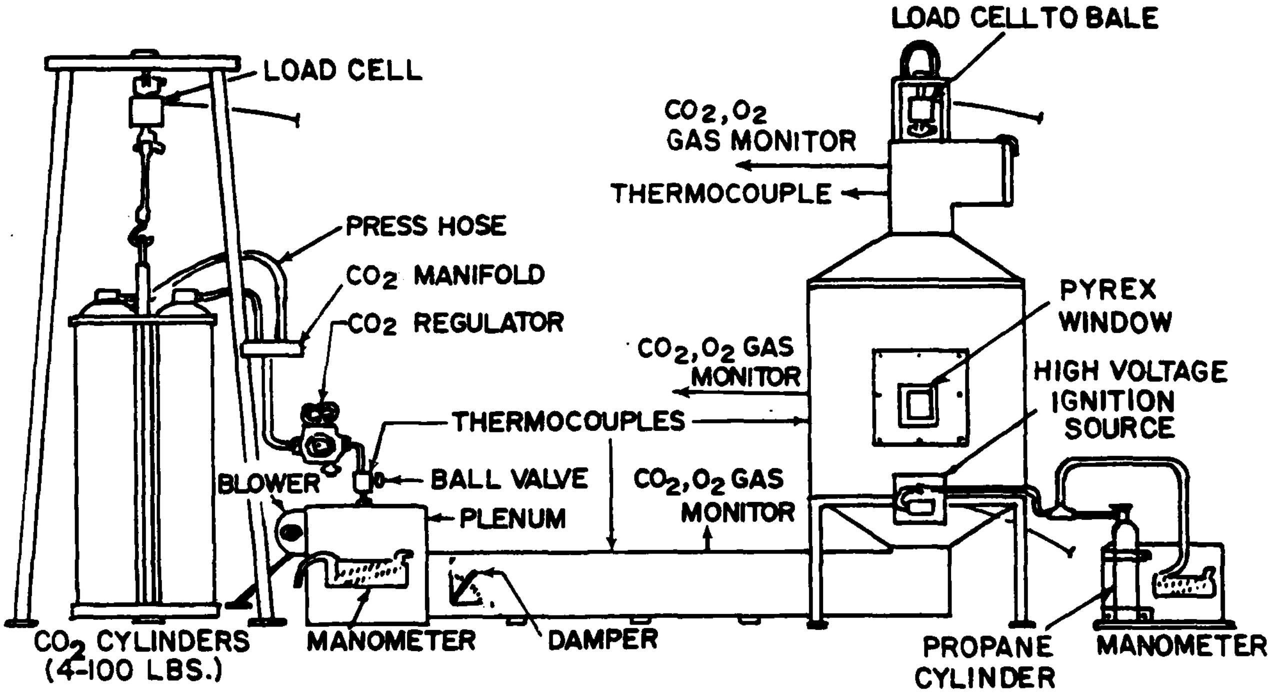


FIGURE 5

Small-Scale Test System for Extinguishment of Class A Fires

TABLE 1

PRELIMINARY FUEL TEST SUMMARY

TEST NUMBER	FUEL	IGNITION MINUTES (1)	CO_2 DISCHARGE MINUTES (2)	CO_2 CONCENTRATION	END TEST MINUTES
1	Corrugated Cardboard (unshredded)	0:00 on 2:00 off	90 on 92 off	Varied	480:00 Bale Smoldering
2	Newspaper	0:00 on 2:00 off	90 on 92 off	60-70%	160:00 Fire out
3	Cotton	0:00 on 2:00 off	90 on 92 off	70%	150:00 Fire out
4	Corrugated Cardboard (unshredded)	0:00 on 2:00 off	90 on 92 off	40-50%	150:00 Bale Smoldering
5	Corrugated Cardboard (unshredded)	0:00 on 2:00 off	90 on 92 off	60-70%	150:00 Bale Smoldering
6	Corrugated Cardboard (unshredded)	0:00 on 5:00 off	90 on 150 off	50%	150:00 Bale Smoldering Slightly
7	Cotton	0:00 on 2:00 off	90 on 92 off	50%	150:00 Bale Smoldering
8	Corrugated Cardboard (unshredded)	0:00 on 2:00 off	90 on 92 off	90%	150:00 Fire out
9	Corrugated Cardboard (unshredded)	0:00 on 2:00 off	No Discharge		150:00 Bale Smoldering Oxygen starvation during last 60 mi limited fire seve

NOTE: (1) - Ignition restarted if fire was not sustained
(2) - Additional quantities discharged as needed to maintain concentration

TABLE 2

COMPARISON OF CLASS A TEST FUELS

MATERIAL	CALORIC VALUE BTU/LB (J/g)	AUTOIGNITION TEMPERATURE	COST/TEST
Baled cotton	7,160 (16,654)	750°F (399°C)	$200,000
Cotton cuttings	7,160 (16,654)	750°F (399°C)	$ 45,000
Mixed rags	7,000-7,500 (16,282-17,445)	600-800°F (316-427°C)	$ 27,000
Hay	6,290 (14,630)	250-400°F (121-204°C)	$ 4,000
Wood pallets	7,180 (16,701)	410°F (210°C)	$ 24,000
Newsprint	7,880 (18,329)	400°F (204°C)	$ 6,800
Corrugated cardboard	5,970 (13,886)	400-450°F (204-232°C)	$ 14,500

This actually represents the cost for a test which completely burns out the cargo hold. In several tests we were able to reuse up to 60 percent of the cargo.

3.2 Determination of Ignition Source

A reliable ignition source for deliberately creating deep-seated cargo fires had never been previously established. For this reason, four possible ignition sources, (1) charcoal ignitors (120V, 525W, and capable of reaching 1100°F (593°C)), (2) sterno-logs (mixtures of sawdust and wax), (3) railroad flares, and (4) propane torches were tested inside cardboard bales aboard the cargo vessel MAYO LYKES. Figure 6 shows how each test bale was embedded with two identical ignition sources and then instrumented to record the resulting temperatures.

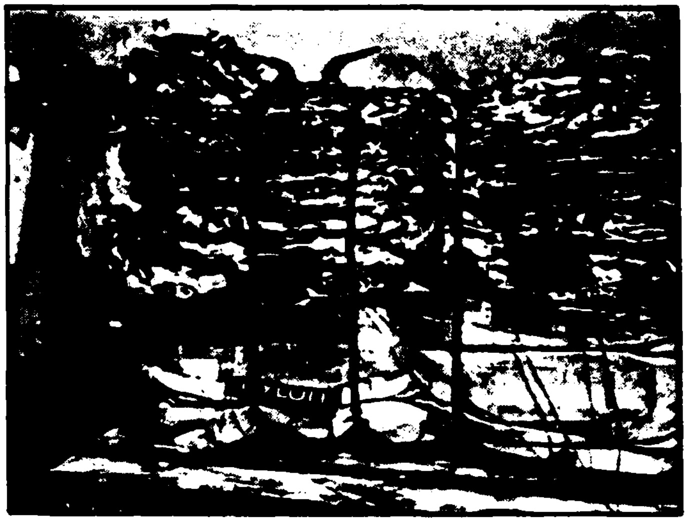
At the conclusion of the test, the charcoal ignitors were determined to be the best possible ignition source because of the consistent high temperatures which could be maintained inside the bale. Figure 7 shows these temperatures. These temperatures were considerably higher than the autoignition temperature of the cardboard (400°F (204°C)) and could be easily maintained for hours. The ignitors were activated and deactivated several times during a test to prevent their getting too hot and burning out. Three hours was decided as the point at which the ignitors could be turned off completely. It was felt that by this time a deep-seated fire had been established since the fire had burrowed its way to the bale's outer edges and created superficial burning.

3.3 Cargo Hold Extinguishment Tests

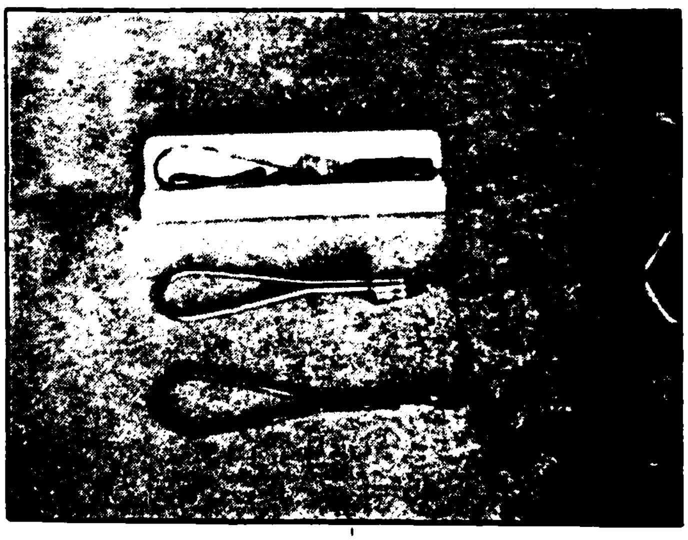
Two full-scale cargo hold tests were conducted on board the test vessel MAYO LYKES. The test area was the uppermost deck level in Cargo Hold Number 3 which had been reduced to an area of approximately 37,000 cubic feet (1,048 cu m) (figure 8). This level was reduced in size to reduce the amount of test fuel and to isolate the fire from the vessel's machinery space. To further complete this isolation, plate steel was welded over the steel I-beams at the lower cargo hatch area. A boom was also provided over the cargo hold to facilitate removal of the hatch covers before and after testing.

For each test, this area was filled with 315 cardboard bales stacked three high on wooden pallets. Figure 9 shows the cargo hold loaded with cardboard bales. Two stacks of three bales located in the center of the hold were designated as the core bales with two of these having two ignitors embedded in each. Figure 10 shows the instrumentation around the ignitors. These ignitor bales were also instrumented to record internal temperatures. The general procedure once a test began was:

1. Activate data acquisition system.
2. Energize ignitors and operate until flames can be seen coming from the bales (usually 1-1/2 to 3 hours).
3. Discharge air into the cargo hold at 1000 cubic feet per minute (28.3 m^3/min) for the first hour that ignitors are energized, then secure blower and cargo hold doors.



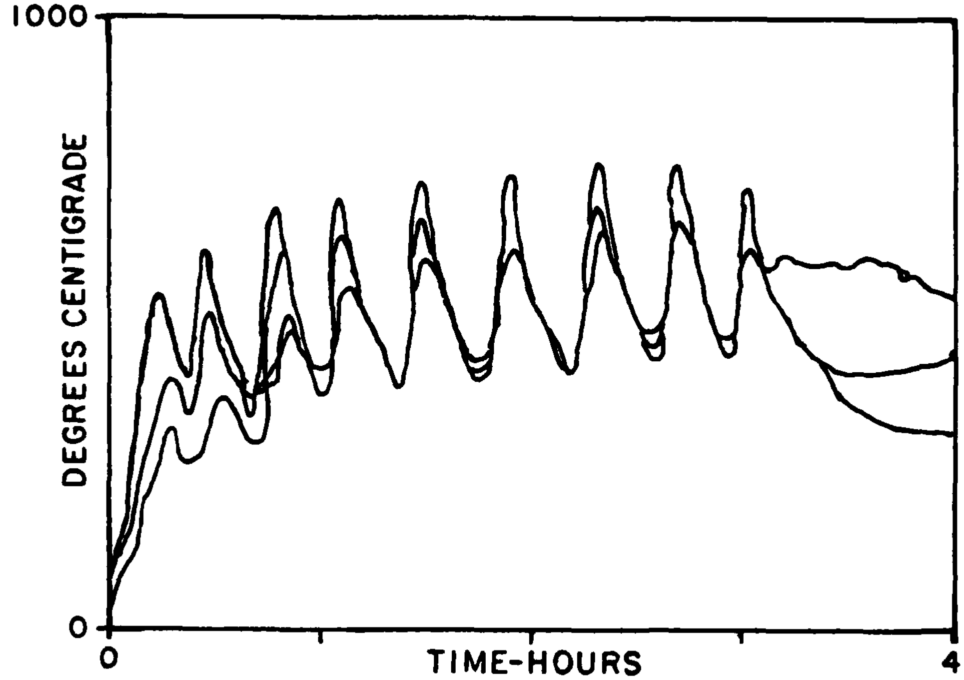
Sterno-Logs



Charcoal Ignitors

FIGURE 6

Ignition Source Testing



1. EACH THERMOCOUPLE LOCATED NEXT TO A DIFFERENT IGNITOR

2. THERMOCOUPLE PEAKS AND VALLEYS SHOW IGNITORS BEING MANUALLY TURNED ON AND OFF TO PREVENT OVERHEATING AND SHORTING OUT

FIGURE 7

Charcoal Ignitor Temperatures

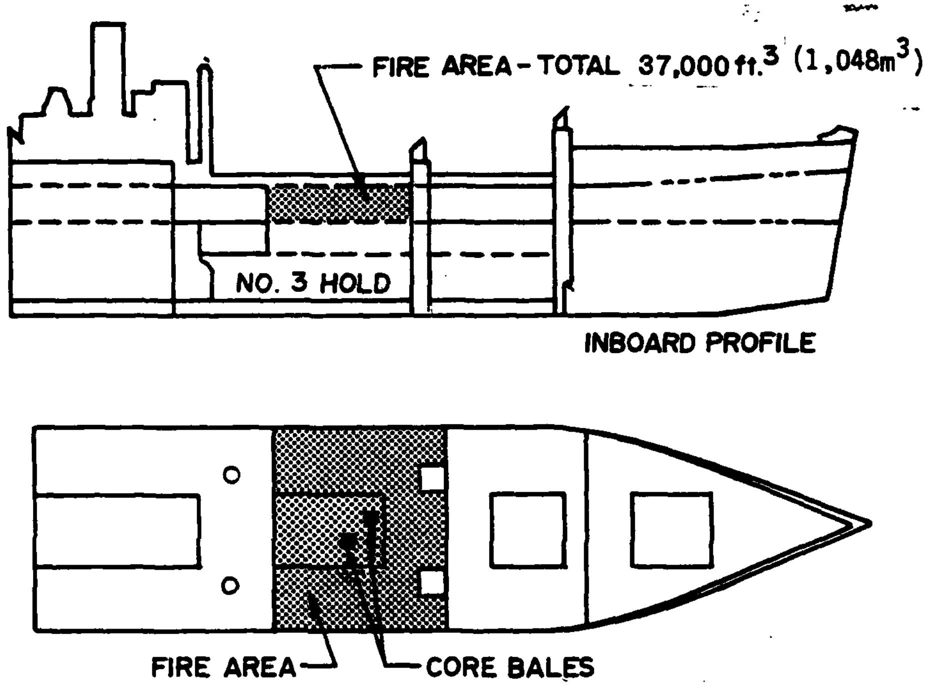


FIGURE 8

Cargo Hold Test Area on SS MAYO LYKES

Installing Instrumentation

Hatches Secured

FIGURE 9

Cargo Arrangement In Hold

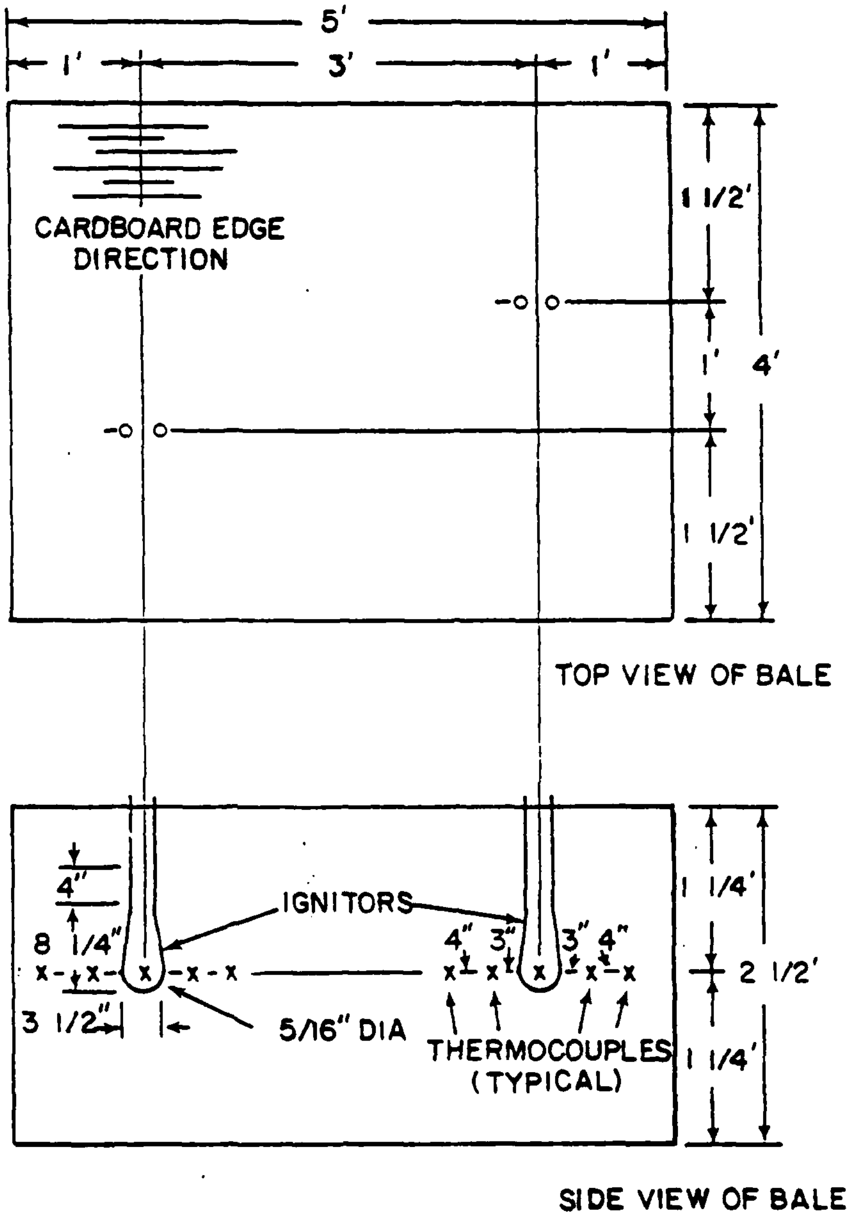


FIGURE 10

Ignitor and Thermocouple Placement in Core Bales

4. Once flames were seen coming from bales, de-energize ignitors and make initial discharge of carbon dioxide to reach desired concentration.

5. Monitor test conditions using data acquisition system and add additional carbon dioxide as needed to maintain desired concentration.

6. Once the test was considered over (either at a predetermined time or once the bale temperatures indicated the deep-seated fire was extinguished), the cargo hold was opened and its contents examined for flames or smoldering combustion.

A medium concentration (45 percent based on free volume) of carbon dioxide was used in Test Number 1, while a low concentration (38 percent also based on free volume) was used in Test Nunber 2.

3.4 Chamber Tests

The two full-scale cargo fires utilizing carbon dioxide were expensive, time consuming, and provided inconclusive data in pinpointing the required agent concentrations and soaking time requirements necessary for extinguishment. Therefore, a single bale test chamber was designed and utilized to determine extinguishment concentrations with the results to be verified through a limited number of full-scale tests.

Twenty chamber tests were conducted. Figure 11 shows two procedures carried out in each test. Each had a different carbon dioxide concentration or soaking time. Each test involved one bale with two ignitors to insure a deep-seated fire. The test chamber was 6 feet x 7 feet x 4.5 feet (1.8 m x 2.1 m x 1.4 m). During the testing, the ignitors were turned on and off for the first three hours. This prevented their getting too hot and shorting out. Fresh air at the rate of 125 cubic feet per minute (3.54 m^3/min) was blown into the chamber while the ignitors were in use. After three hours, the ignitors were turned off, the air flow stopped, and carbon dioxide was discharged into the chamber. Additional carbon dioxide was added as necessary in order to maintain the required concentrations. The ignitor placement in the single bale was identical to figure 10. Four additional thermocouples were later added above and below the ignitors on the outside of the bale to help register flame breakout in these areas.

3.5 Cargo Hold Control Tests

At this point in the carbon dioxide test program, the accumulated data from the twenty chamber tests and the full-scale cargo hold tests indicated that the extinguishment of deep-seated cargo fires was highly unlikely using the quantity of carbon dioxide which can be economically carried by a cargo vessel. Therefore, the control and extinguishment approach was replaced with a more practical and achievable approach defined as control and confinement. The primary objective of this new approach was to determine what carbon dioxide concentrations are effective in controlling and confining a deep-seated fire to its area of origin. This approach required that the ignitors

Securing Gas Bottle

Examining Smoldering Conditions

FIGURE 11

Chamber Tests

in the core bales be activated sequentially to insure that smoldering areas existed as the carbon dioxide concentrations decayed in the hold. This simulated a deep-seated fire, a discharge of carbon dioxide to attempt extinguishment, and subsequent discharges of carbon dioxide to maintain control as air leaks into the hold. In an actual fire, shipboard personnel would monitor the carbon dioxide concentration as it decayed, and when it reached what was considered a critical concentration, additional carbon dioxide would be added.

With this approach in mind, the cargo hold test plan was modified and two more full-scale tests were conducted to verify the results of the containment data collected from all previous tests. The procedure for these two tests is described in the remainder of this section.

3.5.1 Cargo Arrangement

Cardboard bales were stacked three high on pallets throughout the hold. They were tightly arranged with the ends generally facing port and starboard, long side horizontally down, in even rows to fill the entire area.

Three core areas each consisting of a stack of three bales, were located in the hold. Figure 12 shows the positioning of these core areas. Core bales in these areas were designated for ignition of test fires and were more heavily instrumented than the rest of the cargo hold. The area containing these core bales was representative of normal cargo storage. Each bale placed in the core area was approximately 5 feet x 4 feet x 2-1/2 feet (1.5 m x 1.3 m x 0.8 m). Bales in this area were designated by stack location and bottom, middle or top.

3.5.2 Ignition Source

To initiate the fire in the cardboard, two electric ignitors (120V, 525W) were placed in the middle bale of each of the three core areas. The ignitors were positioned in each core bale as shown in Figure 10. The ignitors in the first core area were energized at the start of the test. The ignitors were de-energized once flames were observed breaking out in this area. A calculated quantity of carbon dioxide was then discharged into the hold and the test concentration was reached and maintained for one hour. The concentration was then allowed to slowly decrease through natural leakage of carbon dioxide from the hold. At the time of the initial carbon dioxide discharge, the ignitors in the second core area were energized. If flames broke out in the second core area, the carbon dioxide level was to be increased to the test concentration and maintained for one hour. It would then be allowed to decrease naturally. Once the carbon dioxide level was increased a second time, the ignitors in the third core area were to be energized. If flames broke out in the third core area, the carbon dioxide level would again be increased to the test concentration and maintained until the end of the test. The time span between the flame breakouts and the oxygen concentrations at the time of the breakouts was to be recorded by a data acquisition system (utilizing thermocouples and gas sampling tubes located inside and around the core bales) and a video recording system.

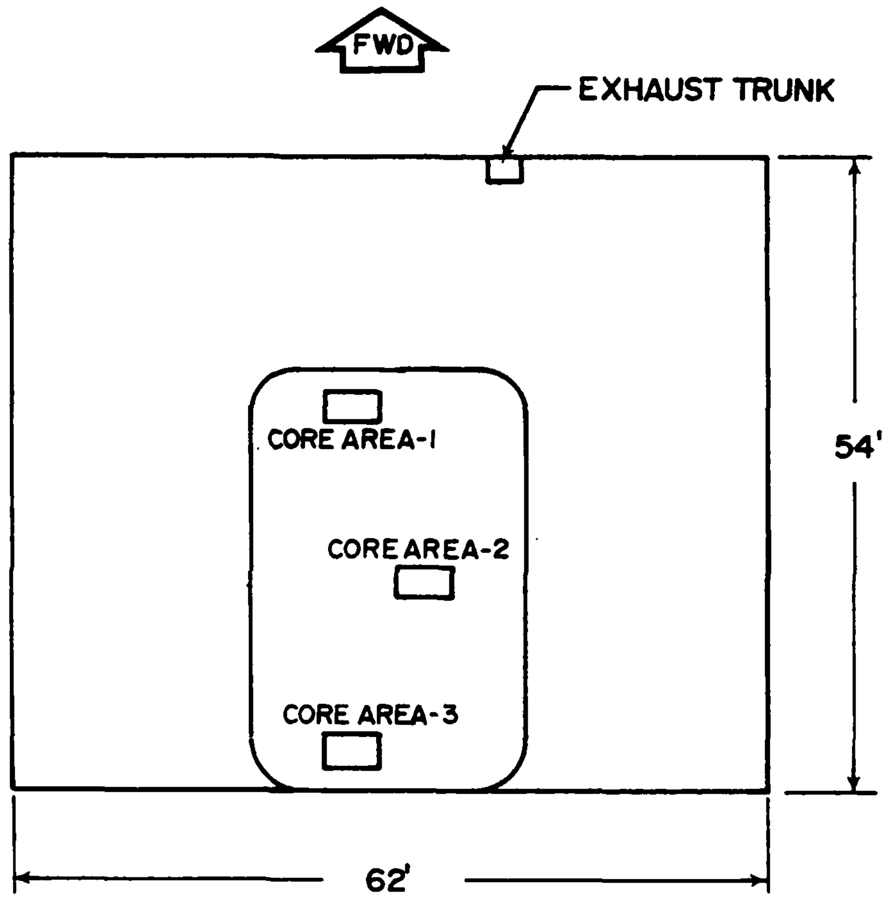


FIGURE 12

Core Area Positions

3.5.3 Ventilation

Just prior to beginning the ignition process, a 1000 cubic feet per minute (28.3 m^3/min) blower was operated to supply air to the hold. It was positioned on the centerline of the after bulkhead at the deck level of the test hold. The starboard exhaust trunk was also open at this time. At sixty minutes into the test, the blower was shut off and both of these ducts were sealed. The initial discharge of extinguishing agent was released after fire broke out of the first core area.

During the tests, the hold was sealed as it would be during an actual fire extinguishment attempt. To this end, the natural exhaust trunks were sealed with metal shutters. The installed ventilation fans and the cargo hatches were also sealed tight. A 1,600 cubic feet per minute (45.3 m^3/min) fan located above the shutter in the starboard exhaust trunk was used to remove extinguishing agent and combustion by-products from the hold after each test. It was operated after the hold had been opened and the cargo was inspected to insure that the fire was completely extinguished. Three exhaust fans, each rated at 125 cubic feet per minute (3.5 m^3/min) were later installed to gradually remove the combustion by-products from the hold during a test.

3.5.4 Carbon Dioxide System

The MAYO LYKES was equipped with an operational 7-1/2-ton low-pressure carbon dioxide system. As shown in figure 13, the piping supplies four discharge nozzles installed in the upper level of Hold 3. The nozzles were located at the center of each quandrant to insure proper dispersion of carbon dioxide. The piping installation conformed to CFR 46, 95.15-15 with the discharge orifice size based on expected pressure in the piping system. Prior to testing, the low-pressure tank was filled with the required quantity of carbon dioxide and the automated refrigeration unit was cycled to maintain tank pressure below 300 PSIG.

Carbon dioxide discharges were regulated from an actuator located in the instrumentation trailer. A digital readout of the carbon dioxide tank weight was provided at the actuator panel. Within five minutes of the fire breaking out of a bale, the prescribed amount of carbon dioxide (see Section 2.3) was discharged. The amount of carbon dioxide discharged was determined by using the remote digital readout of the carbon dioxide tank weight. The final carbon dioxide concentration in the hold was within $\pm$ 5 percent of the prescribed target concentration. Additional carbon dioxide discharges were necessary to maintain the actual concentration within the 5 percent limit.

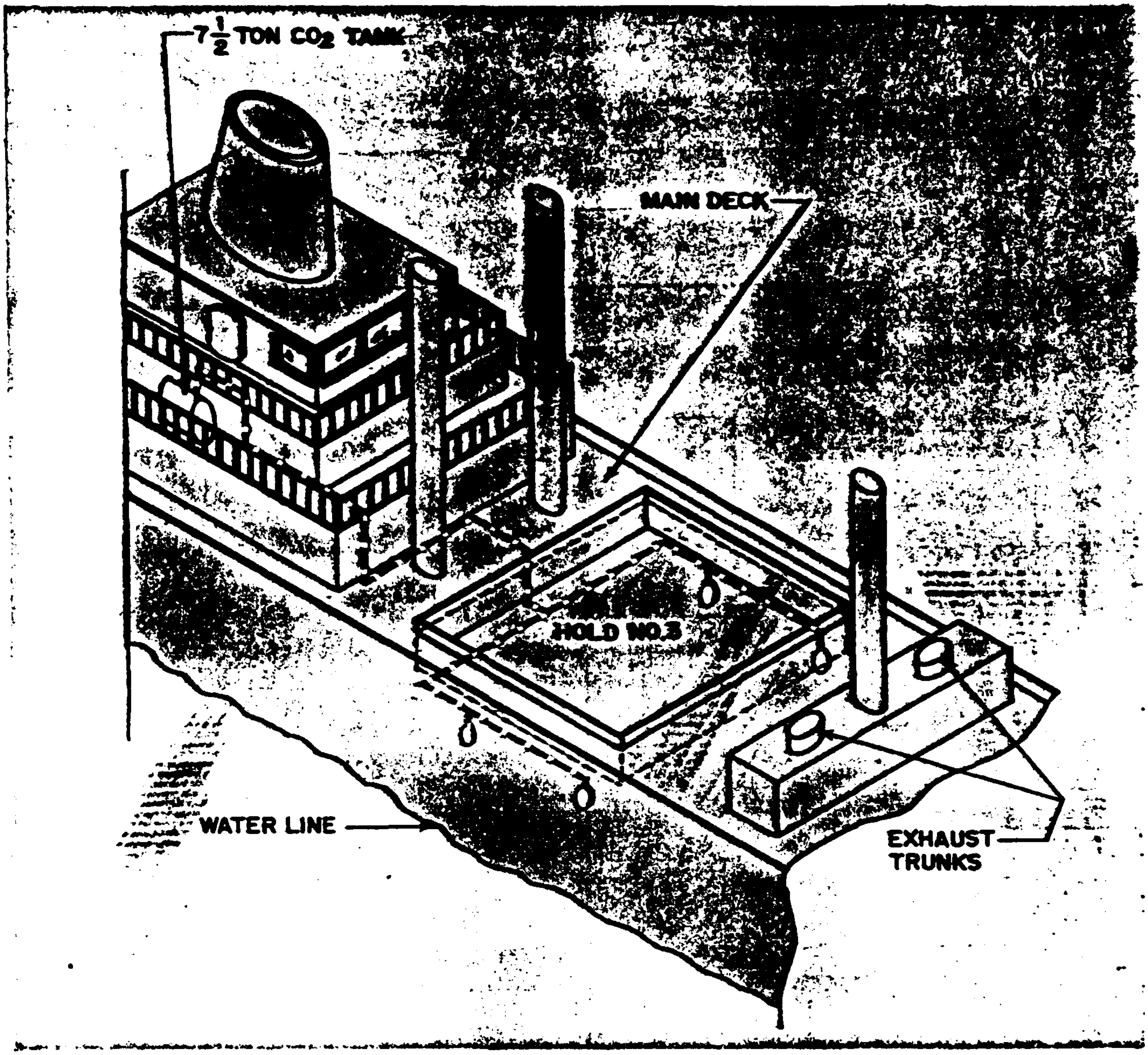


FIGURE 13

Carbon Dioxide System

3.5.5 Test Termination

After energizing core area 3, the soaking period with carbon dioxide lasted until it was determined that either control and containment or extinguishment had been established. The hatch covers were then removed and several hose lines were used to spray water on any smoldering cardboard. At that time, a 1,600 cubic feet per minute (45.3 m^3/min) exhaust fan was turned on to expel all carbon dioxide and combustion gases from the hold. In the event of major reflashes, the hatch covers were replaced, additional carbon dioxide was added, and the overhead sprinkler system was activated. In these cases, the sprinkler system was operated for 5 minutes per hour until it was determined that the deep-seated fire was under control.

3.5.6 Instrumentation

The instrumentation used in the hold and the core areas is described in the following sections.

3.5.6.1 Temperature

Internal bale temperatures were monitored by thirty 1/8-inch (0.3 cm) diameter, Inconel-sheathed, Type K thermocouples. These were positioned within the same layer of cardboard as the ignitors as shown in figure 10. Every effort was made to maintain the thermocouple spacing relative to the ignitors as shown. In order to insure this, each ignitor and the five thermocouples around it were wired to the same piece of cardboard. When this was completed, the assemblies were inserted at the proper location in each bale and the bales were rebanded. Twelve additional crimp tip, Type K thermocouples (four per core bale) were implanted two inches (5.1 cm) deep in the top and bottom of the core bales to monitor any fire breakout in these areas. These were placed above and below the ignitor areas.

Temperatures adjacent to the inlet of the gas sample tubes were measured by six 22-guage, crimp tip, Type K thermocouples. One of these thermocouples was placed within approximately one inch (2.5 cm) of the inlet of each of the six gas tubes. Three more thermocouples were located starboard of core area 2, one each at a height of two, five, and nine feet (0.6, 1.5, and 2.7 m) above the deck.

The temperature of the carbon dioxide nozzles was measured by four crimp tip, Type T thermocouples. One of these thermocouples was located just above each of the four discharge nozzles in firm contact with the pipe.

Three thermocouples (one per core area) were located 9 feet (2.7 m) high on the aft side of the three core stacks of bales. The remaining thermocouples were 22 gauge, crimp tip, Type K and were placed in general locations throughout the hold.

3.5.6.2 Gas Concentration

Gas samples were drawn from six locations through 1/8-inch (0.3 cm) OD steel sampling tubes. One tube was suspended in the hold at each of the following locations:

(a) Starboard of the center of core area 1 and two feet (0.6 m) above the deck.

(b) Starboard of the center of core area 1 and five feet (1.5 m) above the deck.

(c) Starboard of the center of core area 1 and nine feet (2.7 m) above the deck.

(d) Starboard of the center of core area 3 and two feet (0.6 m) above the deck.

(e) Starboard of the center of core area 3 and five feet (1.5 m) above the deck.

(f) Starboard of the center of core area 3 and nine feet (2.7 m) above the deck.

These locations were intended to put the sample tubes between bales and were adjusted to accomplish this. Carbon monoxide, carbon dioxide, and oxygen concentrations were measured with each sample tube.

Carbon monoxide and carbon dioxide concentrations were measured by Lira infrared analyzers and oxygen concentrations by Leeds and Northrup thermomagnetic analyzers. All analyzers were calibrated with the appropriate gas mixtures. The carbon dioxide meters were adjusted to read 100 percent concentration at full scale. Transit time and system time constants were measured by sending a sample of span gas from each gas inlet in the hold. The span time was then determined by recording the time at which the gas analyzer readings level off at a maximum or minimum.

3.5.6.3 Data Collection

Transducer leads and gas analyzing tubes ran beneath the deck to the starboard side. A hole was cut through the deck plate below the core bales to permit cabling to pass into the mid-level of the hold. Transducer terminal boxes were located there and cabling was extended to the instrumentation trailer through a hole in the starboard side of the ship. The instrumentation trailer was located in an F&STD landing craft moored just below the opening. Two people monitored the instrumentation during testing.

Instrumentation leads were wired into the trailer patch panel and then patched to the appropriate terminals on the Channel Scanner as shown in figure 14. The HP9845 Controller/Calculator was used throughout the test series to record and display data via the Fire 1/Fire 2 program. The software provided:

- Data collection at 60+ channels per second

- Storage of data for an entire test on compact tape cartridges

- Capability of varying the time between scans

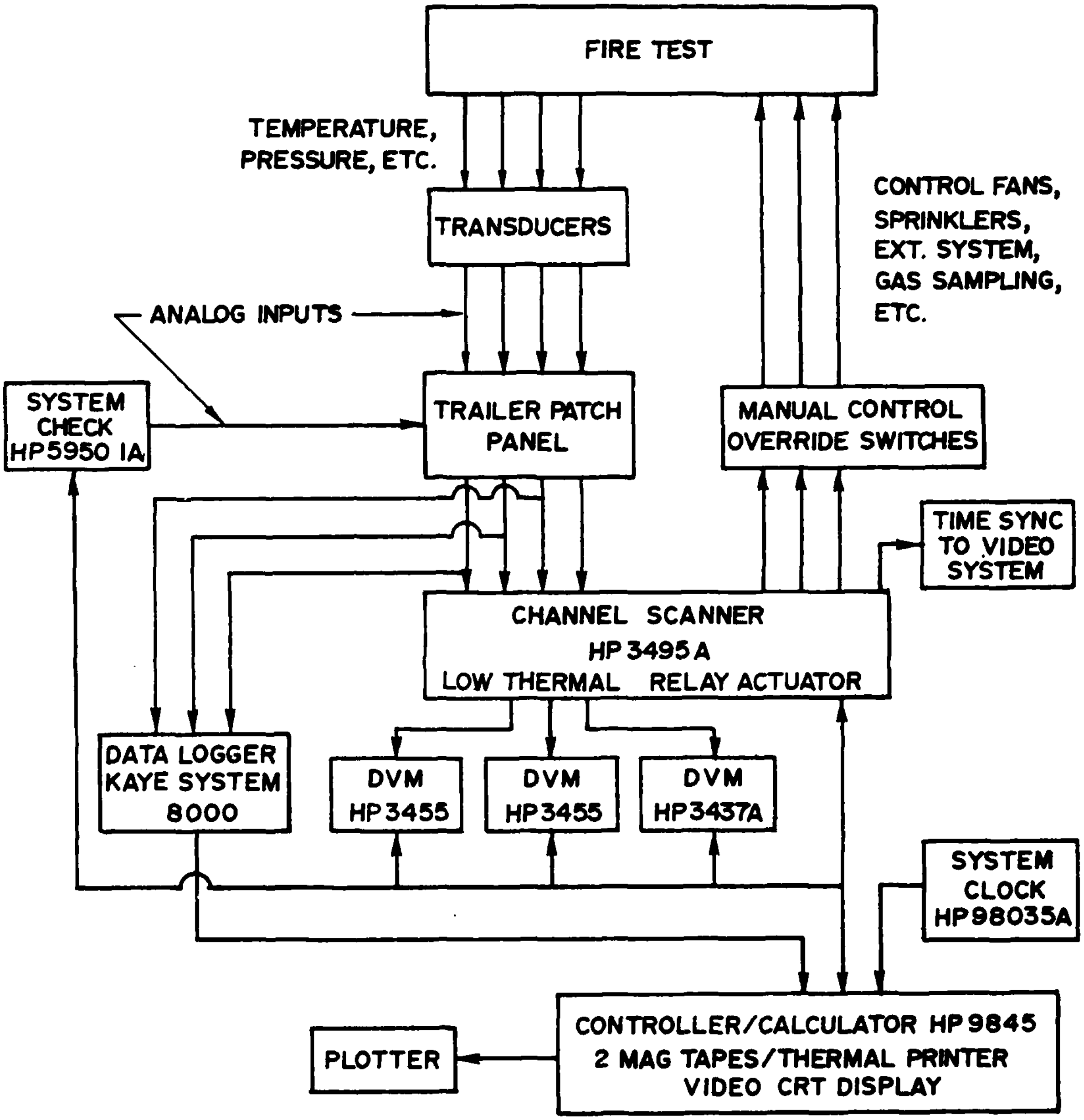


FIGURE 14

Fire Research Data Acquisition System

- Three types of data displays during the test

  (1) A plan view of the test plots with 15 data points superimposed
  (2) Parameter/time plots of any four channels
  (3) A complete listing of data for the most recent scan

- Actuation of events triggered by the HP9845

- Synchronization of all clocks to test time

- Recording of test time when special events occur

The Fire Research Data Acquisition system was activated and all channels were scanned utilizing the Fire 1/Fire 2 program at 15 minutes before the fire was ignited. If during this period any part of the instrumentation system malfunctioned, the test was delayed and the malfunction repaired. The wind conditions, time of day, and moisture conditions of the bales were also recorded. Personnel were briefed on safety precautions and informed of the carbon dioxide warning siren.

3.5.6.4 Video/Photo Documentation

Three color video cameras were used to document the tests. One camera was placed on the deck forward of the hatch coaming overlooking core area 1. It viewed aft across the bales through a 4-inch (10.2 cm) diameter hole cut in the hatch coaming and was protected by a glass window capable of withstanding thermal shock.

A second camera was placed on the deck immediately aft of the hatch coaming overlooking core area 2. It viewed across the top of the bales through a 4-inch (10.2 cm) diameter hole also covered by protective glass.

A third camera was placed on the deck immediately starboard of the hatch coaming overlooking core area 3. It viewed across the top of the bales through a 4-inch (10.2 cm) diameter hole protected with glass. The cables to all cameras were secured off the deck to prevent them from overheating. Sufficient lighting was provided in the hatch to light each camera's field of view and to detect any fire breakout. This lighting was capable of surviving the fire conditions in the hold.

Still color slide photographs were used to document the test setup, cargo hold layout, and the extent of fire damage after each test.

All photographic documentation and test data considered pertinent to the testing is preserved at the United States Coast Guard Research and Development Center, Avery Point, Groton, Connecticut.

4.0 RESULTS AND DISCUSSION

4.1 Cargo Hold Extinguishment Tests

Neither of the two full-scale cargo hold tests achieved an extinguishment of the deep-seated fire. A deep-seated fire was considered established when flames could be observed breaking out of the test bales. At this point, the ignitors were de-energized and a calculated quantity of carbon dioxide was discharged into the hold. This concentration was maintained through the duration of the test by additional discharges of carbon dioxide. At the conclusion of each test, the hatch covers were removed and the cargo examined for flames or deep-seated combustion. Figure 15 shows the flashover and the extinguishment of the deep-seated fire after the hatch covers were removed. The results of these tests are shown in table 3 while the principal characteristics are described in Sections 4.1.1 and 4.1.2.

4.1.1 Test Number 1

Four ignitors (two per core bale, figure 9) were used in test number 1 to insure that a deep-seated fire was started. One hour after the ignitors were actuated, the temperatures inside the two core bales as shown in figure 16, had risen above the ignition temperature of the cardboard. At approximately 3 hours and 40 minutes into the test, the deep-seated fire burned its way outside the core bales to create superficial burning. A video camera system was used to observe and to record the flame breakout. At this time, the temperature readings inside the core bales indicated above 900°F (482°C). At this point, the actuators were de-activated since the criteria for a deep-seated fire had been reached. Once superficial flames could be seen coming from the bales, 2000 pounds (907.2 kg) of carbon dioxide were discharged into the hold. Gas concentrations were monitored at 2-, 5-, and 9-foot (0.6, 1.5, and 2.7 m) heights above the deck near the core bales. The first carbon dioxide discharge reached a peak concentration of 70 percent, while the oxygen level dropped to 5 percent. The carbon dioxide was allowed to decrease and finally maintained at between 35 and 45 percent for approximately 13 hours.

After a 15-hour soaking at this concentration, 3 of the ignitor areas showed temperatures which were still rising. Therefore, the carbon dioxide level was again increased to 70 percent and gradually tapered off to 50 percent. After this carbon dioxide increase, two of the ignitor areas showed large temperature drops; one ignitor area with low temperatures showed little or no effect. The fourth ignitor area showed only a slight temperature drop but then steadily increased. It appears that in three of the four ignitor areas, the increase of carbon dioxide concentration level of over 65 percent caused a noticeable decrease in the internal bale temperatures. As this higher carbon dioxide concentration decreased, however, the declining bale temperatures began to level off. As the carbon dioxide level reached 50 percent, the internal bale temperatures reversed the decline and began to rise again.

Twenty-five hours into the test the carbon dioxide system malfunctioned and the test was terminated. At this point, the thermocouple readings in three ignitor areas were over 572°F (300°C). The hatch covers were then opened to determine the specific smoldering areas. Within ten

Flashover After Opening Hatch

Extinguishing A Deep-Seated Fire

FIGURE 15

Extinguishment Results

TABLE 3

CARGO HOLD EXTINGUISHMENT DATA

TEST	AGENT	AGENT CONCENTRATION (PERCENT)	SOAKING TIME* (HOURS)	FLAMES (END OF TEST)	DATA
1	Carbon Dioxide	45 60	15 7 (Total 22 hours)	Smoldering combustion which soon burst into flames	After a 15-hour soaking of 45 percent carbon dioxide, the temperature readings inside the core bales still indicated 932°F (500°C), therefore the carbon dioxide level was increased to 60 percent. Test ended because of carbon dioxide system failure
2	Carbon Dioxide	28	17 (Total 17 hours)	Smoldering combustion which soon burst into flames	Test ended because all temperature readings dropped below 212°F (100°C), deep-seated combustion burrowed to areas not instrumented.

*Soaking time refers to the number of hours the bales are engulfed in carbon dioxide.

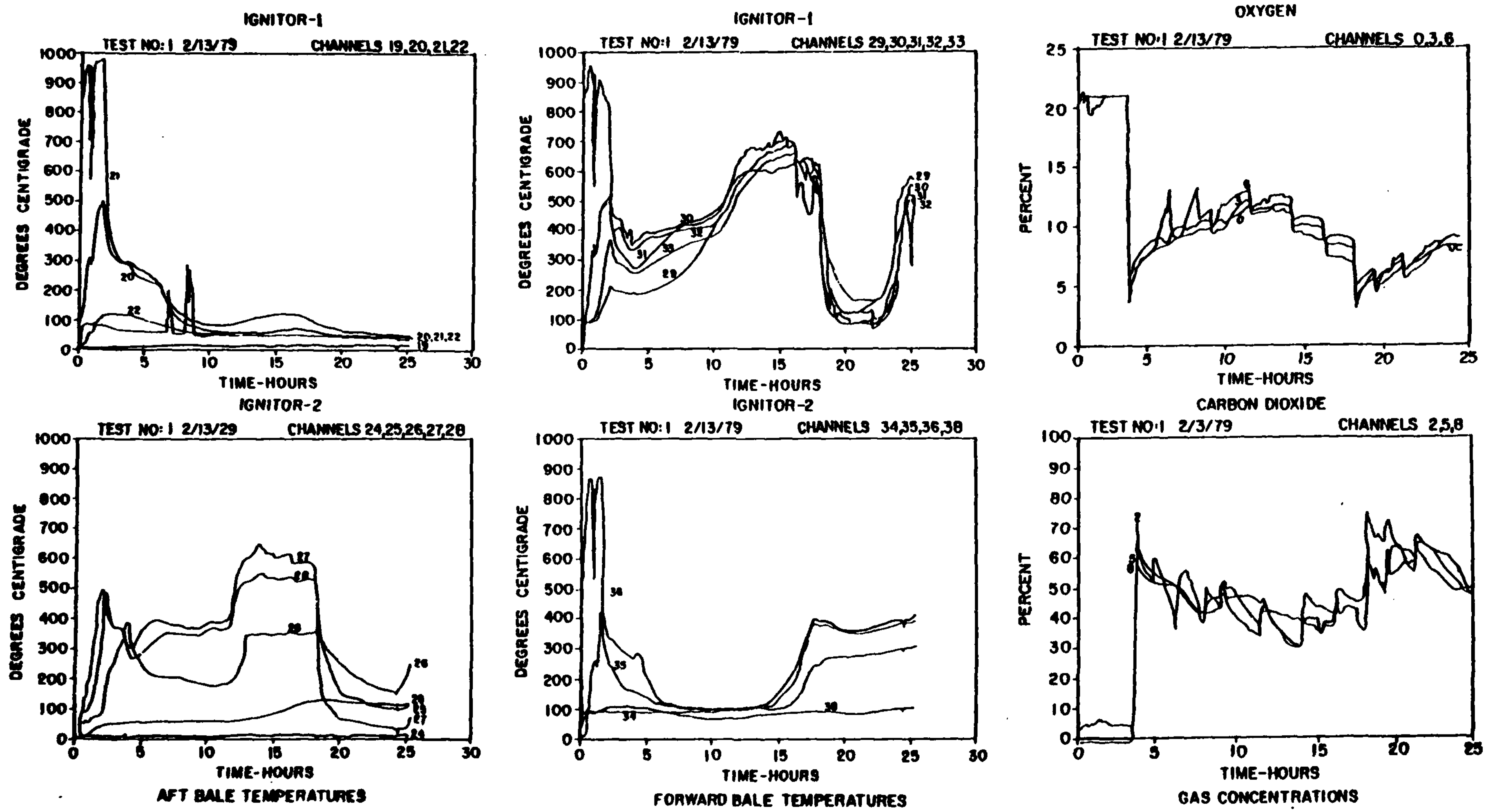


FIGURE 16

Cargo Hold Test 1

minutes, both core areas burst into flames and required copious amounts of water to bring under control. The core bales finally had to be lifted onto the main deck, torn apart, and completely watered down to achieve extinguishment.

4.1.2 Test Number 2

Four ignitors (two per bale) were also used in test number 2. In this test, flames broke out of the core bales after one hour. Because of the short breakout time, it was decided to leave the ignitors on for additional time to insure a deep-seated fire. One hour and thirty minutes into the test, all four ignitors shorted out from the high temperatures. At this time, figure 17 shows that the temperatures at the ignitors were up to 1472°F (800°C). Thirty minutes later, the bale temperatures leveled off between 570°F (300°C) and 935°F (500°C). After two hours and thirty minutes into the test, it was decided that a deep-seated fire was firmly established; therefore, the initial discharge of carbon dioxide (1,300 pounds (590 kg)) was made into the hold to form a 38 percent concentration. The flames in the hold had been extinguished by lack of oxygen before the carbon dioxide was discharged. This was verified on the video-camera system.

The 38 percent concentration was maintained at a 5-foot (1.5 m) height inside the hold throughout the test. It was observed that a lesser concentration (20 percent) was recorded at a 9-foot (2.7 m) height. This data therefore indicates that a stratification of the carbon dioxide occurred in the hold. The carbon dioxide concentration did not appear to have an immediate effect on the temperature levels inside the bales, for as the test progressed, the internal bale temperatures continued to fluctuate between 392°F (200°C) and 842°F (450°C). Thirteen hours into the test, all the bale temperatures began to decrease. Seventeen hours into the test, the data acquisition system failed for half an hour. Once the system was reactivated, it was observed that all the bale temperatures were below the ignition temperature of the cardboard. At this point, the test was ended and the deck hatch covers were opened. The core bales were then removed to the main deck. Once they were placed on the main deck, they burst into flames. They were finally extinguished after being thoroughly torn apart and watered down. Although the flaming combustion had been controlled in the carbon dioxide atmosphere inside the hold, there was still enough oxygen trapped inside the bales for smoldering to continue. Once this smoldering condition was exposed to the outside air containing oxygen, the bales began burning again. The windy conditions on the deck aided this combustion by increasing the rate of oxygen flow to the smoldering area. The smoldering areas were located not on the bale's surface but one to three inches deep inside the layers of charred cardboard. This indicates that a carbon dioxide concentration which will inhibit flaming combustion on the surface of Class A materials will not necessarily extinguish deep-seated smoldering.

4.2 Chamber Tests

The carbon dioxide concentrations, soaking times, and extinguishment results for the chamber tests are listed in table 4. The soaking time includes only the hours that the bale was engulfed in carbon dioxide. The flames column indicates whether or not smoldering combustion was evident in the bale once the hatch cover was removed. The higher concentrations required

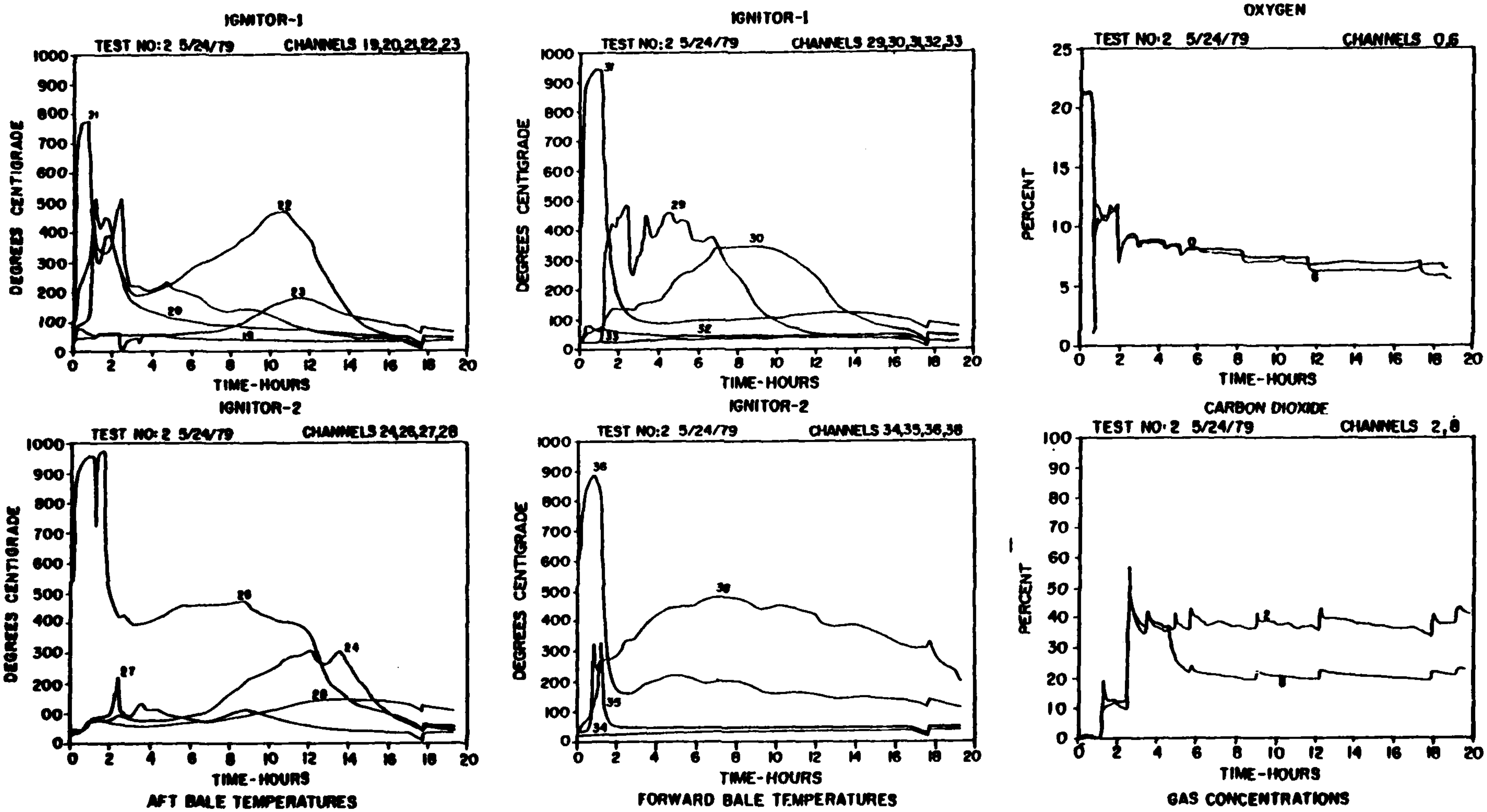


FIGURE 17

Cargo Hold Test 2

TABLE 4

CHAMBER TEST DATA

TEST NUMBER	PERCENT CO_2	SOAKING TIME (HR)	SMOLDERING COMBUSTION*	EXTINGUISHMENT RESULTS		
				SUCCESSFUL	QUESTIONABLE	UNSUCCESSFUL
1	68	19.5	No	X		
2	0	19.5	Yes			X
3	31	27.0	Yes			X
4	46	27.0	No		X	
5	0	25.0	No		X	
6	70	25.0	No	X		
7	31	25.5	Yes			X
8	46	25.5	Yes			X
9	31	44.5	No		X	
10	46	44.5	No	X		
11	46	40.0	No	X		
12	31	40.0	No		X	
13	20	66.0	Yes			X
14	20	66.0	Yes			X
15	78	14.5	No	X		
16	65	14.5	No	X		
17	25	50.0	Yes			X
18	31	50.0	Yes			X
19	40	15.5	No		X	
20	31	62.5	Yes			X

*Changing to flames after opening hatch.

discharges of carbon dioxide at regular intervals to maintain the desired levels. A better understanding of the extinguishment results is illustrated by figure 18. One interpretation of this plot is that at the 46 percent carbon dioxide concentration level, we have reached the bottom edge of the curve which indicates a high probability for successful extinguishment. Between 46 percent and 31 percent carbon dioxide concentrations there is a questionable area where there may or may not be extinguishments. Below the 31 percent carbon dioxide concentration, we can reasonably assume that there will be no extinguishments.

The chamber test data suggests that a successful deep-seated extinguishment depends on a concentration level of approximately 50 percent carbon dioxide for 40 hours, or even greater concentrations for shorter soaking times. In the tests the high carbon dioxide concentrations which required frequent discharges into the chamber accomplished several actions. It forced out air containing oxygen that was necessary for burning and at the same time it replaced this air with an atmosphere void of oxygen. By doing this, the process also lowered the chamber's air temperature by forcing out hot gaseous combustion products. The smoldering fire also lost heat to the incoming carbon dioxide and air. It is suggested that in a long-term fire, this continued heat loss combined with the inerting atmosphere eventually lowers the smoldering cardboard below its ignition temperature and thus extinguishes it. Stated another way, the extinguishing action appears to be a combination of displacing the oxygen needed for burning and the removal of heat from the smoldering area. The chamber tests indicate that only high carbon dioxide concentrations combined with long soaking times are effective in this action. From this, it is surmised that only the higher carbon dioxide concentrations can penetrate into the bale and reduce the oxygen level low enough to complete the extinguishing action.

Another important factor observed in the chamber tests was the difference in oxygen concentration when the smoldering fires were extinguished or when they continued to burn. Figure 19 shows that in the successful extinguishments with carbon dioxide concentrations, it was observed that the oxgyen concentration dropped below 5 percent for up to two hours. In the unsuccessful extinguishments, however, oxygen levels were always recorded above the 5 percent limit. This suggests that a fire smolders in air containing 5 percent oxygen or more, but may be extinguished in air containing less than 5 percent oxygen. Precision laboratory testing is needed to determine the exact oxygen limit needed to sustain or extinguish a smoldering fire.

Data collected from the chamber tests indicates that high concentrations of carbon dioxide extinguished the deep-seated fires while low concentrations did not. Low concentrations did, however, extinguish superficial flames and confined the fire to inside the bales.

4.3 Cargo Hold Control Tests

Two full-scale cargo hold control tests (number 3 and 4 in the overall testing) were conducted. The results are listed in table 5. In each test, superficial flames were extinguished and the deep-seated combustion was confined to the core areas.

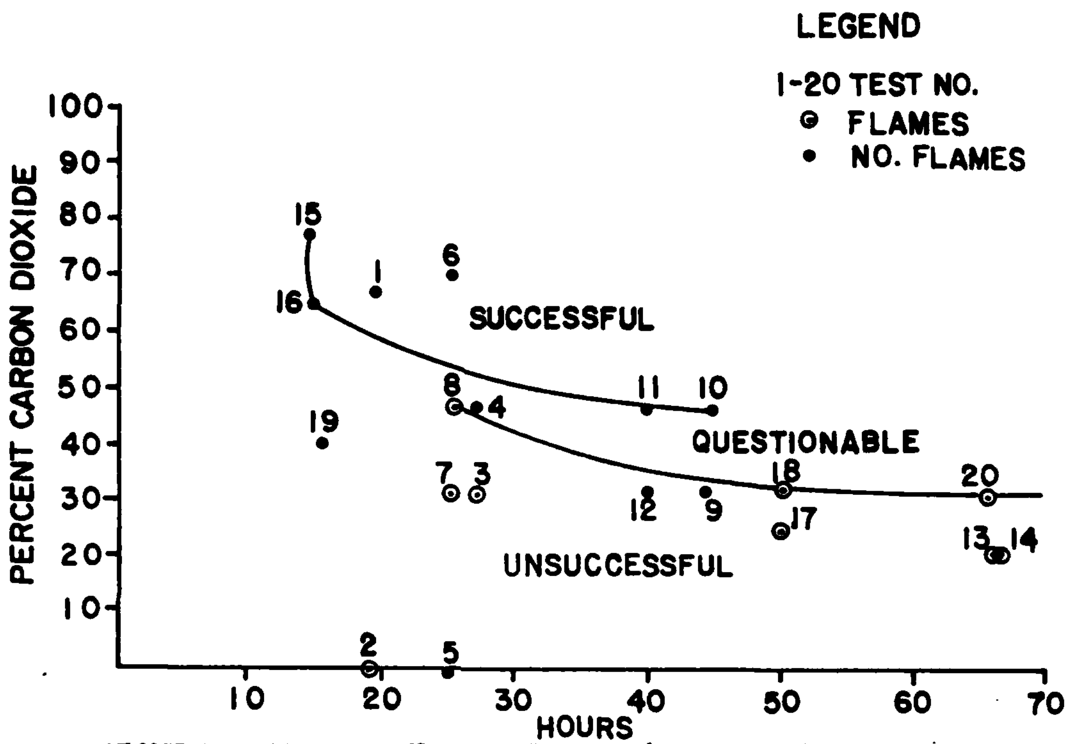


FIGURE 18

Chamber Test Extinguishment Curves

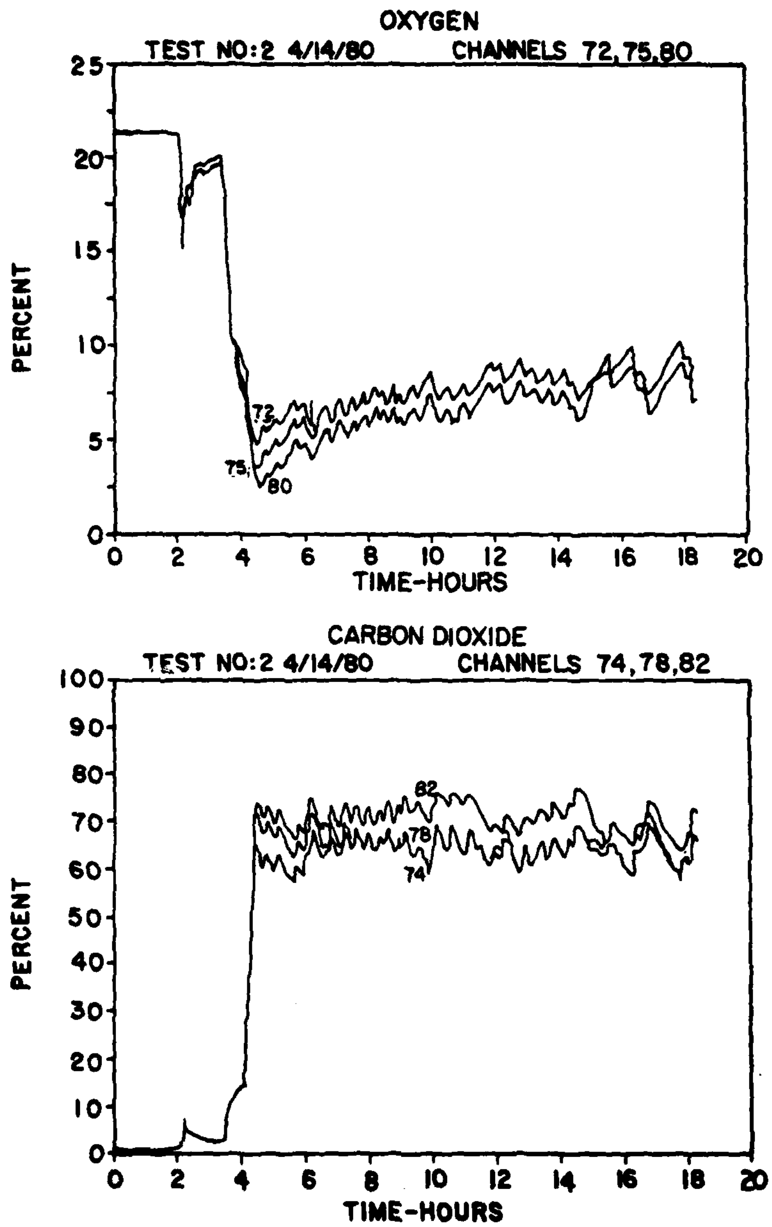


FIGURE 19

Successful Extinguishment Concentration

TABLE 5

CARGO HOLD CONTROL DATA

TEST	AGENT	AGENT CONCENTRATION (PERCENT)	SOAKING TIME* (HOURS)	FLAMES (END OF TEST)	DATA
3	Carbon Dioxide	38-20	68	Superficial flames extinguished during test. After opening hatches, smoldering combustion found to exist and soon burst into flames.	An initial carbon dioxide concentration, 38 percent, was allowed to decrease to 20 percent over a period of 68 hours. At this point, gas concentrations stabilized and it was concluded that no superficial flames would break out. The smoldering combustion had increased, however, to the point that the structural integrity of the vessel might be endangered, therefore, the test was terminated.
			(Total 68 hours)		
4	Carbon Dioxide	40 10	2 10	Superficial flames extinguished during test. Smoldering combustion increased to point of endangering vessel.	An initial carbon dioxide concentration, 40 percent, extinguished the superficial flames. The concentration was lowered to 10 percent and the smoldering combustion increased to a point where it endangered the vessel. At this time, the concentration was increased to 60 percent for 15 hours and then allowed to gradually decrease down to 20 percent. At this point, the test was terminated before the smoldering situation reached a dangerous situation for the test vessel.
		60-20	85	Smoldering combustion contained but soon burst into flames after opening hatches.	
			(Total 97 hours)		

*Soaking time refers to the number of hours the bales are engulfed in carbon dioxide.

Three core areas, each containing a core bale with two ignitors, were used in each test. The ignitors in core bale one were energized first. After flames could be seen breaking out of this area, a calculated quantity of carbon dioxide was discharged into the hold to establish the test concentration. This concentration was based on the requirement for carbon dioxide systems as mandated by Coast Guard Regulations for Cargo Vessels. It was selected to determine the effectiveness of present Coast Guard requirements in controlling and containing deep-seated combustion.

In test number three, the carbon dioxide concentration was to be maintained for one hour after flame breakouts in the different core areas. The second and third core areas were to be energized at successive time intervals. One hour after the carbon dioxide discharge for the first flame breakout, the concentration was permitted to decrease in the hold by natural leakage. This leakage was to be permitted until a second flame breakout occurred. At this point, the carbon dioxide concentration was to be restored. This procedure was to be repeated again for core area three.

In test number four, the procedure for the ignitors and the carbon dioxide discharges were to be identical to test number three with the exception that the carbon dioxide concentration was to be decreased by an exhaust system instead of by natural leakage. This was done to increase the supply of air in the hold and thus shorten the time between flame breakouts.

4.3.1 Test Number 3

Six ignitors (two per core bale) were used in test number three. The ignitors in core area one were energized at the beginning of the test, the ignitors in core area two were energized four hours into the test, and the ignitors in core area three were energized nineteen hours into the test. The three core areas were energized at different times and under varied conditions to determine the oxygen and carbon dioxide concentration which would permit flame breakouts to occur.

Two hours into the test, the deep-seated fire broke out of core area one and started superficial burning. This breakout was recorded on a video camera system. At this point, temperatures inside core bale one were over 752°F (400°C) (figure 20). When flames broke out, core bale one's ignitors were de-energized and core bale two's ignitors were energized. Thirteen hundred pounds (589.7 kg) of carbon dioxide were then discharged into the hold to reach a test concentration of 38 percent. The superficial flames were immediately extinguished but internal bale temperatures indicated that the deep-seated fire still existed. The ignitors in core bale two were operated for ten hours and then de-energized since the internal bale temperatures were above those needed for a deep-seated fire. At twelve hours into the test, oxygen and carbon dioxide concentrations needed for a second flame breakout had not occurred. Eighteen hours into the test, the oxygen and carbon dioxide concentrations showed a slight decline with little evidence of change. At this time, the ignitors in core area three were energized to increase the number of areas in which a flame breakout might occur. This was done because it appeared that the oxygen and carbon dioxide concentrations necessary for recurrence of flame breakout would not be reached by natural leakage from the hold. Therefore, all conditions were optimized to assist a flame breakout in occurring. The test was terminated at sixty-eight hours because the oxygen

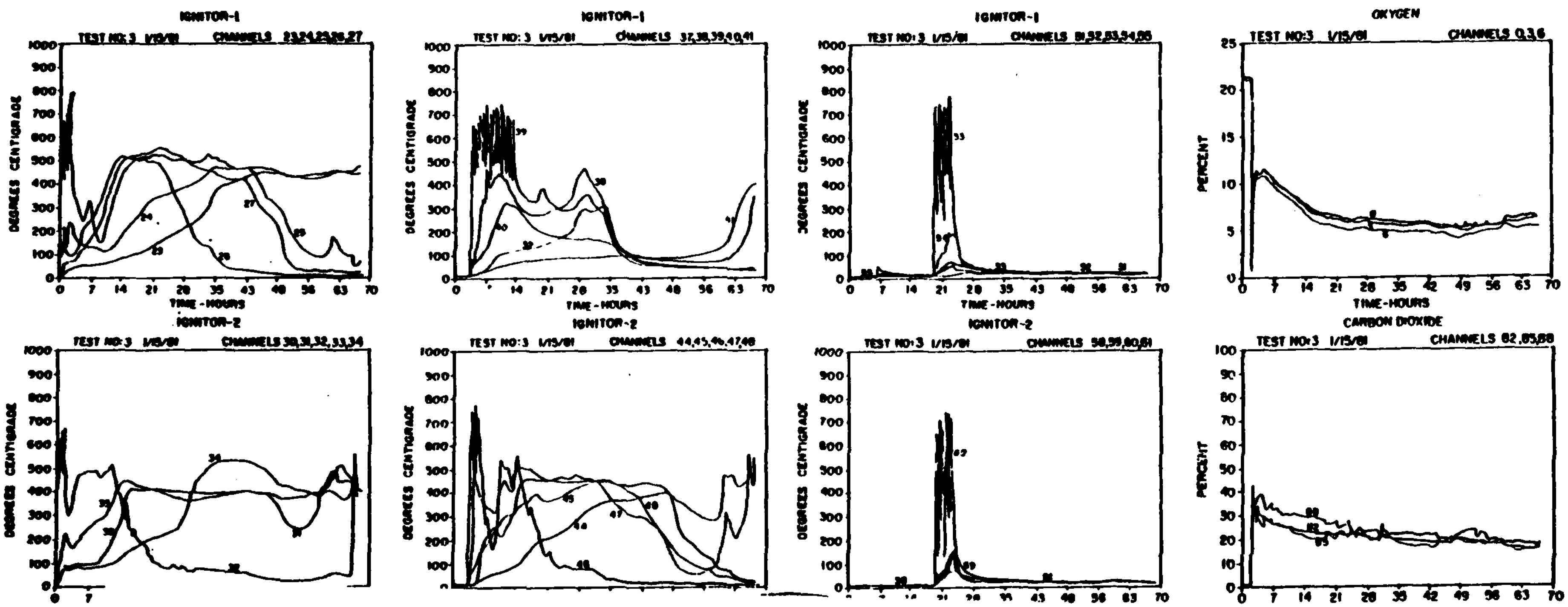


FIGURE 20

Cargo Hold Test 3

and carbon dioxide levels remained relatively stable and gave no indication of reaching the concentrations necessary for a flame breakout. It was felt that the oxygen leaking into the hold was being consumed by the smoldering combustion.

At the conclusion of the test, the hatch covers were removed to determine the extent of the smoldering combustion. No flames could be seen immediately although many bales were still smoldering. This condition was not especially widespread in the one-foot (0.3 m) gaps which existed where the cargo had not been tightly packed. As the hatch covers remained opened, flames began to appear in the gaps between the bales. The gaps appeared to assist in spreading the combustion.

During the test the video camera showed the flaming combustion to be extinguished and controlled by the carbon dioxide. Once the hatch covers were removed, the smoldering combustion rapidly changed to a flaming condition which forced the F&STD crew to replace the hatch covers and use a backup water sprinkler system to bring the fire situation under immediate control. The sprinkler system was operated for five minutes an hour for twelve hours. At this time, the hatch covers were again opened and each core area was thoroughly torn apart and watered down.

4.3.2 Test Number 4

Four hundred bales were loaded into the cargo hold for test number four. The loading was completed in such a manner that the bales were tightly packed with no gaps between them. This created a more realistic situation since a ship's agent would find it more economical to carry a full hold and the cargo would not shift during a vessel's voyage.

In test number four, the ignitors in core area three were energized first. This area contained the best internal lighting to view and record a flame breakout. All core bales and core areas were identical; therefore, it made no difference which core area was energized first.

One hour and forty minutes into the test, flames could be seen coming out of core area three. Figure 21 shows that the internal bale temperatures recorded at this time were over 752^{o}F (400^{o}C). The ignitors in this area were then de-energized and thirteen hundred pounds (589.7 kg) of carbon dioxide were discharged into the hold. This created a carbon dioxide concentration of approximately forty percent in the hold while the oxygen concentration immediately droped below ten percent. One hour after the discharge, the ignitors in core area two were energized and operated for five hours. When the ignitors in core area two were energized, three exhaust fans connected to the hold were also turned on. The intakes for the fans were located below each core area. Each fan was designed to exhaust one hundred cubic feet per minute (2.8 cu m per min) from the hold. Theoretically, this exhaust rate would replace the cargo hold's atmosphere in approximately thirteen minutes. This rapid air change was intended to cause a flame breakout in the hold. Instead, the fans remained on for five hours and no flame breakout occurred.

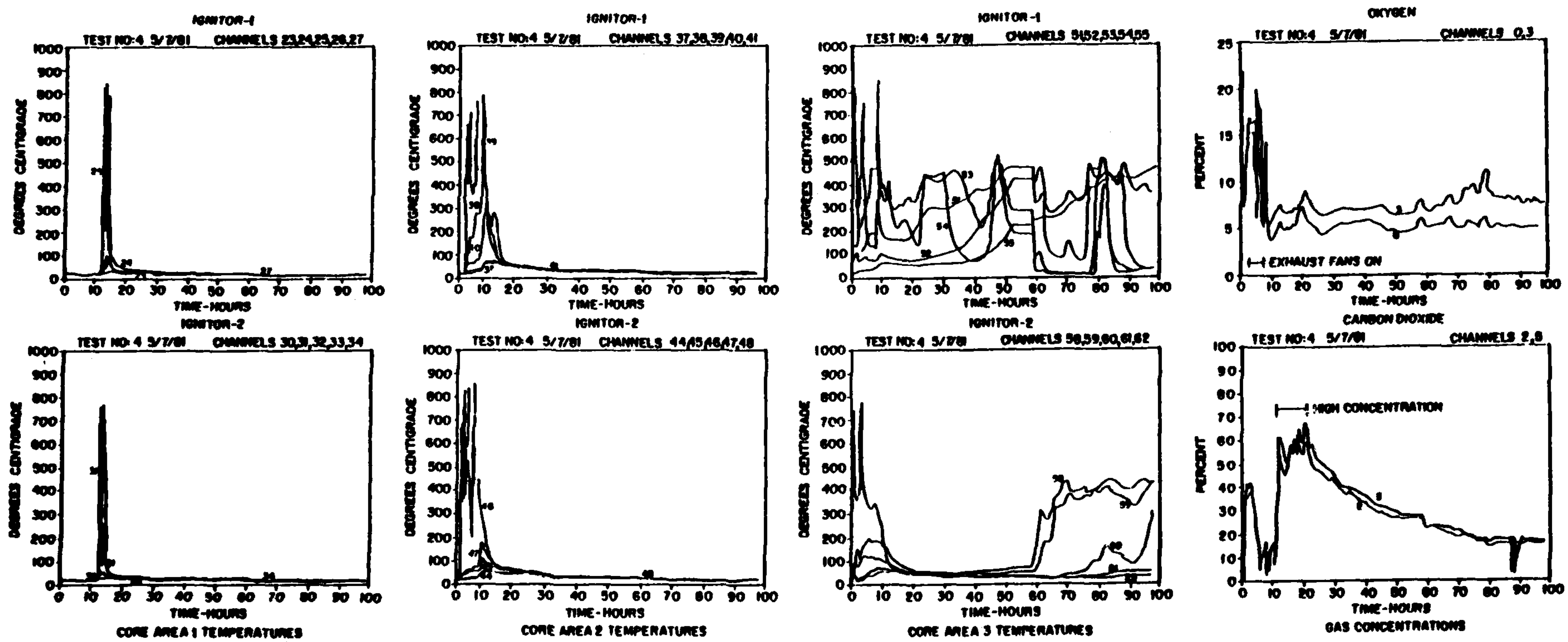


FIGURE 21

Cargo Hold Test 4

Although no flaming combustion could be seen, the smoldering combustion had increased to the point where the deck plates, hatch covers, and steel bulkheads were getting hot enough to endanger the safety of the test ship and its crew. At this point, the exhaust fans were turned off and hose-lines were used to wet down the decks and bulkheads. Five hundred pounds (227 kg) of carbon dioxide were also discharged into the hold to control the increased smoldering.

Based upon what had occurred, it was concluded that a serious smoldering situation would develop and endanger the ship before a second flame breakout would occur in the hold. Therefore, the test procedure was modified and it was decided to use the remaining carbon dioxide in an attempt to extinguish the smoldering combustion. The resulting discharge into the hold produced a fifty-five percent concentration. During this time, the ignitors in core area one were energized for five hours to see if a flame breakout could be developed in an atmosphere containing fifty-five percent carbon dioxide. No flame breakout occurred. This concentration was maintained for ten hours until the test supply of carbon dioxide was practically exhausted. Since the carbon dioxide was leaking from the hold, it was decided to terminate the test when the concentration dropped to twenty percent. This was done to insure ending the test before reaching conditions which might endanger the test ship and requiring that the crew enter the hold.

The test was concluded after ninety-six hours. The hatch covers were then removed to determine the extent of the smoldering areas. Core areas one and two showed no indication of deep-seated combustion. Core area three, however, was smoldering in a ten-foot (3.01 m) diameter circle around the core bale containing the ignitors. Five minutes after the hatch covers were removed over this area, it burst into flames. The flames were then extinguished by applying copious amounts of water and tearing the bales apart.

5.0 SUMMARY/CONCLUSIONS

A carbon dioxide concentration of 25 percent or greater will control a deep-seated fire from a ship master's point of view. That is, the cargo's external flames are extinguished and the deep-seated fire neither increases nor decreases in intensity. The fire is contained and confined to the cargo. As this containment is accomplished, the steel decks, hatches, and bulkheads cool down and are no longer hot to the crew's touch. This containment subsequently reduces the danger to the vessel and allows it time to head toward the nearest port where extinguishment can be accomplished. Once the carabon dioxide concentration drops below twenty-five percent, however, the smoldering combustion begins to increase in intensity and to spread. This situation then develops to the point where it can endanger the safety of the vessel even though flaming combustion has not developed.

The extinguishment of a deep-seated Class A fire is highly unlikely using carbon dioxide concentrations below 60 percent and soaking times of less than 15 hours. Higher concentrations and longer soaking times are necessary to provide the opportunity for extinguishment to occur. Such conditions do not guarantee an extinguishment, but without them there is little or no chance of extinguishment. Based on data collected, an extinguishment is unlikely to occur using the quantity of carbon dioxide carried aboard merchant vessels according to Coast Guard Rules and Regulations. The high carbon dioxide concentrations and the long soaking times necessary for possible extinguishment on a ship at sea would be difficult to achieve and prohibitive in cost.

The time between agent discharges is important from the viewpoint of maintaining a carbon dioxide concentration high enough to (1) extinguish and control superficial burning and to (2) provide the optimum conditions for the possible extinguishment of deep-seated combustion. It is not feasible to identify the time between these discharges in hourly increments because different cargo holds have different leakage rates and prescheduled discharges will not maintain a set concentration. Therefore, rather than base the agent discharge into the hold on a regular time schedule, the concentration should be monitored and discharges made in order to prevent the carbon dioxide concentrations from dropping below 25 percent. Although the chamber tests indicated that a 20 percent concentration of carbon dioxide would extinguish superficial burning and contain the deep-seated fire, the cargo hold tests indicated that an additional 5 per cent should be added as a safety factor to provide for variations in carbon dioxide concentrations recorded at different heights in the cargo hold during testing.

Soaking times are critical for keeping the flaming combustion extinguished and for controlling and containing the deep-seated combustion. The soaking time allows the carbon dioxide to diffuse throughout the cargo and dilute the oxygen concentration below the level required for combustion. At the same time, it allows the heat from the smoldering areas to be absorbed by the air in the hold and to be dissipated to the outside by natural leakage. It also allows time for the deck, bulkheads, and remaining cargo to absorb a portion of this heat and yet at the same time prevents their ignition or overheating. In effect, the soaking time continues the control and extinguishing action by displacing the oxygen needed for burning and by allowing the heat required for combustion to dissipate. If the soaking time is discontinued (i.e., the hold is opened), the smoldering combustion can increase in intensity to the point where it can endanger the vessel even though flaming combustion has not appeared.

The time-temperature curves and the control times of the chamber tests were closely related to those of the large-scale tests during the first 15 hours of a deep-seated fire. After this time, the internal temperatures of the single bales are lower and more uniform than the internal temperatures of the bales deep within the hold. It appears that the bulk cargo surrounding a deep-seated fire tends to insulate and therefore retain the heat generated by the fire. Thus it takes longer for the internal temperature to drop and for an extinguishment to occur. Gas samples compared at 2, 5, and 9-foot (0.6, 1.5, and 2.7 m) heights in the full-scale cargo hold tests indicated that (1) oxygen concentrations seldom varied by more than 3 percent from level to level while (2) carbon dioxide concentrations varied by more than 5 percent but usually less than 15 percent from level to level. These variations in oxygen and carbon dioxide levels suggest that the cargo in the overhead would be prone to both smoldering and flaming combustion while cargo in the lower portion of the hold would be more prone to have only smoldering combustion.

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