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FIRE CONTROL AGENT EFFECTIVENESS FOR HAZARDOUS CHEMICAL FIRES: --ETC(U)
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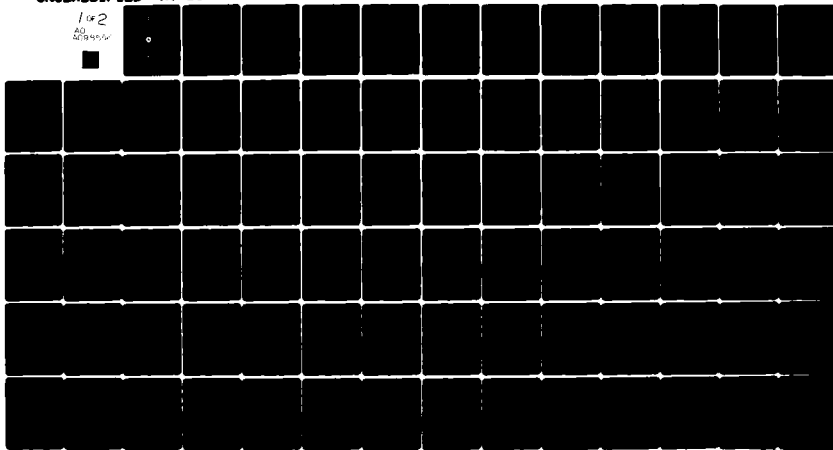
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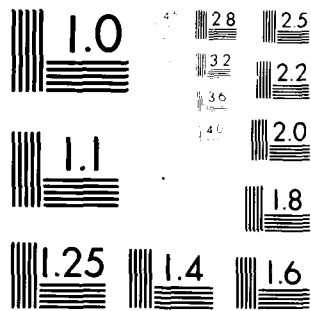
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FIRE CONTROL AGENT EFFECTIVENESS
FOR HAZARDOUS CHEMICAL FIRES:
CARBON DISULFIDE.

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D. W. / Johnson
W. D. / Carver

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J. R. / Walker



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FINAL REPORT

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U.S. DEPARTMENT OF TRANSPORTATION
United States Coast Guard
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16. Abstract Carbon disulfide fires from 25 ^{ft} to 400 ^{ft} were controlled and/or extinguished using four foam agents and water. The most effective agent was high expansion foam, followed by aqueous film forming foam, fluoroprotein foam, and protein foam. Water was less effective in fire control than any foam agent, although it extinguished fires faster than low expansion foams at very high application rates. Dry chemical agents were largely ineffective in extinguishing carbon disulfide fires. These tests showed that the agents usually recommended for carbon disulfide fires, water and dry chemical, are less effective than foam, which is not recommended, confirming a previously reported conclusion that current agent effectiveness data may be unreliable and reinforcing the recommendation for a systematic examination of fire fighting agent effectiveness on fires from Cargoes of Particular Hazard. Carbon disulfide fires were more difficult to control and extinguish than hexane fires that had been studied earlier. These tests continue the series recommended in USCG Report No. CG-D-64-76 (NTIS AD-A026300) using methodology developed for the baseline hexane fire tests reported in Report No. CG-D-50-80 (NTIS AD-A089585)			
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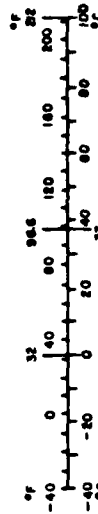
METRIC CONVERSION FACTORS

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				
sq in	square inches	6.5	square centimeters	cm ²
sq ft	square feet	0.09	square meters	m ²
sq yd	square yards	0.8	square meters	m ²
sq mi	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				
teaspoon	teaspoons	5	milliliters	ml
Tablespoon	tablespoons	15	milliliters	ml
fluid ounce	fluid ounces	30	milliliters	ml
cup	cups	0.24	liters	l
pint	pints	0.47	liters	l
quart	quarts	0.95	liters	l
gallon	gallons	3.8	liters	l
cu ft	cubic feet	0.03	cubic meters	m ³
cu yd	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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
km	kilometers	1.1	miles	mi
		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	ac
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	st
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
m ³	cubic meters	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



* 1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Spec. Publ. 295, Units of Weight and Measure, Pt. 6-82.28, SD Catalog No. C13.10.296.

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SUMMARY OF RESULTS

This is a report of the results of fire control and extinguishment tests using four foam agents, water and four dry chemical agents on carbon disulfide fires. The work was conducted for the U. S. Coast Guard under Contract DOT-CG-841340-A. The objectives of the test program were to determine the effectiveness of several foam and dry chemical agents and to compare the responses of carbon disulfide and hexane fires to these agents.

Dry chemical fire extinguishing tests were conducted on 25- and 100-ft² carbon disulfide fires. Extinguishment equipment included 150 and 350-lb wheeled engine fire extinguishers and 30-lb portable fire extinguishers. All of the dry chemical tests used fixed nozzle systems except for a few tests in which manual agent application was used on fires which had been previously controlled by foam application. Sodium bicarbonate (NaHCO_3), potassium bicarbonate (KHCO_3), a urea-potassium bicarbonate reaction product (urea- KHCO_3), and monoammonium phosphate were tried. Agent application rates ranged from 0.078 to 0.412 lb/sec-ft².

Low and high expansion foam and water tests were conducted on 25-, 100-, and 400-ft² carbon disulfide fires with and without obstructions. Several foam generators of different types and capacities were used in the tests. All

of the tests used a fixed nozzle system wherein the foam or water was applied gently at the center of the upwind edge of the fire. The foams tested were protein, AFFF, and fluoro-protein low expansion foams and two high expansion foams. Application rates ranged from 0.037 to 0.69 gpm/ft².

Dry chemical agents were not effective in extinguishing carbon disulfide fires. Even at application rates in excess of 0.2 lb/sec-ft², only 4 of 10 tests resulted in extinguishment. Potassium bicarbonate and the urea-potassium bicarbonate reaction mixture did not extinguish any fires. Sodium bicarbonate extinguished two fires (both of which later reignited) and monoammonium phosphate extinguished two fires. Poor extinguishment results were attributed to the low ignition temperature of the carbon disulfide and the inability of the dry chemical agents to chemically interact with the carbon disulfide combustion mechanism.

Results of the foam and water tests show that high expansion foam is the most effective of the foam agents tested on the carbon disulfide fires, i.e., at a given application rate, high expansion foam showed the fastest control and extinguishment times of the four foams tested.

Of the three low expansion foams tested, AFFF produced the shortest fire control times for any given application rate. It was followed in fire control effectiveness by protein and fluoroprotein foams. For fire extinguishment, the low expansion foams were approximately

equal in their effectiveness. Water was less effective as a fire control agent than the foams. At flow rates below 0.4 gpm/ft², water was less effective than the foams in extinguishing carbon disulfide fires; however, at application rates above 0.4 gpm/ft², it was more effective than the low expansion foams in extinguishing fires.

Fire control time (defined as the time at which the radiant flux to a radiometer located crosswind from the fire is reduced to 5 percent of the initial flux level) proved to be a better parameter for foam agent comparison than did fire extinguishment time. There was one primary reason for this: fire control results were much more repeatable than extinguishment results. Extinguishment times were highly variable because burning continued along the pit sides long after the pit was filled with foam. This behavior was very erratic, with the residual flame sometimes being only an inch or two long.

The concentric circle obstructions used in the fire tests did not have a significant effect on the fire control times.

The fire control results for high expansion foam, AFFF, and protein foam and the fire extinguishment results for the dry chemical agents were compared with the baseline hexane fire control and extinguishment data. High expansion foam, within the accuracy of the test results, was as effective on carbon disulfide fires as on hexane fires. AFFF was

less effective on carbon disulfide fires at low application rates, but at application rates above 0.25 gpm/ft², the AFFF was equally effective on either type of fire. Protein foam was much less effective on carbon disulfide fires at all application rates. Dry chemical agents were not effective on carbon disulfide fires. Of the four dry chemical agents tested, only monoammonium phosphate showed any promise as a carbon disulfide extinguishing agent, and it required very high application rates.

CONCLUSIONS

Based on the results of the carbon disulfide tests, the following conclusions were reached:

- 1) High expansion foam was the most effective agent tested for both fire control and fire extinguishment.
- 2) Low expansion foams controlled the fires faster than water, but at high application rates were less effective than water in fire extinguishment.
- 3) Water applied as a "fog" was no more effective in either controlling or extinguishing carbon disulfide fires than water applied through a low expansion foam nozzle to the fuel surface.
- 4) Dry chemical agents were ineffective in extinguishing carbon disulfide fires.
- 5) Application methods which disturb the liquid surface the least are the most effective in both extinguishment and control.

BACKGROUND

Fires aboard ship have always been a major concern for the U. S. Coast Guard. Much time and effort has been spent in determining how best to control or prevent cargo fires and fires in machinery spaces and crew's quarters. The combustible materials in living quarters and machinery spaces are generally common materials and fire fighting methods have been reasonably well established. Cargo fires are an altogether different problem, particularly in the case of flammable liquids. Containing the fire to a certain area may be nearly impossible. Reactions between various chemicals carried on the same ship can sometimes be violent. The cargo vapors and/or combustion products are often toxic. Certain extinguishing agents are not effective on certain cargoes and, in some cases, may be dangerous to use. Furthermore, the recommended agents may, in some cases, be less effective in controlling and/or extinguishing cargo fires than non-recommended agents.

These problems with cargo fires prompted the USCG to investigate methods for controlling fires for 29 Cargoes of Particular Hazard. The report on this study, entitled "Survey of the Effectiveness of Control Methods for Fires in Some Hazardous Chemical Cargoes," was released in 1976. A major conclusion of the report is that there is an "...almost complete lack of basic, large-scale test data which

would demonstrate the fire extinguishing or fire control effectiveness of available fire control agents on fires in the designated chemicals." The report went on to say,

"Although agents may be recommended, the recommendations may be poorly substantiated and may conflict with recommendations from other sources. Fire-related data on the chemicals which may fuel fires is sometimes unavailable for specific chemicals, and the fire behavior of the chemicals is not always fully understood.

Before any rational assessment of the adequacy of fire control aboard chemical carriers can be made, effective agent application rates must be obtained for fires in each of the specified chemicals. Small tests which demonstrate only that a specific small fire can be overwhelmed with a specific agent do not provide adequate results for assessment purposes, since such results may predicate massively excessive agent requirements for large fires or, conversely, may cause underestimation of agent application rates because effective rates are not linear with fire size. Additionally, the effect of peak mass burning rate is not observable in small tests, so that results would predict inadequate application rates for large fires burning at near peak rates."

Therefore, the USCG decided to develop a standardized test method and baseline data which would allow comparison of specific fire control agent effectiveness against specific hazardous chemical fires and provide engineering data to allow economical design and adequate review.

The results of DOT-CG-42,355-A, Task 6, "EFFECTIVENESS OF FIRE CONTROL AGENTS ON CHEMICAL FIRES, Phase I: Test Methodology and Baseline Hexane Tests" provided a test method (as described in Appendix F) and baseline fire control and extinguishment data with which agent and/or

cargo comparisons could be made. The carbon disulfide tests were run using that test method.

DESCRIPTION OF TEST FACILITIES

The Applied Technology Corp. fire test facility is located on 10 acres of flat land east of Newcastle, Oklahoma. The nearest occupied building is one-half mile west of the site. In the direction of the prevailing wind (southerly to northerly), the unoccupied zone is 1.5 miles in length. The following sections briefly describe the equipment and structures located at the test site. A detailed description of the test facilities is given in the report entitled "EFFECTIVENESS OF FIRE CONTROL AGENTS ON CHEMICAL FIRES. Phase I: Test Methodology and Baseline Hexane Results." Any significant changes or additions are presented in this section.

Structures

There are presently three structures located at the Newcastle test site: 10-ft by 20-ft and 16-ft by 24-ft portable buildings and a 24-ft by 32-ft preformed concrete building. These buildings are located as shown in Figure 1. One portable building serves as an office and visitors' center and the other is used for storage. The concrete building houses the shop, storage area, foam solution piping and valving, and instrument room.

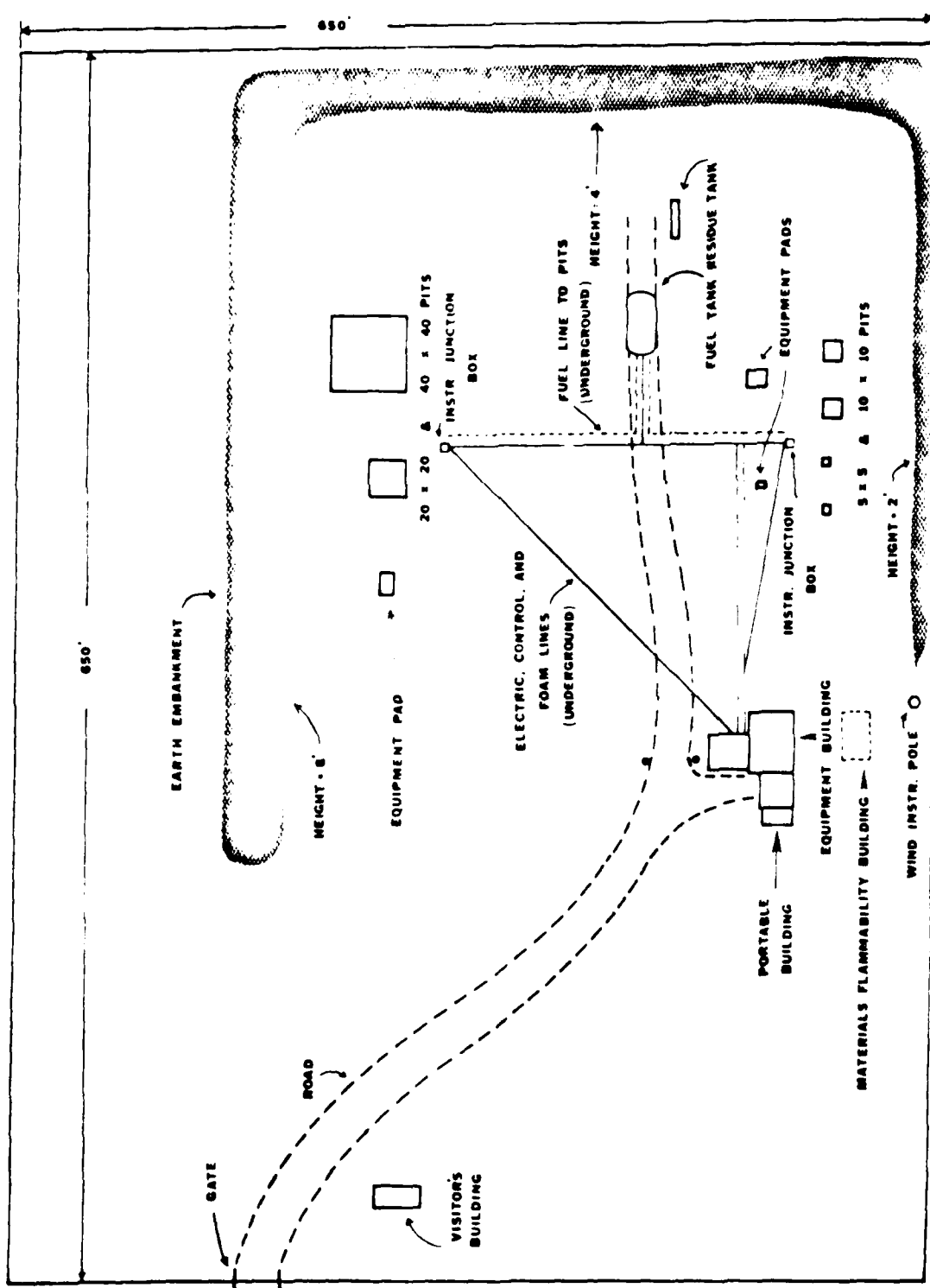


FIGURE 1. FIRE TEST FACILITY LAYOUT.

Fire Pits

The fire extinguishment tests can be conducted in four sizes of square concrete pits constructed to give approximate burning areas of 25, 100, 400 and 1600 ft². All pits are 2 ft deep and are sunk into the ground so that the top of the pit wall is near ground level.

Tankage

Tanks are provided at the test site for water storage, fuel storage, clean up or residue storage, and foam storage and delivery. Water is stored in a 5500-gallon vertical steel tank and the foam holding tanks are standard 500- and 1000-gallon LPG storage tanks. The fuel tank has a capacity of approximately 10,000 gallons and the horizontal residue tank has a capacity of 4,000 gallons. The fuel tank is surrounded by a 4-ft high concrete impounding basin. The basin is equipped with automatic float valves which vent the nitrogen pressure in the fuel tank if a liquid level is sensed in the impoundment area.

Liquid and Gas Delivery Systems

The liquid and gas delivery systems consist of fuel, foam, and nitrogen piping loops. These systems are interconnected so that nitrogen can be used to blow down the liquid lines if necessary. All aboveground, outdoor piping and indoor pressure piping is constructed of schedule 40 steel pipe. Below ground and indoor non-pressurized piping is schedule 40 PVC piping.

Fuel Delivery System

The fuel delivery system, shown in Figure 2, consists of the 10,000-gallon, nitrogen-padded fuel storage tank and necessary piping and valving so that fuel can be routed to any fire pit. All below ground fuel lines are steel.

Foam Delivery System

Due to the large number of foam extinguishment tests to be conducted and the wide range of foam flow rates required for the tests, a rather complex and flexible foam system was designed and constructed. The system allows for premixing of foam concentrate and water for all of the tests. A piping diagram of the foam delivery system is shown in Figure 3.

Nitrogen Distribution System

The nitrogen system provides dry nitrogen for transferring foam and fuel, and for the fuel tank liquid level (bubbler) system. The nitrogen supply is large enough to provide fuel delivery and foam pressurization for a 1600-ft² fire test.

Foam Generators

Two types of low expansion foam nozzles are available. The 2-gpm and 6-gpm nozzles are test nozzles (i.e., not intended for actual fire protection systems). The larger capacity nozzles are "tank side nozzles" (i.e., they are

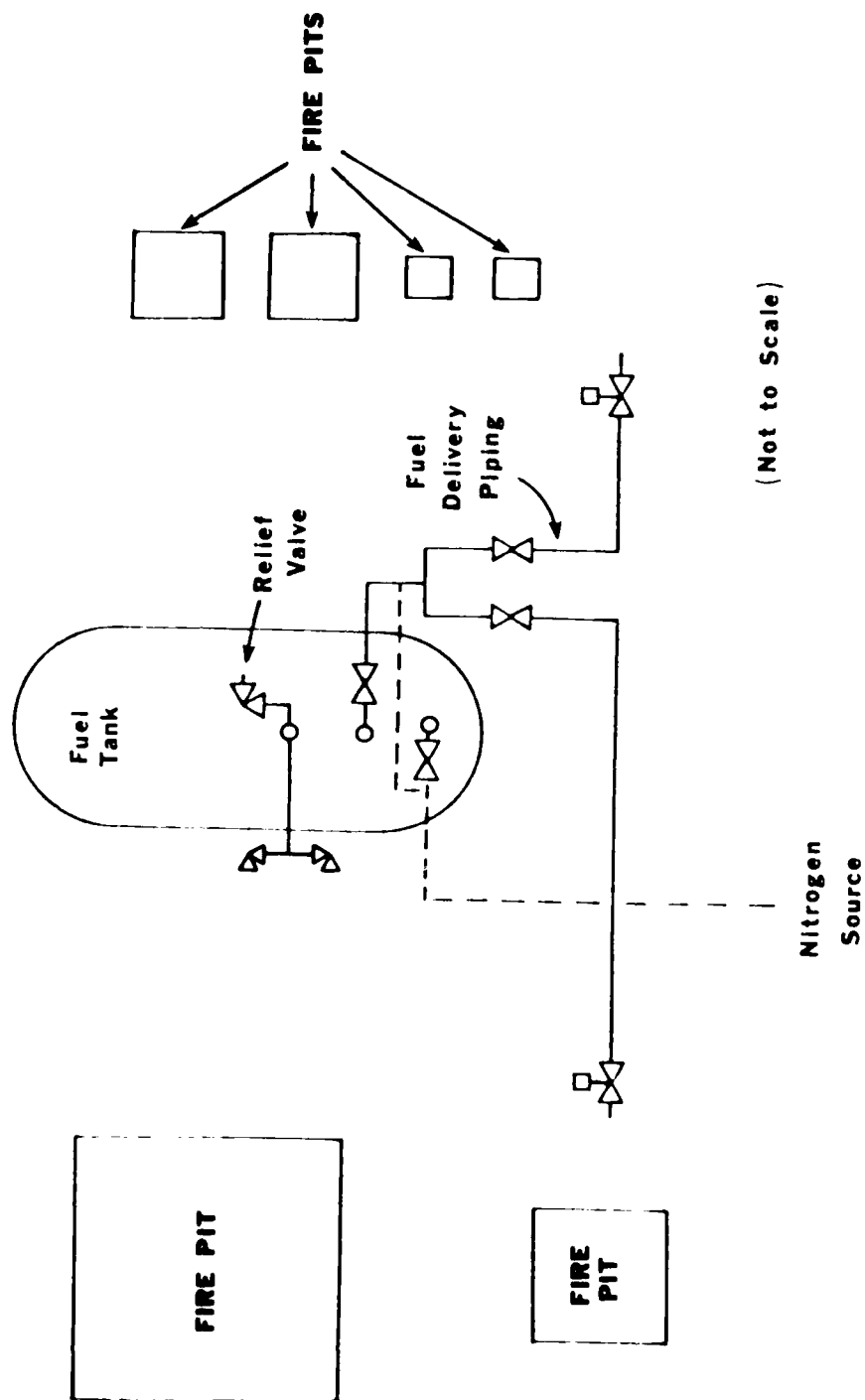


FIGURE 2. SCHEMATIC OF FUEL DELIVERY SYSTEM.

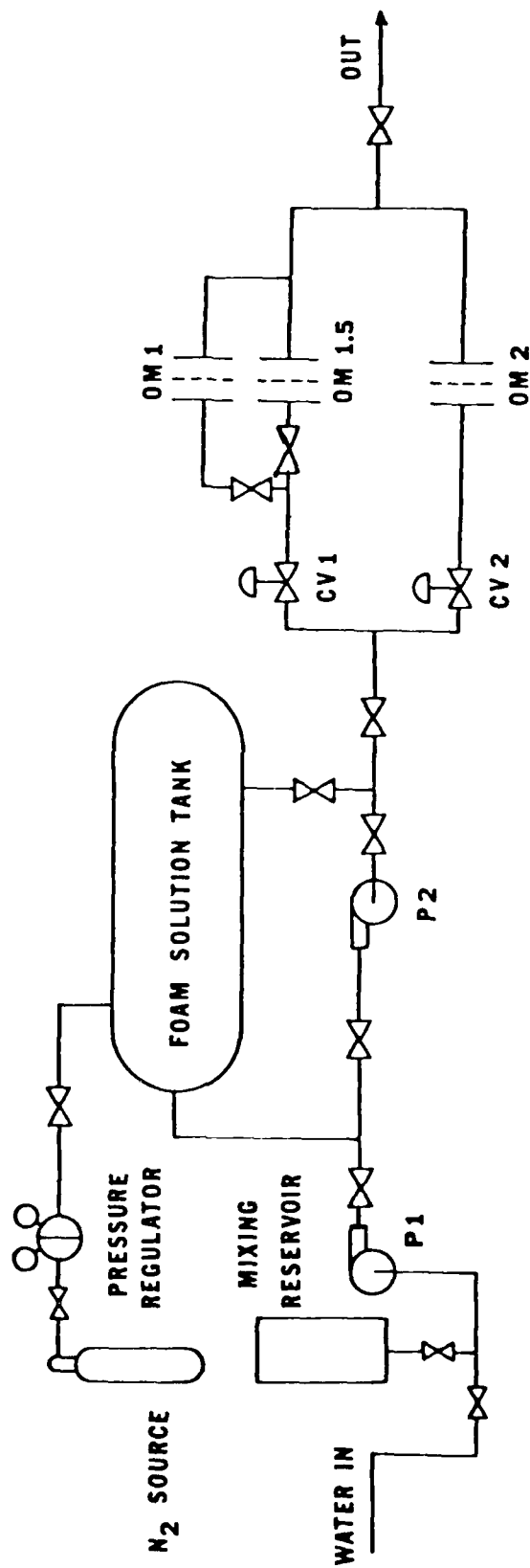


FIGURE 3. SCHEMATIC OF FOAM DELIVERY SYSTEM.

intended to be used inside flammable liquid storage tanks). Both types of nozzles operate by forcing the foam solution through an orifice so that the resulting spray entrains sufficient air to cause the solution to form a foam (see Figure 4).

The high expansion foam generators, shown in Figure 5, produce foam by spraying the foam solution onto a metal screen while simultaneously blowing air through the screen. These generators all include a built-in, electrically operated fan. Foam generators ranged in size from 130 cfm (nominal) to 6000 cfm (nominal) at an expansion ratio of 500:1.

Dry Chemical Units and Nozzles

Three different dry chemical units are available for the dry chemical extinguishment tests. The units differ greatly in capacity (nominal capacities are 150, 350, and 2000 lbs) but are similar in arrangement and construction. Each unit incorporates a cylindrical steel pressure vessel for storing the powdered dry chemical. Nitrogen is supplied from one or more high pressure storage cylinders to a pressure regulator that drops the pressure to the working pressure of the powder storage tank (generally 250 psig). This regulated supply of nitrogen is injected into the tank through multiple orifices in order to create a fluidized mixture of dry chemical powder and nitrogen. This fluidized mixture is routed to the fixed-in-place nozzles by a

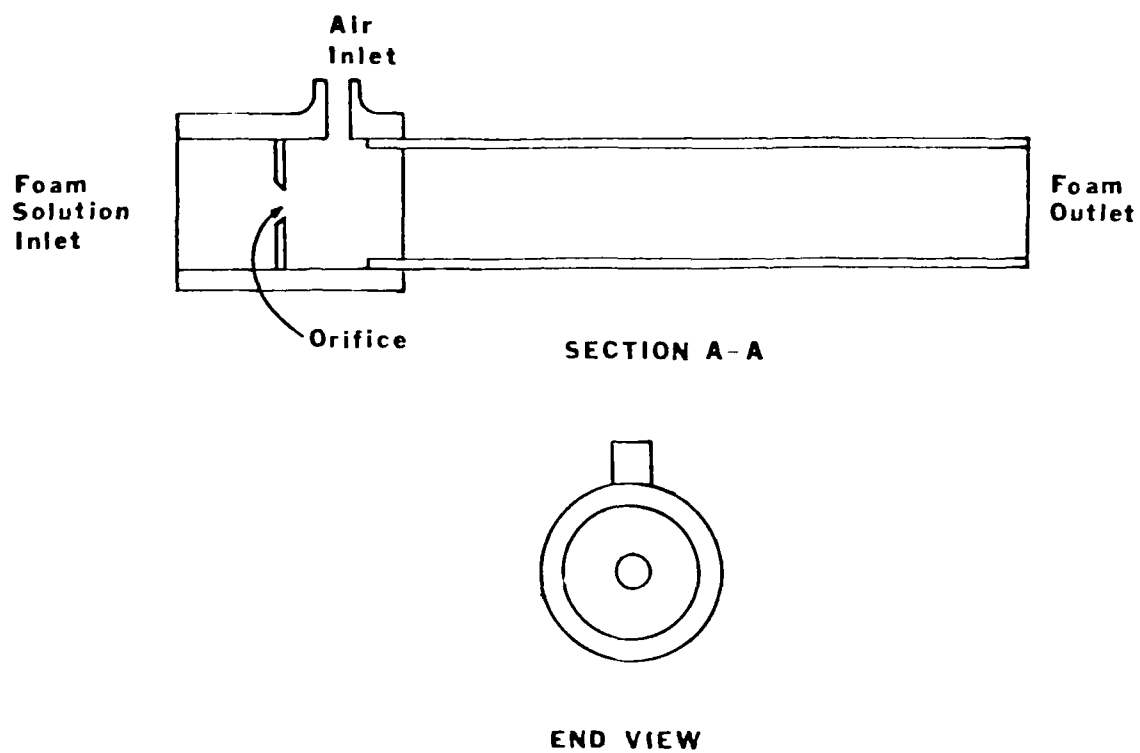


FIGURE 4. DESIGN OF TANK SIDE LOW EXPANSION
FOAM NOZZLES.

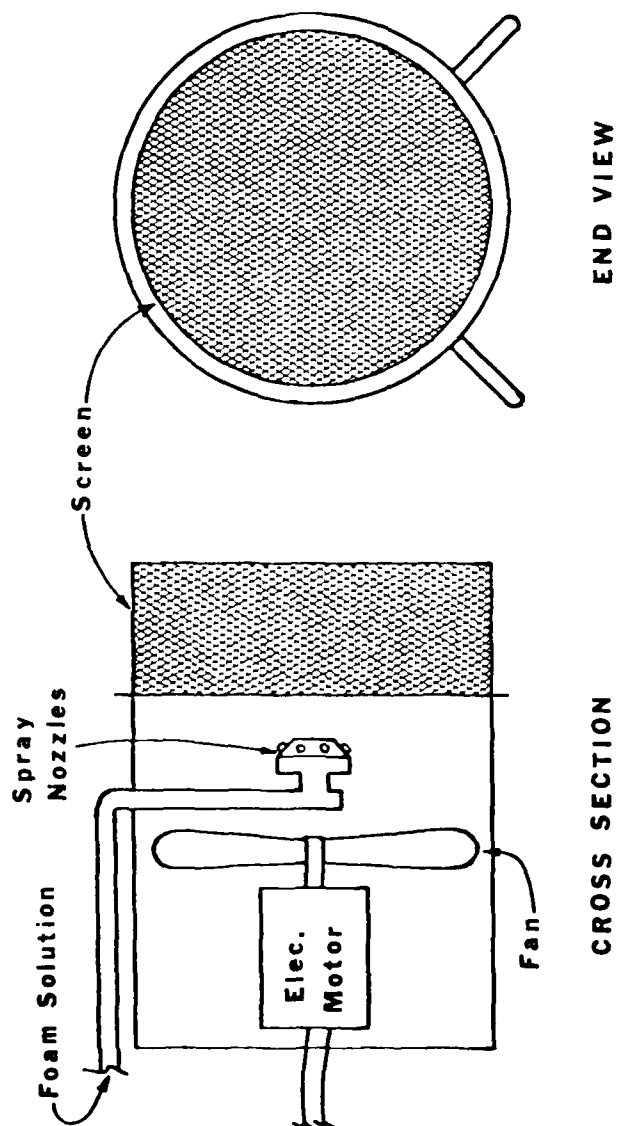


FIGURE 5. DESIGN OF HIGH EXPANSION FOAM GENERATOR.

combination of flexible hoses and steel pipes. A schematic diagram of a dry chemical system is shown in Figure 6.

The nozzle design used in the carbon disulfide tests incorporates a narrow slit through which the powder is dispersed into a flat, fan-shaped spray approximating a 180 degree segment of a circle. The powder enters the nozzle and turns 90 degrees, being discharged perpendicular to the nozzle axis. Figure 7 illustrates this type of nozzle.

Instrumentation and Control

Obtaining the necessary test data and providing adequate control of certain variable test parameters requires a flexible instrumentation and control system with a wide range of test and control instruments. In order to provide this flexibility and still provide adequate protection for the instruments, the system is designed so that all control and recording functions take place in the instrument room. Only sensing devices are located out-of-doors.

Wiring

Instrument wiring runs from individual sensors to a weatherproof junction box located near the test pits. A multiple wire underground cable connects the junction box to control and recording instruments located in the instrument room.

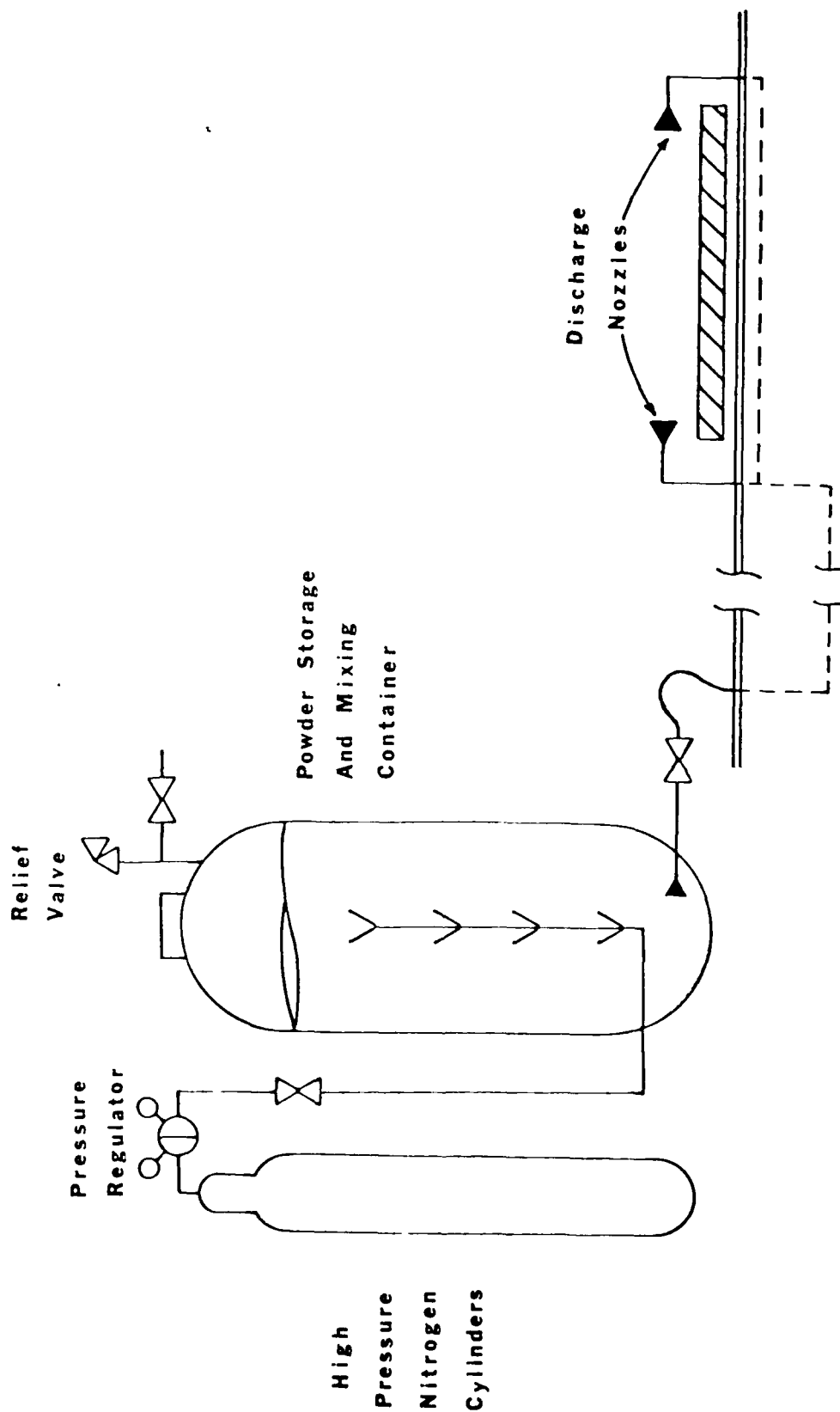


FIGURE 6. SCHEMATIC OF DRY CHEMICAL DELIVERY SYSTEM.

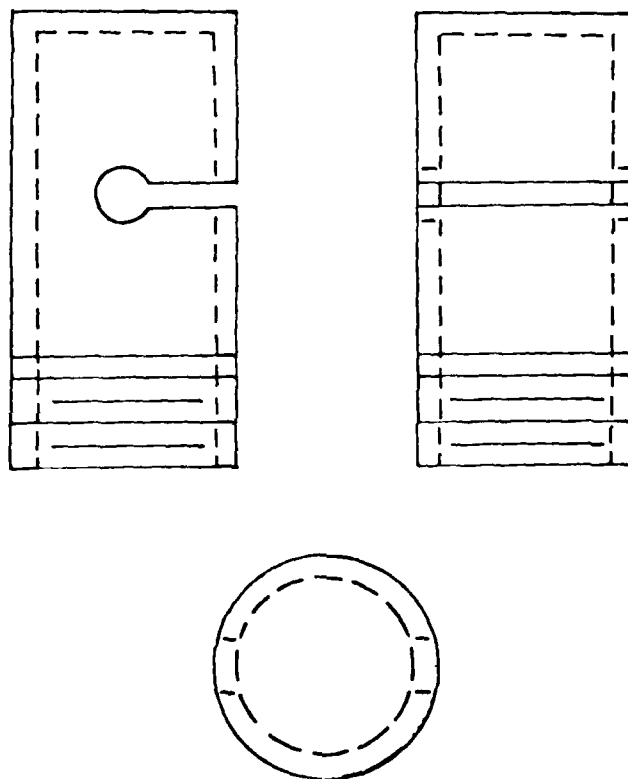


FIGURE 7. DRY CHEMICAL DISCHARGE NOZZLE.

Data Recording

The main data collection device is a digital data-logger capable of handling up to 60 input data sources at a rate of 15 sources per second. Digitized data from the datalogger is recorded on an incremental tape recorder. The tapes that are recorded at the test site can be read, the data converted to engineering units, and printed output obtained on a computer.

Six channels of analog strip chart recording are available via three two-pen strip chart recorders.

For those instruments that require an input voltage, regulated DC voltage can be provided by 0-20 and 0-40 v power supplies.

Wind Speed and Direction

The wind speed and wind direction system consists of a wind vane and anemometer located 10 ft above grade east of the concrete building, and wind speed and wind direction translators located in the instrument room.

Foam System Control

The foam generators are calibrated to give the desired flow rate at a certain foam solution inlet pressure. Therefore, the foam solution flow rate is controlled using an automatic valve to throttle the flow so that the inlet pressure to the foam generator is the same as that used during calibration. In order to provide direct measurement of the foam solution flow rate, orifice meters (calibrated

after installation) are provided. The pressure differential across the orifice is transmitted by a pneumatic differential pressure transmitter to a pneumatic recorder.

Temperature Measurement

Chromel-alumel thermocouples are available to measure the upwind and downwind pit wall temperatures, obstruction temperature, and the fuel temperature. The obstruction thermocouples are "strapped" to the metal parts by metal strips. Pit wall thermocouples are located under the pit wall refractory coating.

Heat Flux Measurement

Two wide angle radiometers (150-degree view angle) and two narrow angle radiometers (7-degree view angle) are available for measuring the radiant heat flux from the fires. The wide angle radiometers are located 5 ft above grade and are generally positioned at 1 and 2 pool diameters from the crosswind edge of the pit. One narrow angle radiometer is located on top of the instrument building. It incorporates a telescopic sight to aid in properly orienting it toward the fire. The second narrow angle radiometer is located two feet above grade and 2 pool diameters from the crosswind edge of the pit.

Liquid Level Measurement

The evaporation rate and burning rate of the fuel in the pit can be measured by monitoring the change in liquid level as a function of time. The system that is used for

sensing a change in liquid depth is based on the principle that the pressure required to blow a gas bubble in a liquid is directly proportional to the depth of liquid (i.e., liquid head pressure) above the bubble forming location.

Dry Chemical Flow Rate and Nozzle Pressure Measurement

The dry chemical flow rate is measured by continuously monitoring the weight loss of the dry chemical unit during discharge. Weighing is accomplished by using a load cell to measure the force required to balance the dry chemical unit which is placed on a lever arm between the load cell and a fulcrum. The skid on which the 2000-lb unit is built serves as the required lever arm. A separate weighing skid, constructed of steel tubing, is used as the lever arm for the 150-and 350-lb units. The pressure at the dry chemical nozzles is measured with a 0-250 psig pressure transducer.

Photographic and Video Equipment

A 16-mm movie camera, a color video camera with recorder, and a 35-mm still camera are available for providing visual recording of the tests.

TYPICAL FIRE EXTINGUISHMENT SETUP AND TEST PROCEDURE

Foam Agents

The experimental equipment and procedure used to perform a fire test with foam agents (either high or low expansion) has been discussed in detail in a previous report (reference 1). The differences between a foam test on a carbon disulfide fire and previous foam tests are as follows:

- 1) Foam delivery was continued until the pit was filled with foam or until the premixed foam solution was used up.
- 2) After each test, the pit contents were pumped out and, if possible, the carbon disulfide recovered.

Fuel Handling

Due to the low auto ignition temperature and toxicity of carbon disulfide, special precautions were taken to minimize the risk of injury during material handling and testing. The carbon disulfide was delivered to the test site in 55-gallon drums. The drums were unloaded, capped with water, and pumped (using a pump with an explosion proof motor) into the fuel storage tank. All personnel dealing with the transfer of liquid from drum to tank were required to wear protective clothing and rubber gloves. Should they be needed, compressed air packs were available for all personnel at the site. During storage, the carbon

disulfide was covered with a water cap and the vapor volume above the water was inerted by maintaining positive nitrogen pressure in the tank at all times. Fuel transfer from the storage tank to the test pit was done from the instrument room by opening and closing an air operated valve located on the fuel tank. After fuel transfer, the transfer lines were purged with nitrogen and then moved to a safe location. During testing, personnel working out-of-doors were required to wear fire protective clothing and remain a safe distance from the test pit.

After each test, the test pit was allowed to cool and the remaining carbon disulfide pumped to a holding tank. In the holding tank the carbon disulfide and water would separate; the carbon disulfide could then be used in another test.

Data Collection

During a foam or dry chemical test, the datalogger was programmed to record 15 channels of data. These 15 channels were assigned to the following variables:

- wind speed
- wind direction
- dry chemical weight
- dry chemical nozzle pressure
- foam nozzle pressure
- 2 wide angle radiometers

- 2 narrow angle radiometers
- fuel temperature
- upwind pit liner temperature
- downwind pit liner temperature
- obstruction temperature
- reference junction temperature
- liquid level

In addition, the time, date, and test number were recorded on the data tapes.

Six channels of strip chart recording were used as a back-up to the datalogger system and also provided a quick visual check on several of the following test variables:

- wind speed
- wind direction
- liquid level
- dry chemical weight
- radiometers
- pit wall thermocouples
- foam nozzle pressure

SUMMARY OF TEST DATA

A total of 87 fire extinguishment tests (57 foam tests, 15 water tests, 12 dry chemical tests, and 3 dual agent tests) were conducted on carbon disulfide fires. The fire fighting agents which were used for the tests included four foams: 1) protein foam, 2) aqueous film forming foam (AFFF), 3) fluoroprotein foam, and 4) high expansion foam; water; and four dry chemicals: 1) sodium bicarbonate (NaHCO_3), 2) potassium bicarbonate (KHCO_3), 3) a powder which is the reaction product of urea and potassium bicarbonate, trade named Monnex, and 4) monoammonium phosphate (commonly known as ABC or Super ABC powder).

Selected data from these tests are listed in Tables 1 through 6. Complete data tables and comments on the individual tests are included in the Appendices. The test data that are reported were obtained as follows:

Burning Rate - The total change in fuel depth during the longest steady state liquid level change before agent application, divided by the time interval.

Application Rate - For the foam and water tests, the application rate is equal to the unexpanded solution flow rate divided by the area of the pit.

- For dry chemical tests, the application rate is determined from the slope of the

TABLE 1. PROTEIN FOAM FIRE TEST DATA

TEST ID	PIT SIZE (SQ FT)	BURN RATE (IN/MN)	APPLICATION RATE (GPM/SQ FT)	CONTROL TIME (SEC)	EXTING TIME (SEC)	WIND SPEED (MPH)	PREBURN TIME (SEC)	OBST. TYPE
1	25	ND	0.101	295	1620	13	256	
2	100	ND	0.367	52	NE	ND	360	
3	100	0.098	0.367	90	1800	ND	600	
4	100	0.111	0.082	322	627	ND	332	CC
5	100	0.115	0.304	152	NE	ND	300*	CC
6	100	0.156	0.086	142	629	9	332	CC
7	100	ND	0.037	500	1830	10	340	CC
8	100	0.107	0.037	NC	NE	11	315	CC
9	100	0.104	0.037	188	NE	10	320	
10	100	0.166	0.085	100	ND	ND	313	
11	400	0.095	0.292	245	NE	9	319	
12	400	0.115	0.105	109	NE	14	312	
13	400	0.126	0.038	419	1950	10	308	
14	400	0.112	0.098	426	1185	15	341	CC
15	100	0.124	0.183	39	1140	11	428	

ND = NO DATA, NC = NOT CONTROLLED, NE = NOT EXTINGUISHED

* = PLANNED PREBURN TIME

TABLE 2. FLUOROPROTEIN FOAM FIRE TEST DATA

TEST ID	PIT SIZE (SQ FT)	BURN RATE (IN/MN)	APPLICATION RATE (GPM/SQ FT)	CONTROL TIME (SEC)	EXTNG TIME (SEC)	WIND SPEED (MPH)	PREBURN TIME (SEC)	OBST. TYPE
1	100	0.149	0.367	147	802	8	299	
2	100	0.153	0.366	172	1006	11	370	CC
3	100	0.122	0.171	155	468	9	327	CC
4	100	0.123	0.100	210	737	11	362	CC
5	100	0.098	0.246	117	447	11	313	CC
6	100	ND	0.041	NC	NE	6	300*	CC
7	100	0.119	0.077	176	NE	9	320	
8	100	0.115	0.029	777	NE	8	300*	
9	400	0.104	0.289	279	465	17	300*	
10	400	0.093	0.094	259	1170	13	315	
11	400	0.118	0.038	191	900	11	330	
12	400	0.109	0.100	188	NE	14	304	
13	400	0.138	0.100	258	NE	9	307	CC
14	100	0.136	0.055	423	NE	8	300*	
15	100	0.092	0.036	NC	NE	7	300*	

ND = NO DATA, NC = NOT CONTROLLED, NE = NOT EXTINGUISHED

* = PLANNED PREBURN TIME

TABLE 3. AFFF FIRE TEST DATA

TEST ID	PIT SIZE (SQ FT)	BURN RATE (IN/MN)	APPLICATION RATE (GPM/SQ FT)	CONTROL TIME (SEC)	EXTNG TIME (SEC)	WIND SPEED (MPH)	PREBURN TIME (SEC)	OBST. TYPE
1	25	0.154	0.333	119	600	5	336	
2	100	ND	0.367	40	NE	10	300*	
3	100	0.087	0.131	118	ND	10	321	
4	100	0.107	0.121	82	ND	13	323	
5	100	0.178	0.366	219	1320	ND	321	CC
6	100	0.138	0.089	121	NF	ND	378	CC
7	100	0.120	0.087	74	NF	6	320	
8	100	0.137	0.037	NC	NE	7	315	
9	400	0.143	0.235	31	NE	11	239	
10	400	0.135	0.093	91	1118	14	308	
11	400	0.127	0.047	157	1170	12	316	
12	400	0.122	0.038	NC	NE	13	306	
13	400	0.141	0.094	114	NE	10	301	CC

ND = NO DATA, NC = NOT CONTROLLED, NE = NOT EXTINGUISHED

* = PLANNED PREBURN TIME

TABLE 4. HIGH EXPANSION FOAM FIRE TEST DATA

TEST ID	PIT SIZE (SQ FT)	BURN RATE (IN/MN)	APPLICATION RATE (GPM/SQ FT)	CONTROL TIME (SEC)	EXTNG TIME (SEC)	WIND SPEED (MPH)	PREBURN TIME (SEC)	OBST. TYPE
1	25	0.058	0.142	37	NE	11	267	
2	25	0.083	0.055	49	NE	16	332	
3	25	0.093	0.060	39	NE	18	326	
4	25	0.073	0.064	40	240	5	372	
5	25	0.122	0.040	34	410	3	357	
6	25	0.076	0.054	50	190	7	317	
7	100	0.138	0.087	28	NE	11	304	
8	100	ND	0.087	23	360	9	68	
9	100	0.148	0.062	23	180	10	305	CC
10	100	0.107	0.090	130	515	11	320+	CC
11	100	0.117	0.062	24	180	10	291	CC
12	100	0.179	0.043	36	NE	7	314	
13	100	0.090	0.054	60	450	10	304	
14	400	0.095	0.035	76	NE	13	306	
15	400	0.119	0.036	50	1080	14	305	
16	400	0.111	0.036	80	NE	13	302	
17	100	0.136	0.294	21	60	11	925	

ND = NO DATA, NC = NOT CONTROLLED, NE = NOT EXTINGUISHED

* = PLANNED PREBURN TIME, + = APPLIED AS LOW EXPANSION FOAM

TABLE 5. WATER FIRE TEST DATA

TEST ID	PIT SIZE (SQ FT)	BURN RATE (IN/MN)	APPLICATION RATE (GPM/SQ FT)	CONTROL TIME (SEC)	EXTNG TIME (SEC)	WIND SPEED (MPH)	PREBURN TIME (SEC)	OBST. TYPE
1	25	0.094	0.129	NC	NE	15	591	
2	25	0.094	0.102	NC	NE	4	549	
3	25	ND	0.687	82	168	4	300*	
4	25	0.097	0.463	118	277	4	592	
5	100	0.150	0.360	198	315	8	279	
6	100	0.112	0.138	NC	NE	9	390	
7	100	0.130	0.275	212	285	7	326	
8	100	0.150	0.103	1195	NE	4	303	
9	100	0.121	0.095	NC	NE	8	431	
10	100	0.087	0.374	205	360	9	335	CC
11	100	0.111	0.176	1340	1650	9	346	CC
12	400	0.105	0.316	NC	NE	6	386	
13	400	0.134	0.286	493	900	5	308	
14	400	0.121	0.300	NC	NE	10	330	CC
15	100	0.129	0.551	NC	NE	7	320+	

ND = NO DATA, NC = NOT CONTROLLED, NE = NOT EXTINGUISHED

* = PLANNED PREBURN TIME, + FOG TYPE NOZZLE

TABLE 6. DRY CHEMICAL FIRE TEST DATA

TEST ID	PIT SIZE (SQ FT)	BURN RATE (IN/MN)	APPLICATION RATE (LB/SEC-SQ FT)	AGENT TYPE	EXTNG TIME (SEC)	WIND SPEED (MPH)	PREBURN TIME (SEC)
1	25	ND	0.303	MAP	8.0	10	40
2	25	ND	0.318	NaH	22.0*	7	36
3	25	0.099	0.234	KH	NE	8	34
4	25	0.089	0.215	UKH	NE	10	53
5	25	0.084	0.412	MAP	5.6	8	127
6	25	0.109	0.208	NaH	NE	15	306
7	25	0.095	0.260	NaH	27.5*	12	314
8	25	ND	0.266	MAP	NE	13	324
9	25	ND	0.270	NaH	NE	7	355
10	25	ND	0.078	MAP	NE	9	735
11	100	ND	0.061	NaH	NE	9	70
12	100	ND	0.053	MAP	NE	12	66

ND = NO DATA, NE = NOT EXTINGUISHED

MAP = MONOAMMONIUM PHOSPHATE, NaH = SODIUM BICARBONATE

KH = POTASSIUM BICARBONATE, UKH = UREA-POTASSIUM BICARBONATE

* = REIGNITION

straight-line portion of the dry chemical unit weight vs. time curve which is recorded on a strip chart recorder.

Control Time - The fire control time is defined as the length of time required to reduce the radiant flux to 5 percent of its initial value. The fire control time was the average of the fire control times for all properly operating radiometers used during a specific test.

Extinguishment Time - The time given is the average of the times recorded by at least two observers using stop-watches. Extinguishment time was the time at which the fire was completely out, with no detectable flame of any size remaining.

Wind Speed - The wind speed listed for each test is the average wind speed for the entire test; instantaneous wind speeds sometimes varied by as much as 50 percent from the average.

Preburn Time - The time interval between ignition and the beginning of agent application.

DATA ANALYSIS

Carbon Disulfide Burning Rates

As Tables 1 to 6 show, burning rates (in inches of carbon disulfide per minute) were obtained for a majority of the tests. The burning rate for carbon disulfide (see Appendix E for composition) is almost completely dependent on the radiant and convective energy transmitted from the fire to the carbon disulfide pool since the evaporation rate for carbon disulfide was determined to be only about 0.0050 in/min. The burning rate is therefore influenced by the wind speed: as wind speed increases, the flame from the burning pool is tilted farther from the vertical position (as shown in Figure 8) and, consequently, less radiant energy is fed back into the pool. In order to determine the burning rate under calm conditions, burning rates for each pit size were plotted against wind speed and extrapolated to calm conditions. Figure 9 is a typical example showing the 10 by 10 ft pool burning rates versus wind speed. The "calm wind" burning rate for the 25-ft² pit is 0.12 in/min. The 100-ft² and 400-ft² pits have a "calm wind" burning rate of 0.16 in/min.

The burning rate of a liquid pool fire generally increases with an increase in pool size until the fire is large enough to be "optically thick". Further increases in

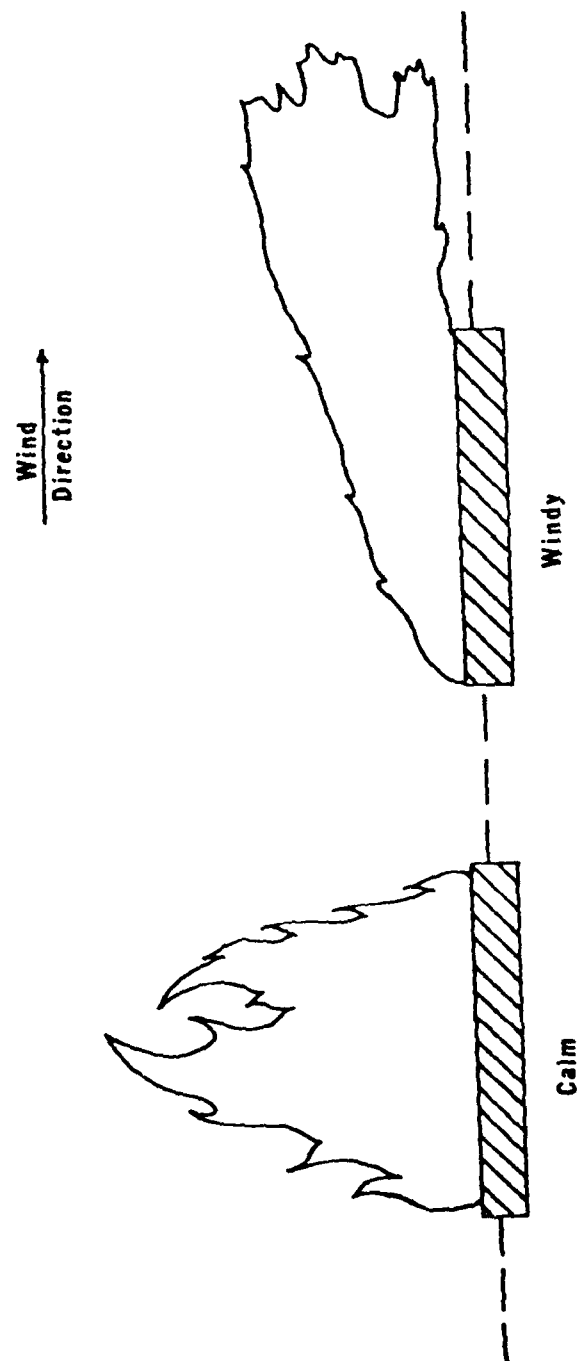


FIGURE 8. EFFECT OF WIND ON FLAME PATTERN.

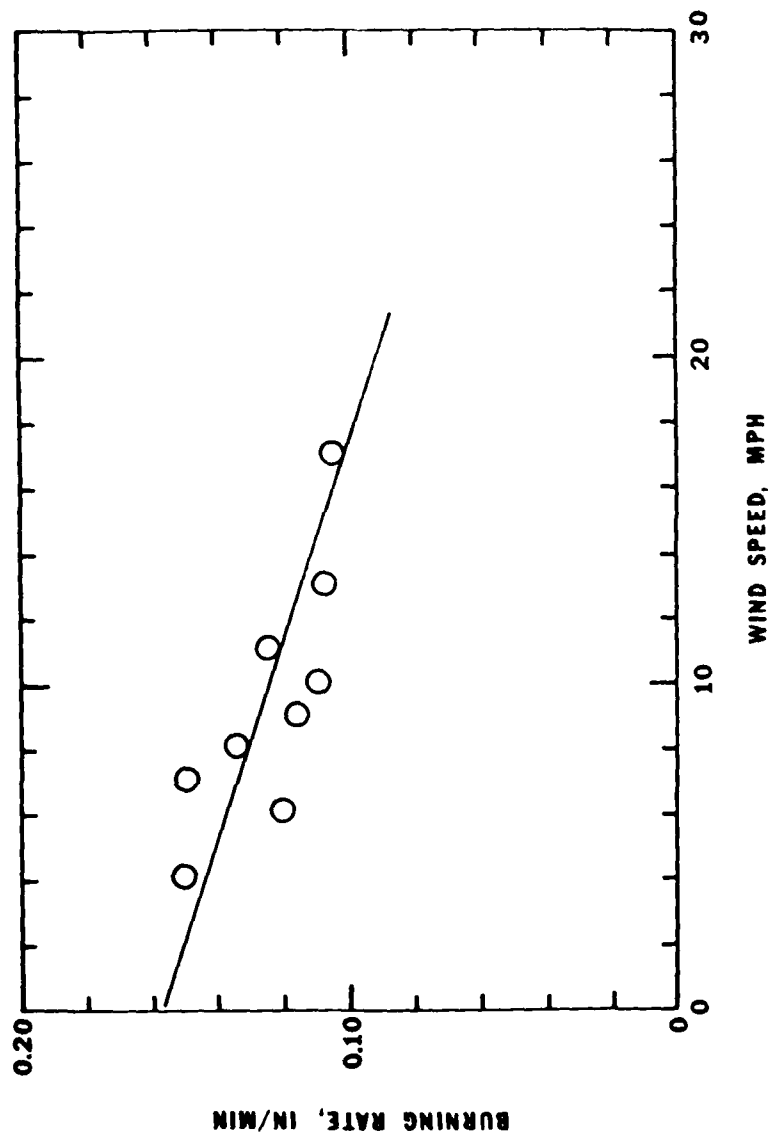


FIGURE 9. VARIATION OF BURNING RATE WITH WIND SPEED FOR 10 X 10 FT. PITS.
(BURNING RATE DATA AVERAGED AT EACH WIND SPEED.)

pool size do not increase the burning rate since the rate of energy feed-back from the flame to the pool is already at its maximum. The minimum pool size at which the burning rate reaches its maximum is influenced by the optical character of the flame. For carbon disulfide fires, the maximum burning rate is reached at a fairly small pool size ($\sim 100 \text{ ft}^2$).

High and Low Expansion Foams

The data from the foam tests were correlated using the equation:

$$t - t_m = K / (A_r - A_m)^a \quad \text{Eq. 1}$$

where: t = control or extinguishment time, sec
 t_m = minimum control or extinguishment time, sec
 A_m = agent application rate, gpm/ft^2
 A_r = minimum application rate for fire control,
 gpm/ft^2
 a, K = constants

This equation was developed to accomodate the following assumptions:

- a) Higher application rates result in shorter control and extinguishment times.
- b) Minimum control and extinguishment time exist.
- c) A minimum application rate exists. Below this rate, the fire evaporates the foam as fast as it is applied, thus the fire is never controlled or extinguished.

In order to determine the minimum application rate, it was necessary to determine the heat available for evaporating the foam. This was done by using Equation 2 to compute the heat flux required to cause the observed burning rate.

$$q = B_r (\rho_w) (\Delta H_v) \quad \text{Eq. 2}$$

where: q = radiant and convective heat flux, Btu/hr-ft²

B_r = burning rate, ft/hr

ρ_w = density of burning liquid, lb/ft³

ΔH_v = latent heat of vaporization of liquid, Btu/lb

Using a burning rate of 0.16 in/min (0.80 ft/hr), the value of q is calculated to be about 9,500 Btu/hr-ft². The minimum application rate is then calculated from

$$A_m = q / (60 \rho_l \Delta H_w) \quad \text{Eq. 3}$$

where ρ_l is the density of water (lb/gal), ΔH_w is the heat of vaporization of water (Btu/lb), and q is the effective heat absorption rate calculated from the burning rate of carbon disulfide. A_m is computed to be 0.020 gpm/ft². This value cannot be easily confirmed experimentally, and is based on the burning rates for larger pits. The data for the three low expansion foam agents and water show no fires controlled at rates lower than 0.036 gpm/ft².

Tests for which portions of the data were missing or tests in which fires were not controlled or extinguished were not included in the analysis. The concentric circle obstruction required foam to flow through the 90-degree opening in the outer ring and then reverse direction to flow through the 90-degree opening in the inner ring, all with only a portion of the total foam flow. The foam depth had to increase more than usual to provide the flow reversal so control for tests using the concentric circle obstruction were expected to require longer application times. However, test data indicated that the obstruction had little, if any, effect on control or extinguishment times.

The lack of a substantial difference in control time for obstructed and unobstructed tests may be caused partly by the degradation of the foam near its leading edge. Foam movement was therefore slowed, and penetration required movement of fresh foam underneath the degraded foam zone at the leading edge of the layer. Movement of the layer around the concentric circles was therefore about as fast as movement across the pool. Because the effect of the obstructions was minor, the data for obstructed tests was included with the data for unobstructed tests in determining the constants for Equation 1.

Within the accuracy of the data, logarithmic plots of control or extinguishment times versus $1/(A_r - 0.020)$ were linear and a straight line fit was used to determine the remaining constants. Table 7 (in "DISCUSSION OF RESULTS") summarizes these constants.

Dry Chemicals

Data from previous fire tests were correlated using an equation of the form:

$$t_e - t_m = K / ((A_r - CB_r) / B_r)^a \quad \text{Eq. 4}$$

where: t_e = extinguishment time, sec
 t_m = minimum extinguishment time, sec
 A_r = dry chemical application rate, lb/sec-ft²
 B_r = burning rate, in/min
 a, K, C = constants

This equation was developed to accommodate the following assumptions:

- a) For a given burning rate, higher application rates result in faster extinguishment.
- b) The application rate required to extinguish the fire in a given time is proportional to the burning rate.
- c) A minimum extinguishment time exists.
- d) A minimum application rate (given as CB_r) exists. Below this rate, the fire is never extinguished regardless of the application time.
- e) The minimum application rate is proportional to the burning rate.

No attempt was made to correlate the data from the dry chemical tests since only a few of the tests resulted in fire extinguishment. The available data is compared later in the report to the results of tests on hexane fires.

DISCUSSION OF RESULTS

Low Expansion Foams

The results presented in the previous sections support the following conclusions concerning the low expansion foam tests. Of the three low expansion foams tested and the one test with high expansion foam applied through a low expansion nozzle, AFFF produced the fastest fire control for a given application rate. It was followed in effectiveness by protein and fluoroprotein foam. Within the accuracy of the data, all three low expansion foams were equally effective in extinguishing carbon disulfide fires.

Fire control time proved to be a better parameter for agent comparison than did fire extinguishment time. There was one primary reason for this: fire control results were much more repeatable than extinguishment results. If a given foam application rate provided fire control in one test, it would usually control a fire (at the same application rate) in another test. This statement could not be made for extinguishment times. A fire would be extinguished using a given foam at a given application rate during one test, but during another test, the same agent at the same application rate would not always extinguish the fire. The cause of the poor extinguishment results can be attributed to the influence of the pit wall. Any changing of the

foam's ability to seal at the wall surface, i.e., wall deterioration, would change the extinguishment time. Control times, which were not subject to these wall effects, would therefore be more repeatable and the data less scattered. The standard deviations " " between the test data and the correlation curves for the four foams (see Table 2) show that control times exhibited significantly less scatter than extinguishment times.

The effectiveness of a low expansion foam in controlling a carbon disulfide fire appeared to be directly related to the foam's fluidity (ability to flow across the carbon disulfide surface). All three low expansion foams appeared to be equally fluid as they exited the foam nozzle. However, the leading edge of the protein and fluoroprotein foams stiffened considerably when exposed to the fire. The "edge stiffening" effect slowed the movement of the foam across the liquid surface and resulted in longer control times. The high expansion foam, when applied through a low expansion nozzle, did not exhibit appreciable edge stiffening and controlled the fire in about the same time (at equal application rates) as the AFFF.

The ability of a low expansion foam to control a carbon disulfide fire (within the limitations of the present test series) appears to depend upon two factors: 1) foam application rate (gpm/ft^2) and 2) foam fluidity. Both of these factors directly affect the speed of surface coverage.

TABLE 7. SUMMARY OF CORRELATION CONSTANTS
DEVELOPED FROM FOAM FIRE CONTROL
AND EXTINGUISHMENT TEST DATA.

TYPE OF FOAM	FIRE CONTROL			FIRE EXTINGUISHMENT		
	tm (sec)	K	(*) (sec)	tm (sec)	K	(+) (sec)
PROTEIN	122.5	4.55	122	520.0 ^a	23.1 ^a	226 ^a
AFFF	13.8	6.60	24			
FLUOROPROTEIN	124.4	5.92	32			
HIGH EXPANSION	23.8	0.53	12	150.0	4.9	95
WATER	52.3	49.7	100**	57.2	73.6	192 ⁺⁺

* Standard deviation for fire control time.

+ Standard deviation for fire extinguishment time.

** with $A_p = 0.06$, ⁺⁺ with $A_p = 0.13$

^a Data from protein, AFFF, and fluoroprotein foams are combined to estimate extinguishment because of limited extinguishment data. See text and data tables.

At equal application rates, the more fluid foams will tend to spread and cover the fire more quickly. Likewise, higher application rates will tend to distribute the foam over the surface faster. Whether or not foam depth has a significant effect on control time (i.e., whether or not extremely fluid foams will control even faster) has not been investigated in this test program. However, water, which is more fluid than the low expansion foams, was not as effective in controlling the fires. A reason for this result is presented in a following section which discusses the water results.

Figures 10 to 12 show the control times for each low expansion foam. The curve representing the "best fit" of the data, using the constants presented in Table 7, is also shown.

There are insufficient data available for any one low expansion foam to perform a statistical analysis of fire extinguishment data. The combined data for AFFF, protein, and fluoroprotein foams are shown in Figure 13 along with the curve best describing that data. Within the accuracy of the data, the low expansion foams were equally effective in extinguishing carbon disulfide fires. The extinguishment mechanism of low expansion foams may be a strong function of foam to carbon disulfide and foam to solid (heated) surface heat transfer. Due to its low ignition temperature, the carbon disulfide vapor will continue to ignite until all surrounding surfaces have been cooled to near ambient

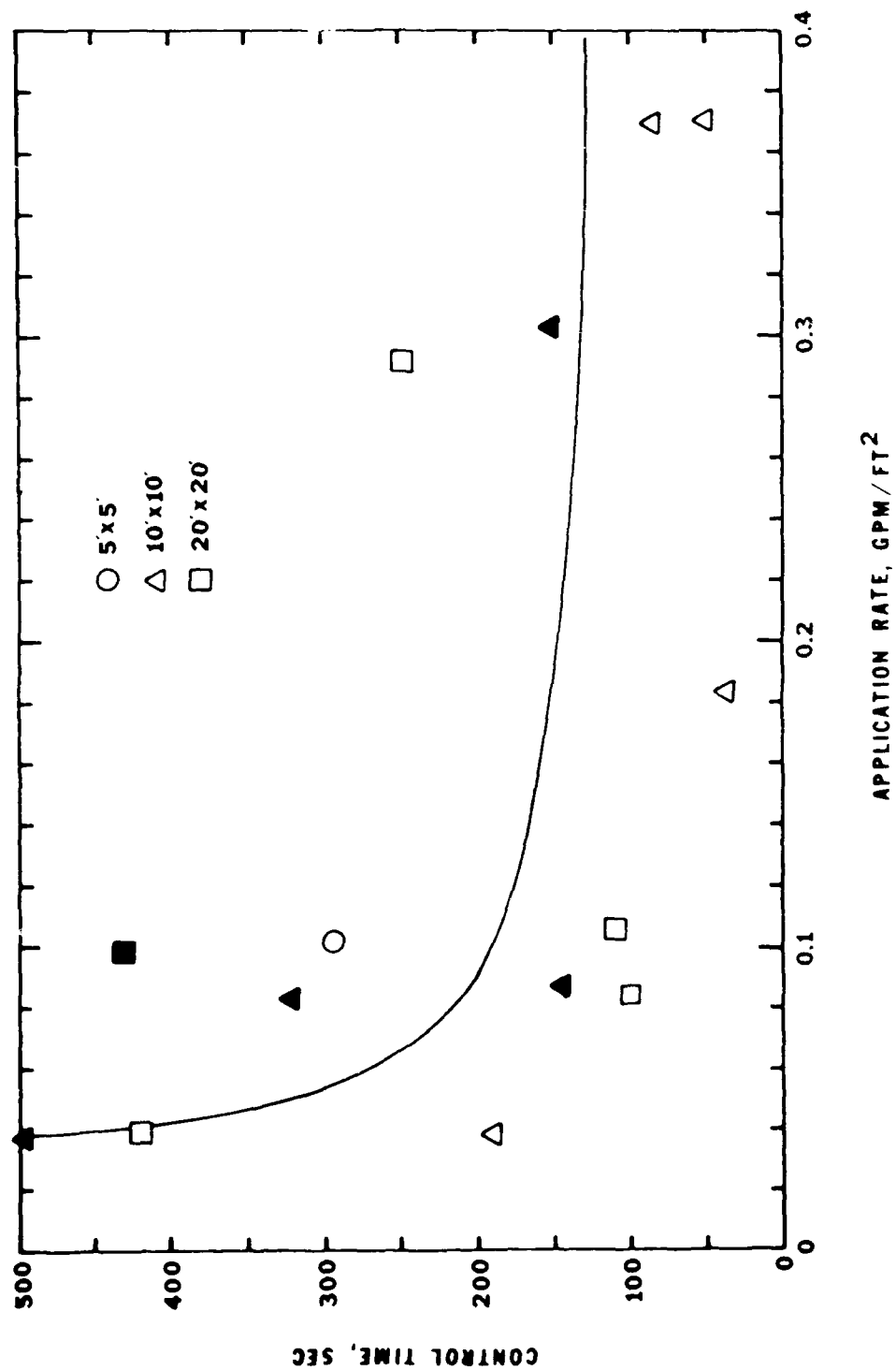


FIGURE 10. PROTEIN FOAM FIRE CONTROL DATA FOR CARBON DISULFIDE FIRES. SHADED POINTS ARE OBSTRUCTED TESTS.

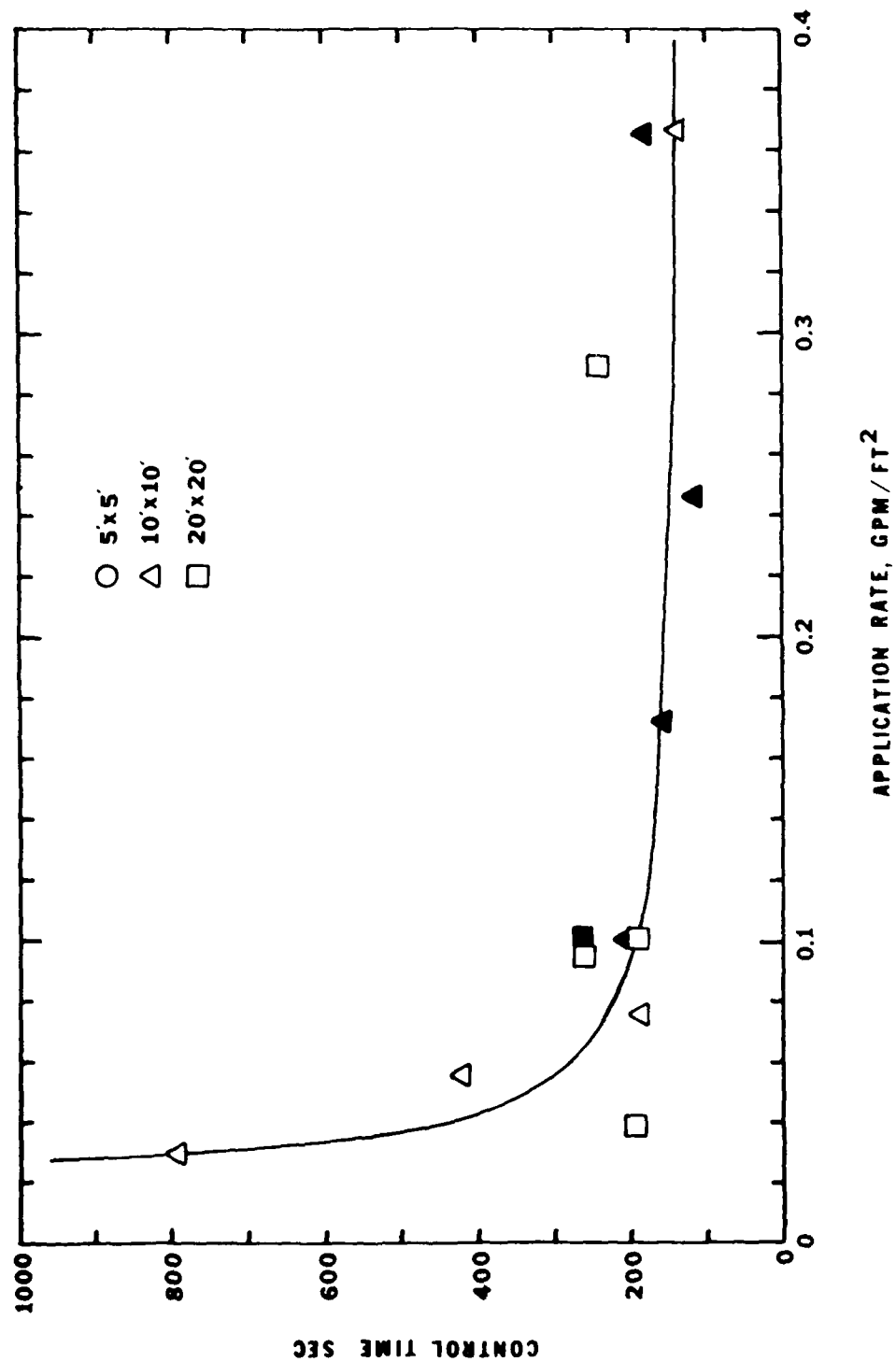


FIGURE 11. FLUOROPROTEIN FOAM FIRE CONTROL DATA FOR CARBON DISULFIDE FIRES. SHADED POINTS ARE OBSTRUCTED TESTS.

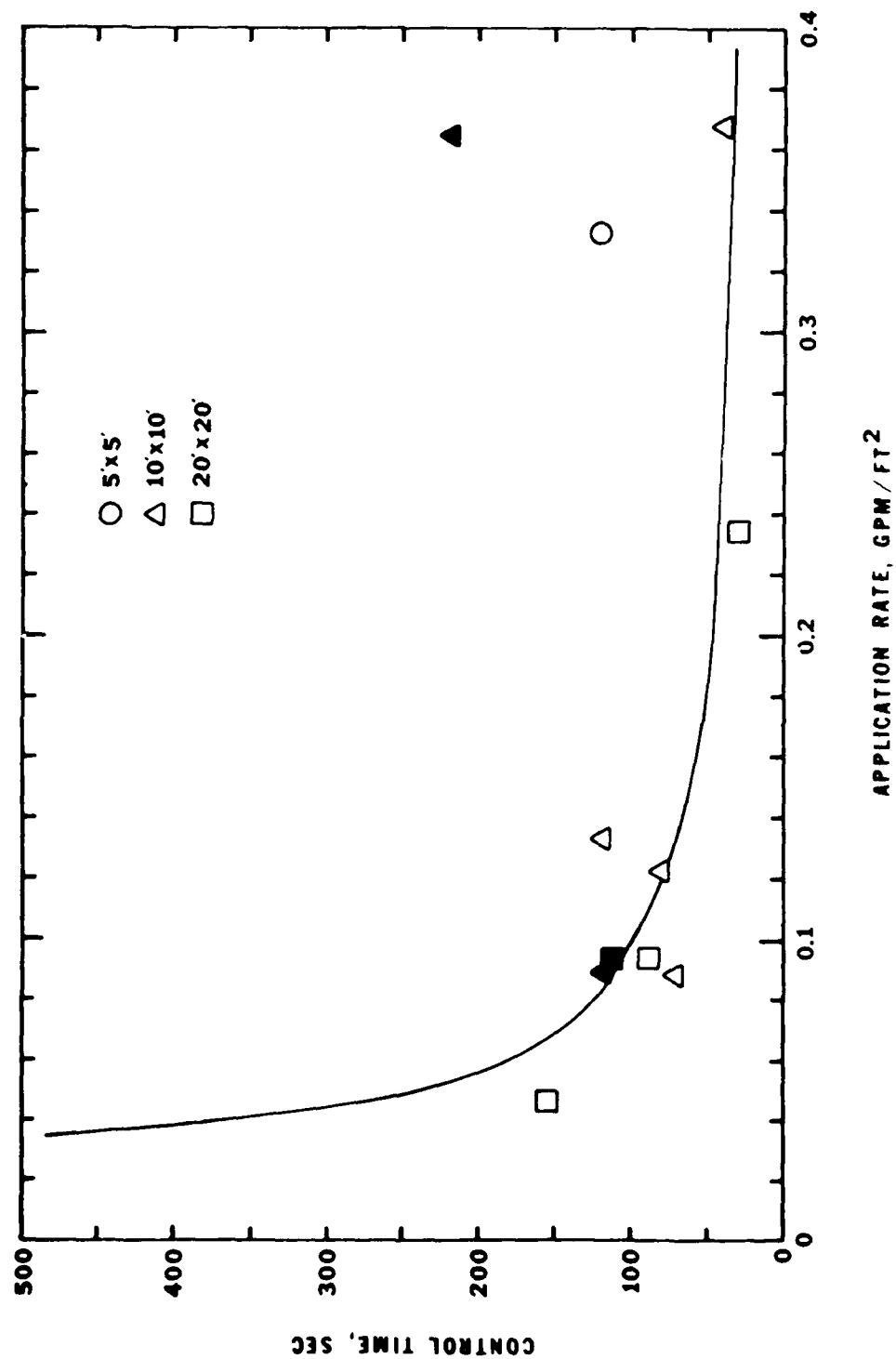


FIGURE 12. AFFE FIRE CONTROL DATA FOR CARBON DISULFIDE FIRES.
SHADED POINTS ARE OBSTRUCTED TESTS.

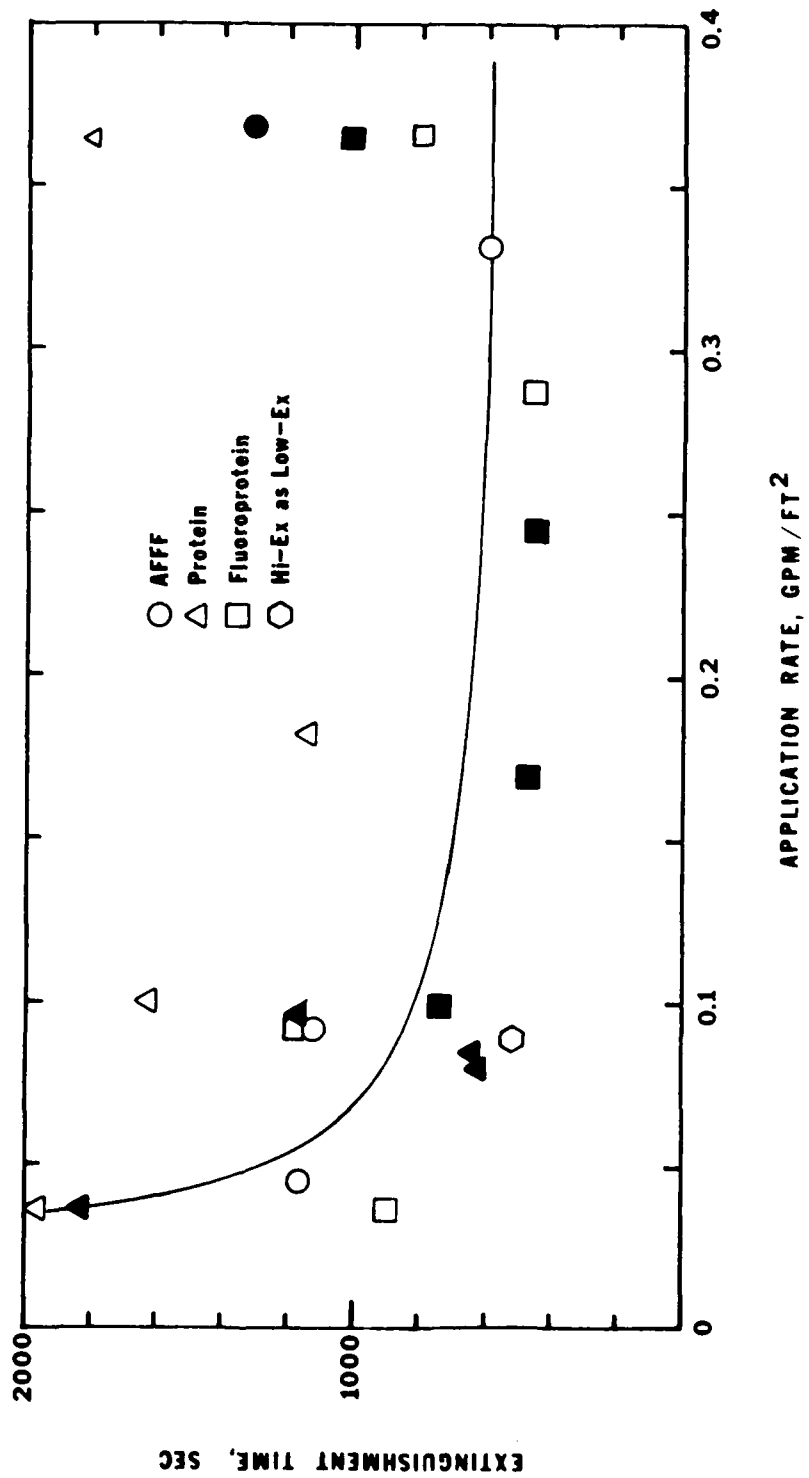


FIGURE 13. EXTINGUISHMENT DATA FOR LOW EXPANSION FOAMS.
SHADED POINTS ARE OBSTRUCTED TESTS.

temperatures. Likewise, the entire carbon disulfide pool, heated to its boiling point by back radiation from the fire (unlike hexane which heats up only in the top 0.5-inch of the fuel layer, see the section "OTHER OBSERVATIONS"), must be cooled before vapor production decreases to a level where extinguishment can occur. The fire extinguishment ability of a low expansion foam is a function of at least two foam properties: 1) foam fluidity and 2) foam to solid and liquid heat transfer rate. The foam fluidity determines how fast a foam can cover the burning liquid surface and block radiation from reaching the pool. The foam's heat transfer (cooling) ability determines how fast the foam will cool the surrounding surfaces to a temperature below the auto ignition point and how fast the liquid pool itself will be cooled. It should be noted that the edge sealing ability of a foam will influence its apparent heat transfer ability, for if a foam has difficulty making contact with the pit wall surfaces, it cannot cool the surfaces effectively.

Within the accuracy of the experimental results, the concentric circle obstructions had little, if any, effect on the fire control or extinguishment times. Due to its fluidity, the AFFF control times should have been the least affected by the obstruction. Likewise, the "edge stiffening" exhibited by the protein and fluoroprotein foams would be expected to hamper the foam's penetration into the obstruction, resulting in longer control and extinguishment times.

This did not prove to be the case, as control and extinguishment times did not show a significant increase for fires with obstructions when protein or fluoroprotein foams were used. Observations made during the obstructed protein and fluoroprotein fire tests indicated that although the foam's leading edge would not easily flow into the obstruction, fresh foam from beneath the edge would flow into the opening and control the fire.

The low expansion foams showed no scaling effects. At the same application rate (in gpm/ft²) both the large and small fires were controlled or extinguished in the same time (within the accuracy of the experimental data). Wind speed did not appear to have any influence on the fire fighting ability of the low expansion foams (other than on the location of the last appearance of flame); neither did the burning rate of the carbon disulfide pools.

High Expansion Foam

High expansion foam was the most effective of the foam agents tested on the carbon disulfide fires, i.e., at a given application rate (gpm/ft²), high expansion foam showed the fastest control and extinguishment times of all the foams tested. As found with the low expansion foams, the concentric circle obstruction had little effect on either control times or extinguishment times. Two types of high expansion foam were used in the tests. MSA type "DG" foam was used for the first two tests and MSA type "EL" thereafter. Both were equally effective in their action on

carbon disulfide fires.

High expansion foam, due to its approximately 500:1 expansion ratio, forms a deep and relatively quick-covering foam blanket. Obstructions that do not extend for large distances above the fuel level are simply engulfed in the flowing foam. Since the high expansion foam is not deflected into the pit (it is blown directly in from the upwind side of the pit), the foam has an initial velocity which aids in quickly covering the fire area. The fuel vapors do not penetrate through the thick layer of high expansion foam as readily as through the low expansion foams because of the greater foam depth and lower foam temperature. These reasons are felt to be most responsible for the excellent performance of the high expansion foam.

Control and extinguishment data for the high expansion foam tests are presented in Figures 14 and 15. Although the extinguishment data are sparse, a "best fit" line was determined. It is shown in Figure 15; included for comparison is the extinguishment curve for the low expansion foams.

Although high expansion foam was the most effective of the foams agents tested, it is not without problems. Due to its high expansion ratio, it is difficult to apply against the wind. Also, high expansion foam does not flow readily over large distances and may require the use of ducts to guarantee coverage of large fires.

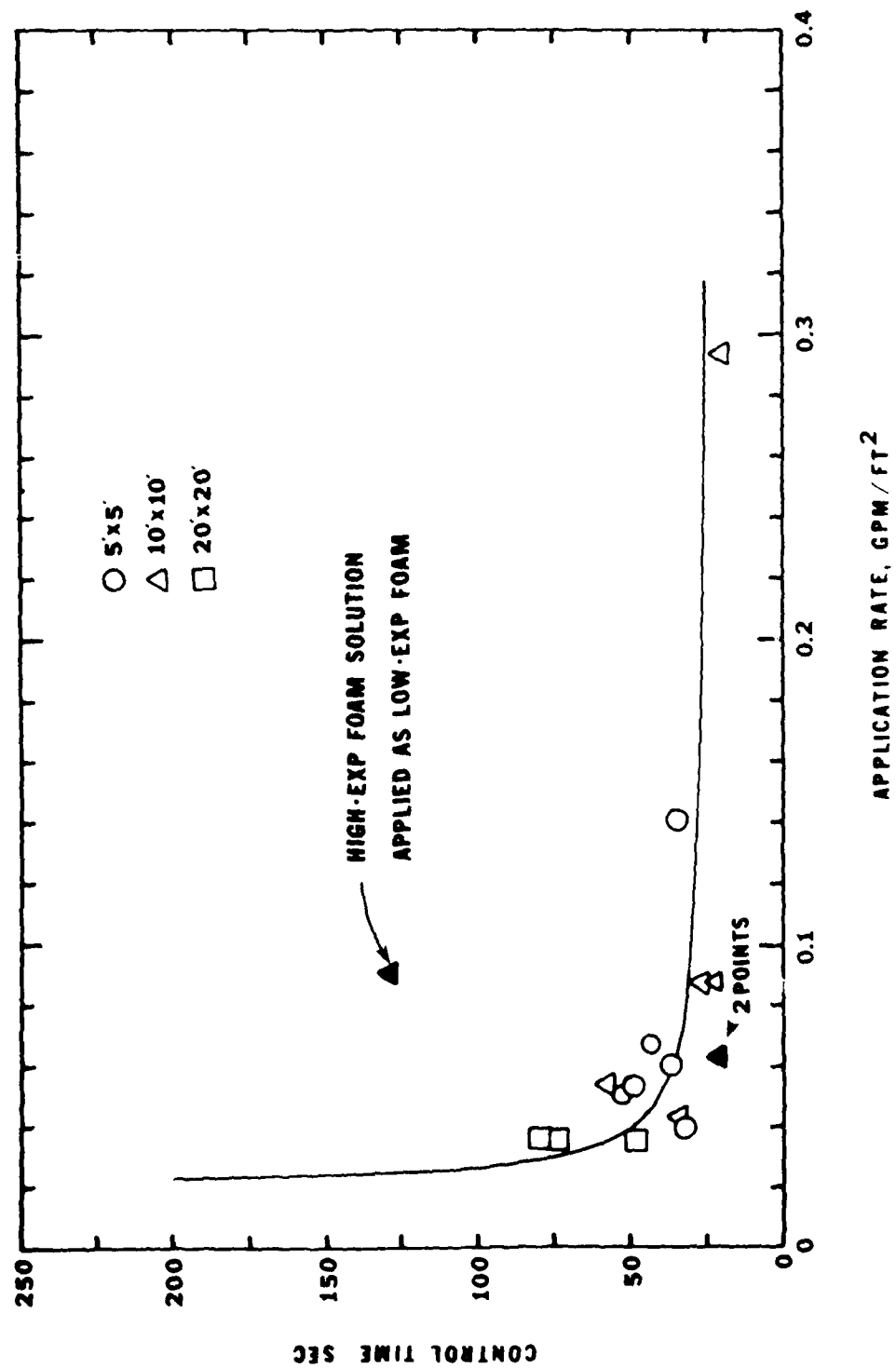


FIGURE 14. HIGH EXPANSION FOAM FIRE CONTROL, DATA FOR CARBON DISULFIDE FIRES. SHADED POINTS ARE OBSTRUCTED TESTS.

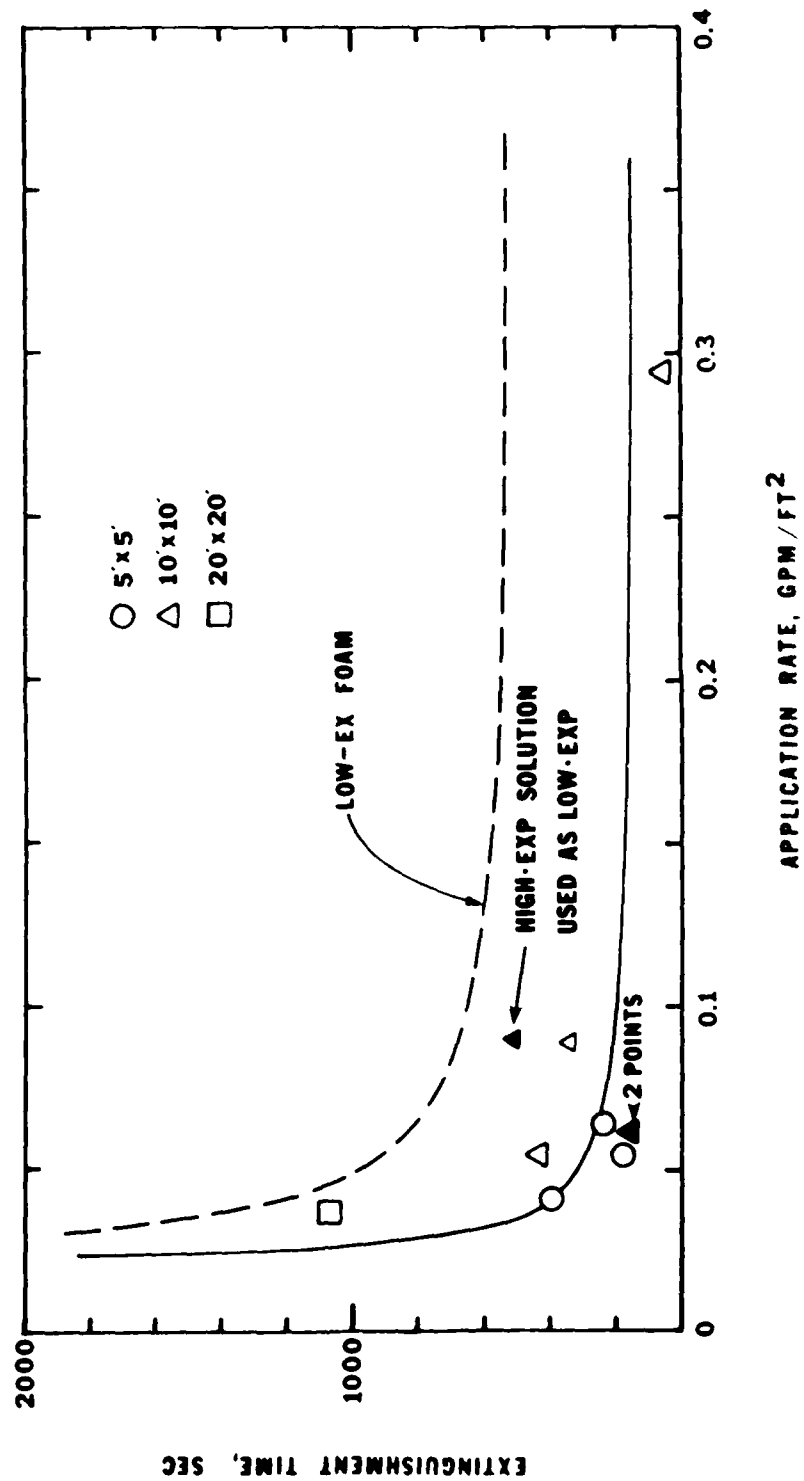


FIGURE 15. HIGH EXPANSION FOAM EXTINGUISHMENT DATA.
SHADED POINTS ARE OBSTRUCTED TESTS.

Water

At all application rates, water was less effective than the foams in controlling the carbon disulfide fires. At application rates below 0.3 gpm/ft^2 , water was a less effective fire extinguishment agent than the low expansion foams. However, at application rates above 0.3 gpm/ft^2 , water was more effective than the low expansion foams in extinguishing carbon disulfide fires.

Figure 16 shows the fire control data for water along with the "best fit" curve for the data. Figure 17 compares the "best fit" curves for water and the high and low expansion foams used in the test program. As Figure 17 shows, when water was applied through a low expansion foam nozzle, it was considerably less effective in controlling carbon disulfide fires than any of the foams. The minimum application rate at which water would control a carbon disulfide fire was greater than 0.095 gpm/ft^2 . This was a considerably higher rate than the $0.02\text{--}0.025 \text{ gpm/ft}^2$ that appeared to be the minimum for the foams. Apparently, water allows some of the carbon disulfide fire radiation to pass through it and heat the liquid pool. The liquid boil off remains high and the fire control time is increased. Foam, on the other hand, is opaque to the fire radiation; when the pool is covered with foam, the radiant energy reaching the fuel is greatly diminished and the boil off rate, i.e. the burning rate, is substantially lowered.

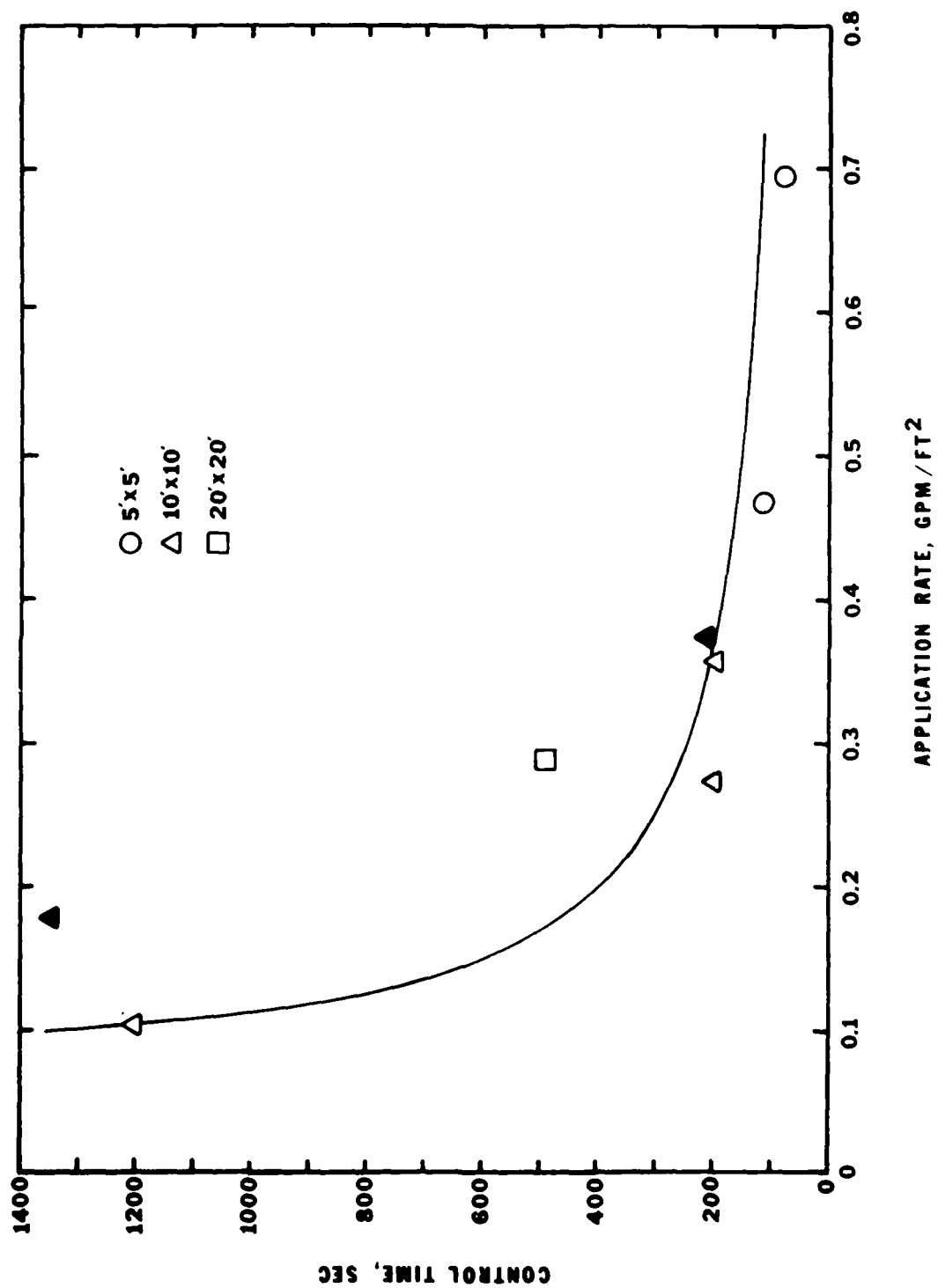


FIGURE 16. WATER FIRE CONTROL DATA FOR CARBON DISULFIDE FIRES.
SHADED POINTS ARE OBSTRUCTED TESTS.

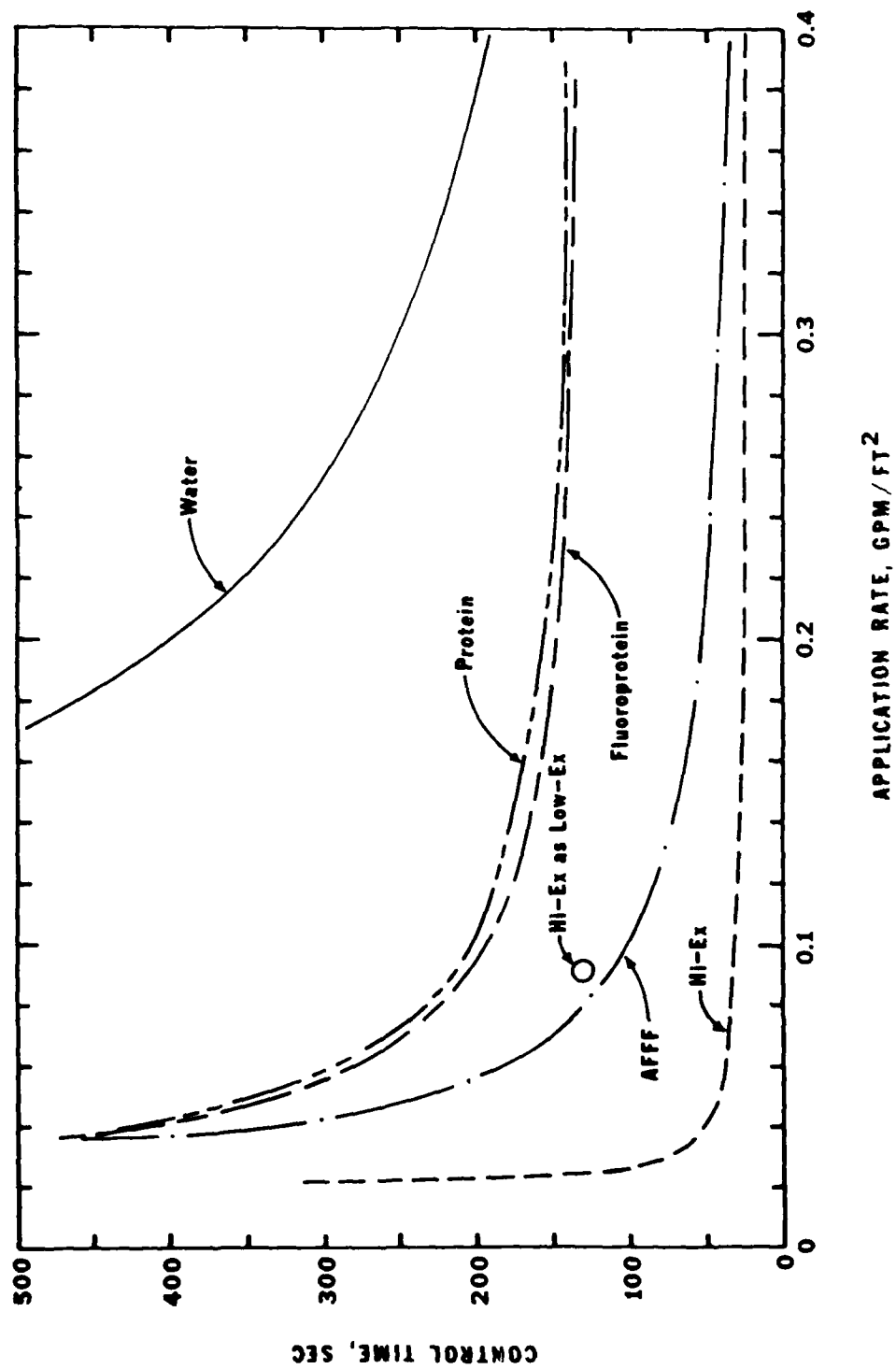


FIGURE 17. COMPARISON OF FIRE CONTROL TIMES FOR FOAM AND WATER AGENTS ON CARBON DISULFIDE FIRES.

As an extinguishing agent at application rates above 0.3 gpm/ft², water proved to be more effective than the low expansion foams. Figure 18 compares the water results to the curve for the low expansion foams. In contrast to the fire control results, the heat transfer (cooling) ability of water was the dominant factor in its fire extinguishing effectiveness. Water, even while allowing radiation to pass through and heat the pool, had a sufficiently greater cooling ability, when compared to the low expansion foams, so that, at high application rates, it was more effective in extinguishing carbon disulfide fires. The results discussed above concerning the comparison between the fire extinguishing ability of water and low expansion foams are subject to some uncertainty since few low expansion foam tests were conducted at application rates above 0.4 gpm/ft².

During one test, water was applied manually with a "fog" type nozzle at a rate which would have been expected to control and extinguish the fire. After 540 seconds, the fire radiation was reduced to about 25 percent of its initial value. Further reductions in radiation did not appear to be forthcoming, so the test was ended.

Obstructions did not significantly increase either the control or extinguishment times for water.

Dry Chemical Agents

Dry chemical agents were not effective in extinguishing carbon disulfide fires. Twelve dry chemical tests

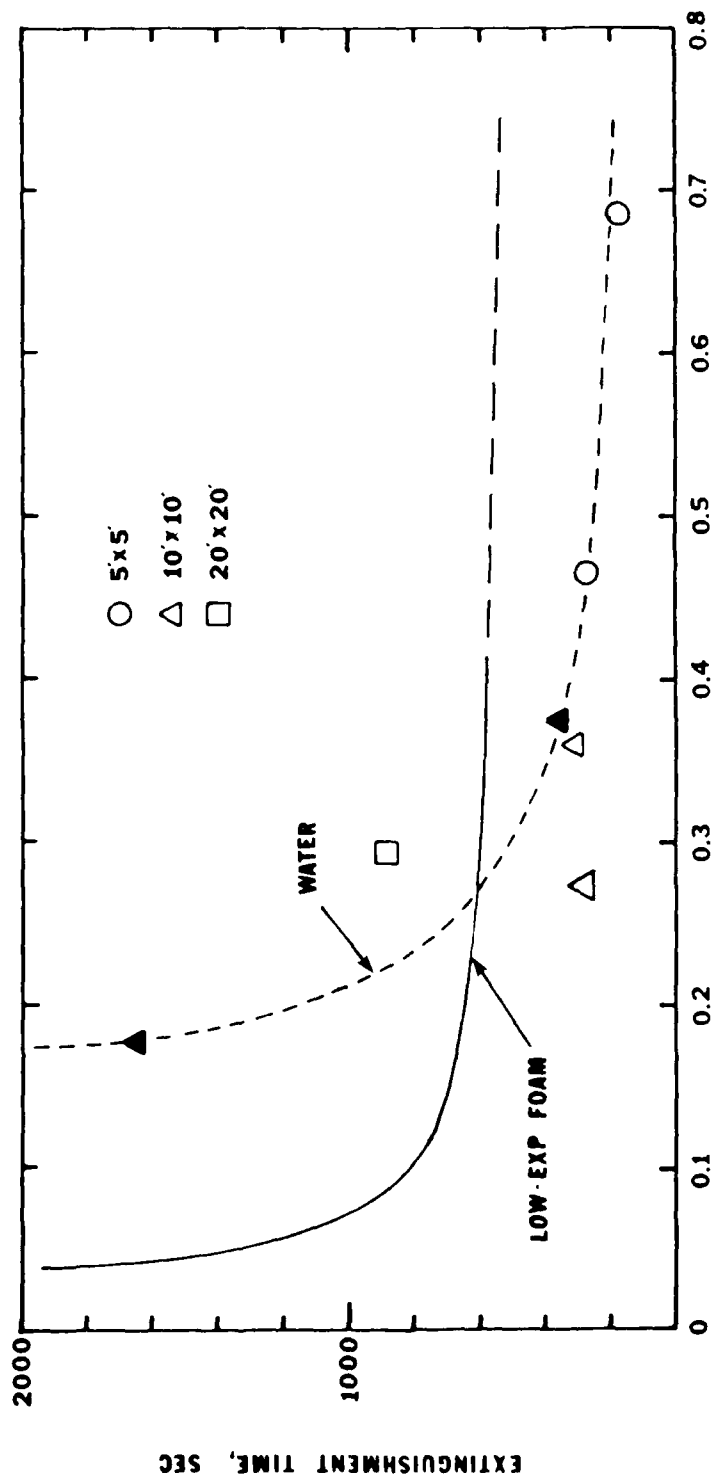


FIGURE 18. COMPARISON OF WATER FIRE EXTINGUISHMENT DATA WITH "BEST FIT" CURVE OF LOW EXPANSION FOAM DATA. SHADED POINTS ARE OBSTRUCTED TESTS.

were run in the 25- and 100-ft² pits using sodium bicarbonate (NaHCO_3), potassium bicarbonate (KHCO_3), urea-potassium bicarbonate, and monoammonium phosphate (ABC). Eleven tests used fixed nozzle placement and were run at application rates above 0.20 lb/sec-ft². One manual test was tried at 0.0775 lb/sec-ft². Even using high application rates, only four of the twelve tests resulted in extinguishment. Sodium bicarbonate extinguished two fires at application rates of 0.260 and 0.318 lb/sec-ft², but the pool reignited after dry chemical flow stopped. The monoammonium phosphate powder extinguished fires at 0.303 and 0.412 lb/sec-ft² application rates. The extinguishments achieved with the monoammonium phosphate powder were accomplished on fires which had short preburn times (40 and 127 seconds). Normal preburn times were 300 or more seconds. With short preburn times, pit wall and surrounding surfaces do not have time to heat up to high temperatures. Thus, the surfaces were more likely to cool below the auto ignition temperature of carbon disulfide before powder application stopped. It is likely that if 300 second or longer preburn times had been used, the monoammonium phosphate tests would not have extinguished the fires without reignition.

The ineffectiveness of the dry chemical agents in extinguishing a carbon disulfide fire is probably due to one or both of the following reasons: 1) low ignition temperature of the carbon disulfide and 2) inability of the dry

chemical powder to break or inhibit the combustion mechanism of the fire. Solid surfaces in the vicinity of the fire were quickly heated to a temperature above the carbon disulfide ignition temperature (194°F). During the short duration of agent application (about 40 seconds), the heated surfaces did not have time to cool below the ignition temperature and continuous reignition occurred. Dry chemical agents are theorized to extinguish fires by breaking the combustion chain or by inhibiting the chemical reactions involved in the burning process. NFPA 17 discusses the extinguishing mechanism of dry chemicals and indicates that one of the most important mechanisms involves the scavenging of H and OH radicals by the dry chemical. The H and OH radicals are necessary to propagate the combustion reaction, so hydrocarbon flames are extinguished readily by dry chemicals. Carbon disulfide oxidation does not involve either H or OH radicals. Rather, radicals such as O, SO, and CS are formed. Apparently, these radicals are not scavenged effectively by dry chemicals. Thus, the dry chemical agents tested, while effective on hydrocarbon fires, would be chemically unable to extinguish a carbon disulfide fire.

The extinguishments which were achieved using dry chemical agents were probably the result of 1) shadowing, i.e., the diminishing of back radiation due to agent opacity, and the subsequent cooling of the surrounding sur-

faces or 2) inerting of the fire area.

Dual Agent Tests

Three dual agent tests were performed using low expansion foam to control the fire followed by an attempt to extinguish the fire using dry chemical agents. The rationale for dual agent application is the following. Foam is used to control the fire, cool the liquid pool (thereby slowing liquid vaporization), and cool the surrounding heated surfaces. After the fire is controlled, dry chemical can be applied with less chance of reignition and extinguishment may be possible at lower application rates. Even after the fire was controlled and burning was occurring only at a few points near the pit walls, the monoammonium phosphate agent could not extinguish the fire.

OTHER OBSERVATIONS

This section presents a discussion of observations made during the carbon disulfide fire tests. The observations are included either because they helped to explain the experimental results or because they might be useful in comparing results between different fuel types.

Several fire tests were run using deep carbon disulfide pools in order to determine the manner in which the carbon disulfide pools were heated by flame radiation. An inspection of the absorption spectra of liquid carbon disulfide, as shown in Figure 19, indicated that much of the fire radiation could pass through the liquid, subsequently heating the walls and bottom of the container. The walls and bottom would then transfer heat to the bulk of the liquid, and the liquid would be heated, more or less uniformly, to its boiling point. In order to test this idea, thermocouples were placed 3, 4.5, 6, 9, and 10.5 inches from the pool bottom of a 33 inch diameter metal container. Fuel depth was initially set at approximately 12 inches. Figure 20 shows the response of each thermocouple with respect to time. It is obvious from Figure 20 that some of the radiation was absorbed by the liquid since the upper layers of the pool heated faster than the lower layers. The important point, however, is that the entire pool was heated

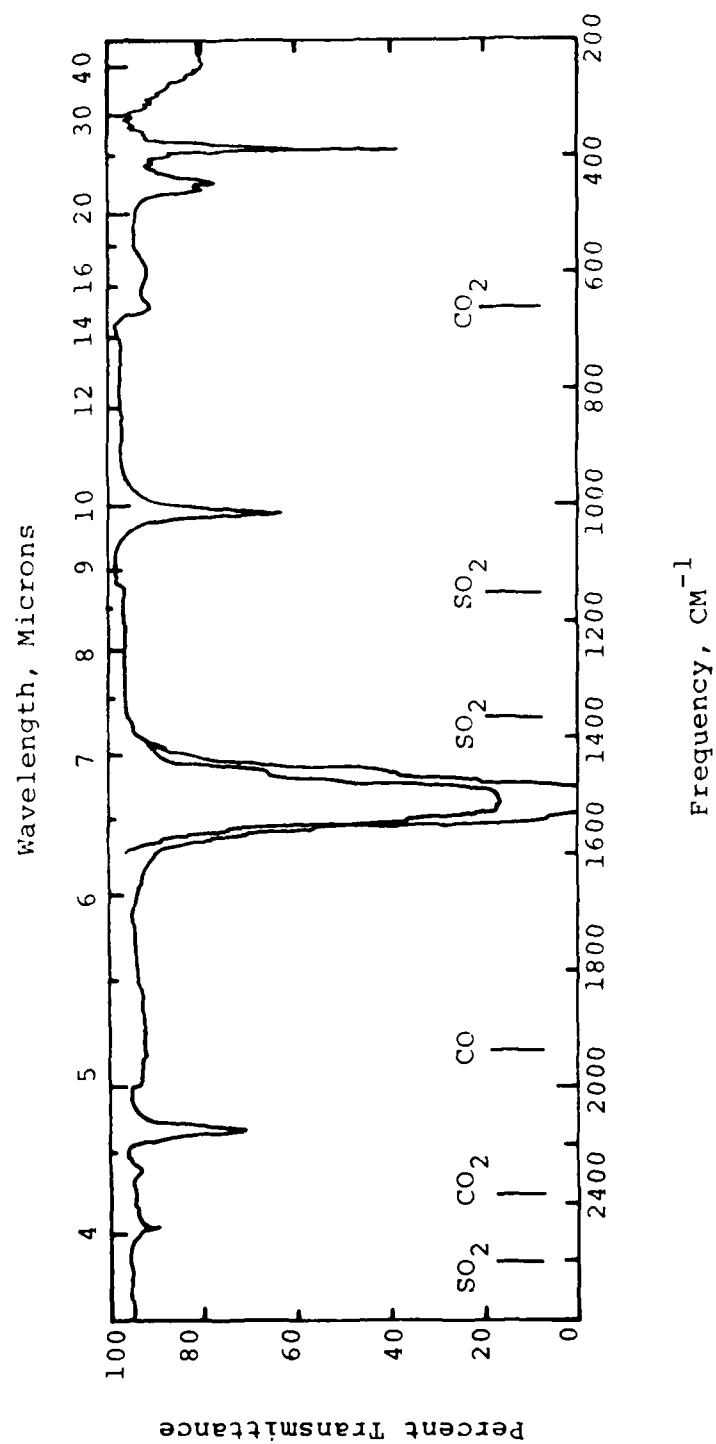


FIGURE 19. ABSORPTION SPECTRA OF CARBON DISULFIDE.

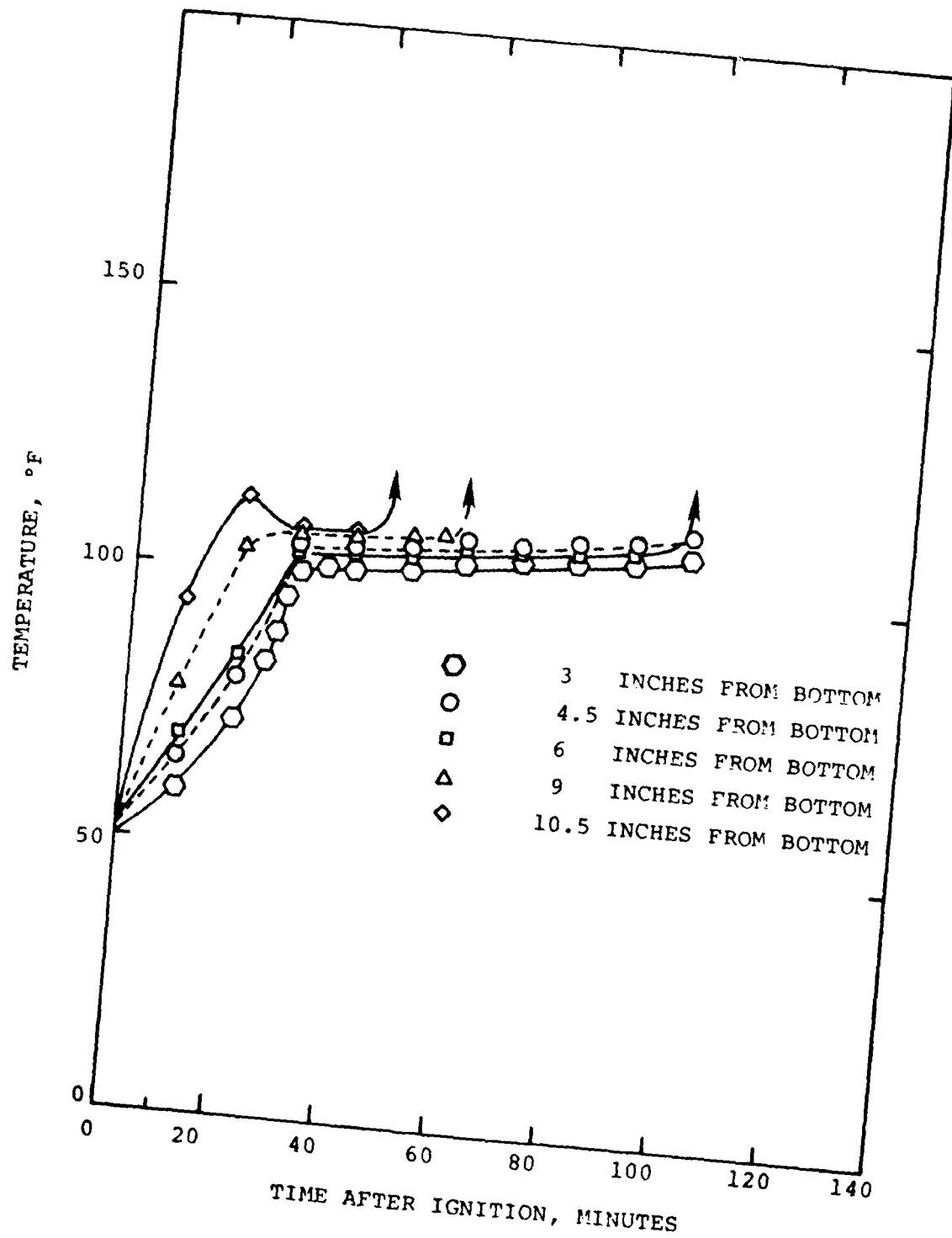


FIGURE 20. CARBON DISULFIDE POOL HEATUP WITH TIME.

to its boiling point within 30 minutes or before 2.5 inches of carbon disulfide had burned away. For larger pits with initial liquid depths of only 2-3 inches, heating the entire pool to its boiling point would take only 2-3 minutes. The above observations are in direct contrast with the observed heating of hexane pools. Virtually all of the radiant energy entering a hexane pool is absorbed within the first 0.5 inches of the pool surface. The remainder of the pool stays relatively cool. Thus, any agent which relies primarily on pool cooling to extinguish or control a fire will be less effective on carbon disulfide fires.

Determining the fire extinguishment times was difficult since the flame was colorless and produced little smoke. The only evidence that a fire was burning was the observation of "heat waves" above the liquid pool. Directly above the boiling liquid, a yellow-orange color could be observed. This color was probably due to elemental sulfur. The flames from the carbon disulfide fires reached about one pool diameter above the liquid surface for the 25- and 100-ft² fires and approximately three-quarters of a pool diameter above the surface for the 400-ft² fires. Flame length was judged by observing the convective motion in the space above the burning pool.

COMPARISON OF AGENT EFFECTIVENESS ON CARBON DISULFIDE AND HEXANE FIRES

This section compares the fire control results obtained with foams and the extinguishment results obtained with dry chemical agents on carbon disulfide fires to the baseline results obtained using similar agents on hexane fires. The test methodology used, as described in Appendix F, was identical to that used on the baseline hexane tests. Therefore, any differences in agent effectiveness should not be the result of differing test procedures.

High expansion foam was the most effective foam tested (in terms of control time at a given application rate) for both carbon disulfide and hexane fires. As Figure 21 shows, within the accuracy of the data, there was very little difference in the ability of the high expansion foam to control either hexane or carbon disulfide fires.

Aqueous film forming foam (AFFF) was a less effective agent than high expansion foam, but a more effective agent than protein or fluoroprotein foam. The "best fit" curves of AFFF data for carbon disulfide and hexane fires are shown in Figure 22. As this figure shows, at low application rates (less than 0.15 gpm/ft^2) hexane fires were more easily controlled than carbon disulfide fires. At application rates above 0.20 gpm/ft^2 , AFFF was as effective in controlling carbon disulfide fires as in controlling hexane

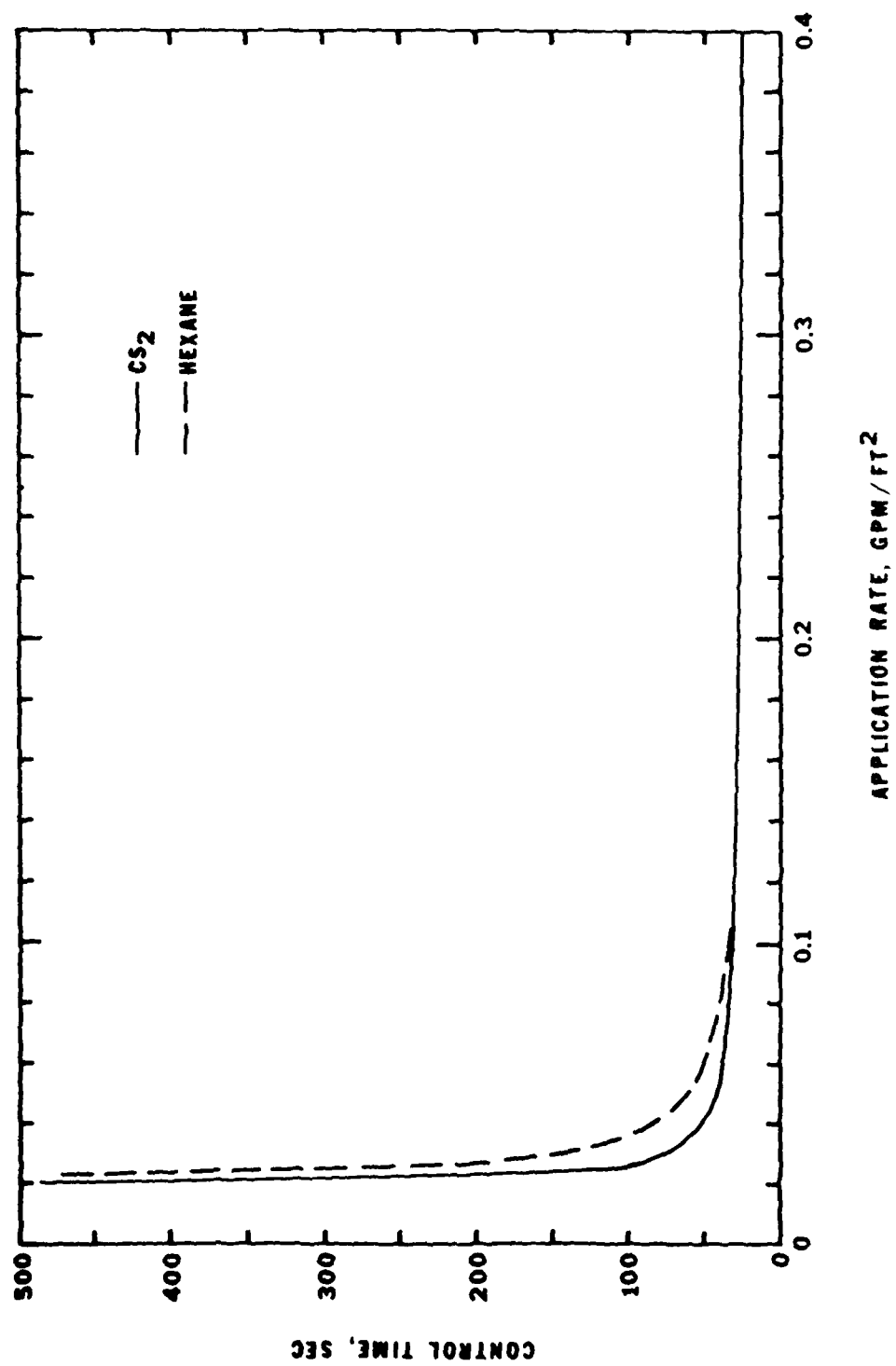


FIGURE 21. COMPARISON OF HIGH EXPANSION FOAM FIRE CONTROL TIMES FOR CARBON DISULFIDE AND HEXANE FIRES.

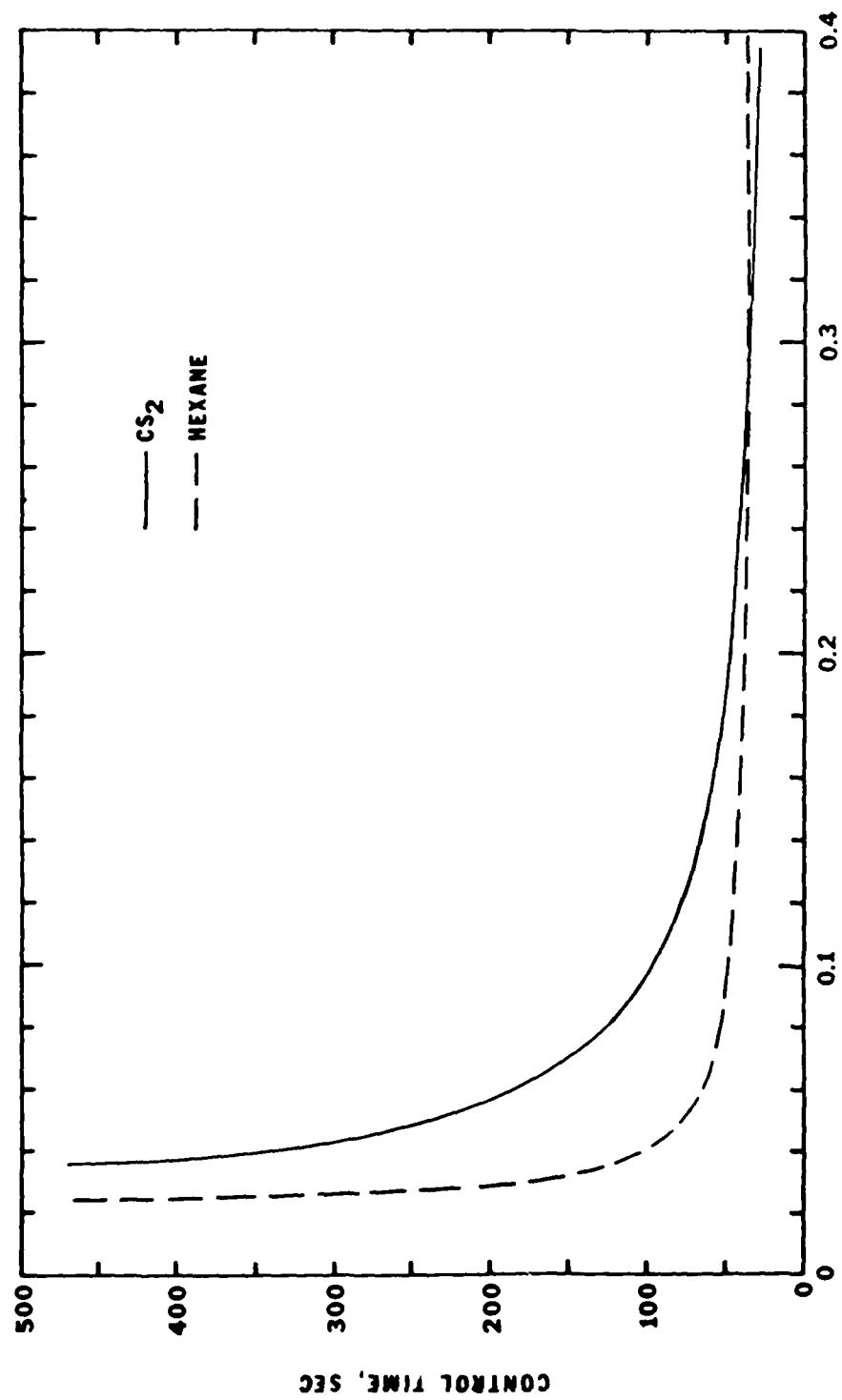


FIGURE 22. COMPARISON OF AFFF FIRE CONTROL TIMES FOR CARBON DISULFIDE AND HEXANE FIRES.

fires. Protein low expansion foam, the least effective foam on carbon disulfide fires, was also the least effective foam on hexane fires. Figure 23 shows the "best fit" curves for protein foam control times on carbon disulfide and hexane fires. At all application rates, protein foam was more effective on hexane fires.

It is interesting to note that for all foams compared above, the minimum foam application rate, for a given foam, appears to approach the same value for either the carbon disulfide or the hexane fires. Barring possible chemical reactions between the foam and fuel, this is not an unexpected result. The computed minimum application rates for carbon disulfide and hexane fires are 0.020 and 0.021 gpm/ft², respectively. Thus, a minimum application rate of about 0.02 gpm/ft² for either fuel would appear reasonable. It might also be expected that at high application rates (above 0.25 gpm/ft²) the control times for either type of fuel (for a specific foam) would be the same. This is the same as saying that at high application rates the foam fluidity, i.e. the foam's surface coverage ability, limits the fire control ability of a foam. At application rates above 0.25 gpm/ft², for either the carbon disulfide or hexane fires, high expansion and AFFF foams had virtually the same fire control times (although the control times were different for each foam). At high application rates, protein foam had significantly higher fire control times for

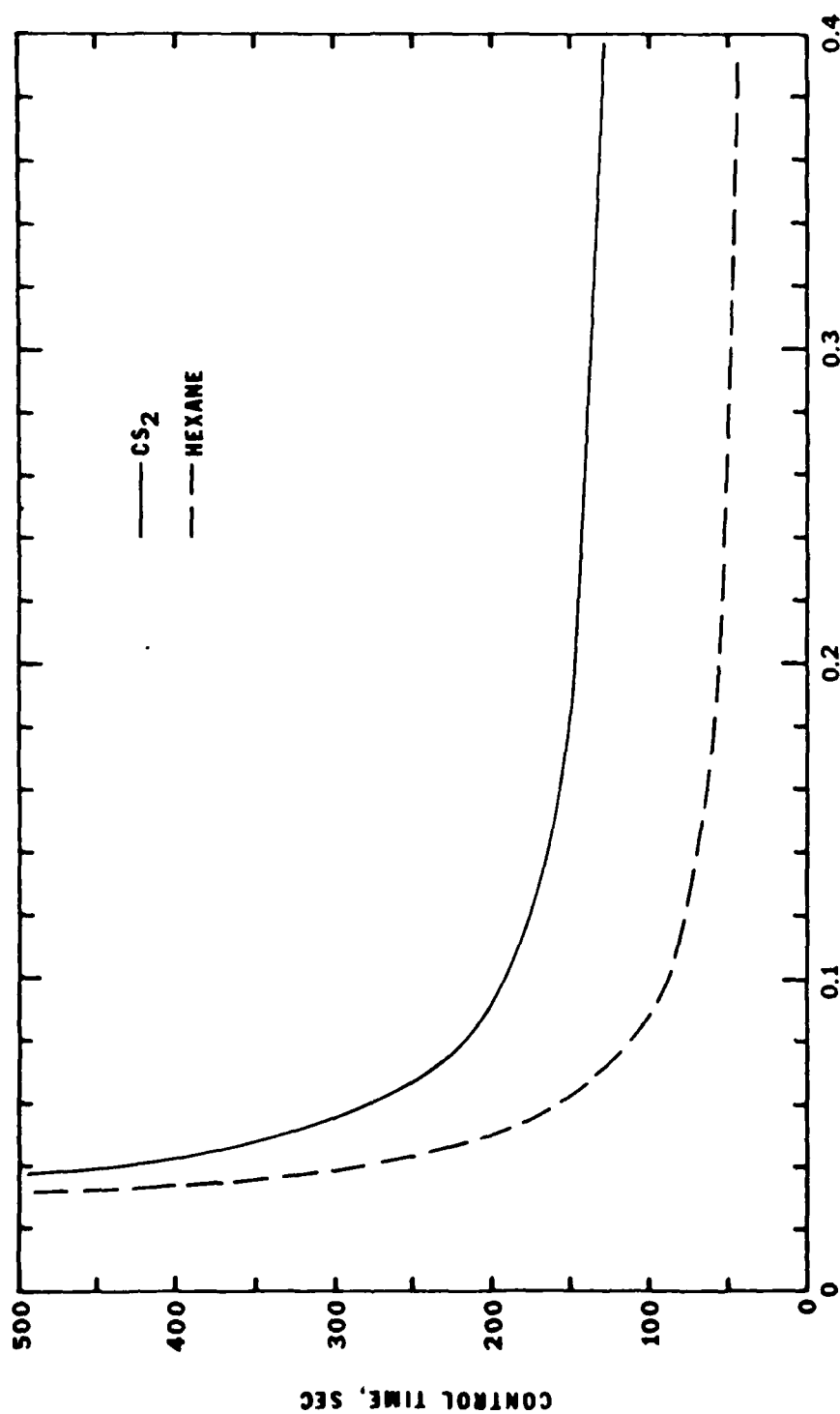


FIGURE 23. COMPARISON OF PROTEIN FOAM FIRE CONTROL TIMES FOR CARBON DISULFIDE AND HEXANE FIRES.

carbon disulfide fires than for hexane fires. Apparently, the protein foam was more fluid on the hexane fires. Why the protein foam was less fluid on carbon disulfide fires is not readily apparent from the test results. One possible explanation is that the leading edge of the protein foam reacted chemically with the carbon disulfide or combustion products, becoming stiffer and less mobile than the edge that formed on a hexane fire. Thus, the foam would be slower to cover the fire surface, resulting in longer control times.

As previously mentioned, most dry chemical agents were unable to extinguish carbon disulfide pool fires. Monoammonium phosphate was the only agent that extinguished carbon disulfide fires without reignition and it required application rates above 0.3 lb/sec-ft^2 . One reason the monoammonium phosphate was successful in extinguishing the two fires was because both tests had short preburn times. Thus, the pit walls and surroundings were not heated to a high temperature and could cool to below the carbon disulfide ignition temperature before the agent application was over. In contrast to this, all dry chemical agents used on hexane fires (NaHCO_3 , KHCO_3 , and urea- KHCO_3) were effective in extinguishing the fires and fires as large as 400 ft^2 were successfully extinguished. Figure 24 compares the two monoammonium phosphate extinguishment points to the "best fit" curve of the NaHCO_3 data from hexane fires

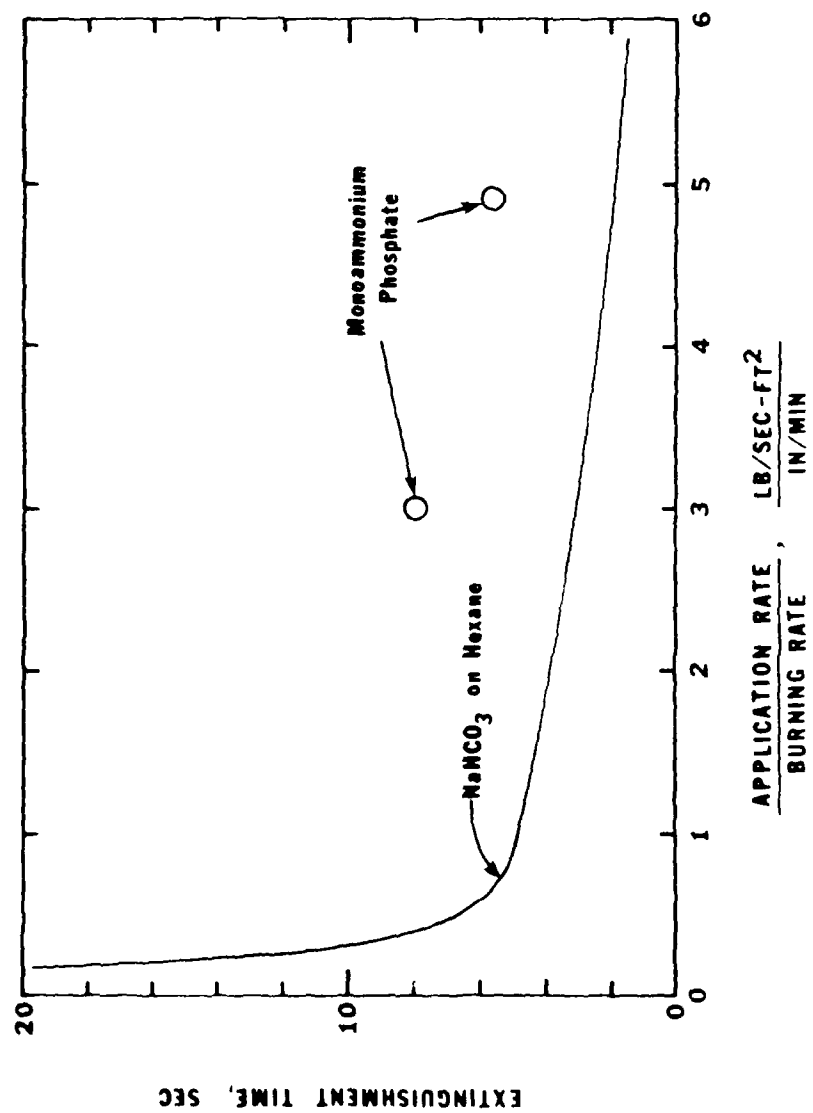


FIGURE 24. COMPARISON OF DRY CHEMICAL FIRE EXTINGUISHMENT DATA FOR CARBON DISULFIDE AND HEXANE FIRES.

(NaHCO_3 was the least effective of the dry chemical agents used on hexane fires). As the figure shows, when extinguishment of a carbon disulfide fire was possible, it required an extinguishment time 2-3 times as large as a hexane fire would at the same application rate and approximately 8 times the application rate to achieve the same extinguishment time.

APPENDIX A

TEST DATA AND COMMENTS

The six tables presented in this section, Tables A-1 through A-6, include the pertinent test data and, where necessary, comments about specific tests. In some cases, certain pieces of data are missing from the tables. This may be attributed to any one of several causes, e.g., data-logger or strip chart recorder malfunction, sensor failure, etc.

The Run Number column indicates the order in which the tests were conducted on a specific day. The Obstruction column states whether or not a concentric circle obstruction was used. Fires which were not controlled by foam application are listed as "NC"; those not extinguished by foam or dry chemical are listed as "NE".

TABLE A-1. PROTEIN FOAM DATA

TEST ID	DATE	RUN NO.	PIT SIZE (SQ FT)	BURNING RATE (IN/MIN)	APPLICATION RATE (GPM/SQ FT)	CONTROL TIME (SEC)	EXTING. TIME (SEC)	WIND SPEED (MPH)	PREBURN TIME (SEC)	OBSTRU. TYPE	COMMENTS
01	06-05-80	1	25	ND	0.101	295	1620	13	256		BURN RATE DATA BAD
02	06-27-80	1	100	ND	0.367	52	NE	ND	360		NO DATALOGGER DATA
03	06-27-80	2	100	0.098	0.367	90	1800	ND	600		NO DATALOGGER DATA
04	07-09-80	2	100	0.111	0.082	322	627	ND	332	CC	NO WIND SPEED DATA
05	07-09-80	3	100	0.115	0.304	152	NE	ND	300*	CC	NO WIND SPEED DATA
06	07-10-80	1	100	0.156	0.086	142	629	9	332	CC	NO WIND SPEED DATA
07	07-15-80	1	100	ND	0.037	500	1830	10	340	CC	NO FOAM DEFLECTOR
08	07-15-80	2	100	0.107	0.037	NC	NE	11	315	CC	
09	07-24-80	1	100	0.104	0.037	188	NE	10	320		
10	07-24-80	2	100	0.166	0.085	100	ND	ND	313		NO DATALOGGER DATA, DUAL AGENT
11	07-29-80	2	400	0.095	0.292	245	NE	9	319		
12	08-06-80	1	400	0.116	0.105	109	NE	14	312		
13	08-08-80	1	400	0.126	0.038	419	1950	10	308		
14	08-19-80	2	400	0.112	0.098	426	1185	15	341	CC	
15	08-29-80	1	100	0.124	0.183	39	1140	11	428		

NC = FIRE NOT CONTROLLED, ND = NO DATA, NE = FIRE NOT EXTINGUISHED

* = PLANNED PREBURN TIME

TABLE A-2. FLUOROPROTEIN FOAM DATA

TEST ID	DATE	RUN NO.	PIT SIZE (SQ FT)	BURNING RATE (IN/MIN)	APPLICATION RATE (GPM/SQ FT)	CONTROL TIME (SEC)	EXTING. TIME (SEC)	WIND SPEED (MPH)	PREBURN TIME (SEC)	OBSTRU. TYPE	COMMENTS
01	06-26-80	2	100	0.149	0.367	147	802	8	299		
02	07-07-80	2	100	0.153	0.366	172	1006	11	370	CC	
03	07-08-80	1	100	0.122	0.171	155	468	9	327	CC	
04	07-08-80	2	100	0.123	0.100	210	737	11	362	CC	
05	07-09-80	1	100	0.098	0.246	117	447	11	313	CC	
06	07-16-80	1	100	ND	0.041	NC	NE	6	300*	CC	
07	07-23-80	1	100	0.119	0.077	176	NE	9	320		
08	07-23-80	2	100	0.115	0.029	777	NE	8	298		
09	08-05-80	1	400	0.104	0.289	279	465	17	310		
10	08-06-80	2	400	0.093	0.094	259	1170	13	315		
11	08-14-80	1	400	0.118	0.038	191	900	11	330		
12	08-15-80	1	400	0.109	0.100	188	NE	14	304		
13	08-22-80	1	400	0.138	0.100	258	NE	9	307	CC	
14	08-26-80	1	100	0.136	0.055	423	NE	8	305		
15	08-27-80	1	100	0.092	0.036	NC	NE	7	315		DUAL AGENT

NC = FIRE NOT CONTROLLED, ND = NO DATA, NE = FIRE NOT EXTINGUISHED

* = PLANNED PREBURN TIME

TABLE A-3. AFFF DATA

TEST ID	DATE	RUN NO.	PIT SIZE (SQ FT)	BURNING RATE (IN/MIN)	APPLICATION RATE (GPM/SQ FT)	CONTROL TIME (SEC)	EXTING. TIME (SEC)	WIND SPEED (MPH)	PREBURN TIME (SEC)	OBSTRU. TYPE	COMMENTS
01	06-20-80	2	25	0.154	0.333	119	600	5	336		
02	07-02-80	2	100	ND	0.367	40	NE	10	300*		
03	07-03-80	1	100	0.087	0.131	118	ND	10	321		
04	07-03-80	2	100	0.107	0.121	82	ND	13	323		
05	07-07-80	1	100	0.178	0.366	219	1320	ND	321	CC	
06	07-11-80	2	100	0.138	0.089	121	ND	ND	378	CC	
07	07-24-80	3	100	0.120	0.087	74	NE	6	320		
08	07-24-80	4	100	0.137	0.037	NC	NE	7	315		
09	08-01-80	1	400	0.143	0.235	31	NE	11	239		
10	08-06-80	3	400	0.135	0.093	91	1118	14	308		
11	08-07-80	1	400	0.127	0.047	157	1170	12	316		
12	08-07-80	2	400	0.122	0.038	NC	NE	13	306		
13	08-21-80	1	400	0.141	0.094	114	NE	10	301	CC	

NC = FIRE NOT CONTROLLED, ND = NO DATA, NE = FIRE NOT EXTINGUISHED

* = PLANNED PREBURN TIME

TABLE A-4. HIGH EXPANSION FOAM DATA

TEST ID	DATE	RUN NO.	PIT SIZE (SQ FT)	BURNING RATE (IN/MIN)	APPLICATION RATE (GPM/SQ FT)	CONTROL TIME (SEC)	EXTING. TIME (SEC)	WIND SPEED (MPH)	PRETURN TIME (SEC)	OBSTRU. TYPE	COMMENTS
01	06-11-80	1	25	0.058	0.142	37	NE	11	267		DG FOAM
02	06-12-80	1	25	0.083	0.055	49	NE	16	332		DG FOAM
03	06-13-80	1	25	0.093	0.060	39	NE	18	326		EL FOAM
04	06-16-80	1	25	0.073	0.064	40	240	5	372		EL FOAM
05	06-18-80	1	25	0.122	0.040	34	410	3	357		EL FOAM
06	06-20-80	1	25	0.076	0.054	50	190	7	317		EL FOAM
07	07-01-80	1	100	0.138	0.087	28	NE	11	304		EL FOAM
08	07-02-80	1	100	ND	0.087	23	360	9	68		EL FOAM
09	07-14-80	1	100	0.148	0.062	23	180	10	305	CC	EL FOAM
10	07-14-80	2	100	0.107	0.090	130	515	11	320	CC	EL FOAM, LOW EXPANSION
11	07-14-80	3	100	0.117	0.062	24	180	10	291	CC	EL FOAM
12	07-25-80	1	100	0.179	0.043	36	NE	7	314		EL FOAM
13	07-25-80	2	100	0.090	0.054	60	450	10	304		EL FOAM
14	08-18-80	1	400	0.095	0.035	76	NE	13	306		EL FOAM
15	08-18-80	2	400	0.119	0.036	50	1080	14	305		EL FOAM
16	08-19-80	1	400	0.111	0.036	80	NE	13	302		EL FOAM
17	08-29-80	2	100	0.136	0.294	21	60	11	925		EL FOAM

NC = FIRE NOT CONTROLLED, ND = NO DATA, NE = FIRE NOT EXTINGUISHED

TABLE A-5. WATER DATA

TEST ID	DATE	RUN NO.	PIT SIZE (SQ FT)	BURNING RATE (IN/MIN)	APPLICATION RATE (GPM/SQ FT)	CONTROL TIME (SEC)	EXTING. TIME (SEC)	WIND SPEED (MPH)	PREBURN TIME (SEC)	OBSTRU. TYPE	COMMENTS
01	06-06-80	1	25	0.094	0.129	NC	NE	15	591		
02	06-09-80	1	25	0.094	0.102	NC	NE	4	549		
03	06-10-80	1	25	ND	0.687	82	168	4	300*		
04	06-10-80	2	25	0.097	0.463	118	277	4	592		
05	06-24-80	1	100	0.150	0.360	198	315	8	279		
06	06-25-80	1	100	0.112	0.138	NC	NE	9	390		
07	06-25-80	2	100	0.130	0.275	212	285	7	326		
08	06-26-80	1	100	0.150	0.103	1195	NE	4	303		RAN OUT OF FUEL
09	07-10-80	2	100	0.121	0.095	NC	NE	8	431		
10	07-10-80	3	100	0.087	0.374	205	360	9	335	CC	
11	07-11-80	1	100	0.111	0.176	1340	1650	9	346	CC	
12	07-28-80	1	400	0.105	0.316	NC	NE	6	386		
13	07-29-80	1	400	0.134	0.286	493	900	5	308		
14	08-25-80	1	400	0.121	0.300	NC	NE	10	330	CC	
15	08-27-80	2	100	0.129	0.551	NC	NE	7	320		WATER FOG TEST

NC = FIRE NOT CONTROLLED, ND = NO DATA, NE = FIRE NOT EXTINGUISHED

* = PLANNED PREBURN TIME

TABLE A-6. DRY CHEMICAL DATA

TEST ID	DATE	RUN NO.	PIT SIZE (SQ FT)	BURNING RATE (IN/MIN)	APPLICATION RATE (LB/SEC-SQ FT)	EXTING. TIME (SEC)	WIND SPEED (MPH)	PRESURN TIME (SEC)	OBSTRU. TYPE	COMMENTS
01	05-23-80	1	25	ND	0.303	8.0	10	40		MONAMMONIUM PHOSPHATE
02	05-27-80	1	25	ND	0.318	22.0	7	36		SODIUM BICARBONATE, REIGNITION
03	05-28-80	1	25	0.099	0.234	NE	8	34		POTASSIUM BICARBONATE
04	05-28-80	2	25	0.089	0.215	NE	10	53		MONNEX
05	05-30-80	1	25	0.084	0.412	5.6	8	127		MONAMMONIUM PHOSPHATE
06	06-02-80	1	25	0.109	0.208	NE	15	306		SODIUM BICARBONATE
07	06-02-80	2	25	0.095	0.260	27.5	12	314		SODIUM BICARBONATE, REIGNITION
08	06-03-80	1	25	ND	0.266	NE	13	324		MONAMMONIUM PHOSPHATE
09	06-23-80	1	25	ND	0.270	NE	7	355		SODIUM BICARBONATE
10	06-23-80	2	25	ND	0.078	NE	9	735		MONAMMONIUM PHOSPHATE, MANUAL TEST
11	06-30-80	1	100	ND	0.061	NE	9	70		SODIUM BICARBONATE
12	06-30-80	2	100	ND	0.053	NE	12	66		MONAMMONIUM PHOSPHATE

ND = NO DATA, NE = FIRE NOT EXTINGUISHED

APPENDIX B

OBSTRUCTIONS

Concentric circle obstructions, illustrated in Figure B-1, were available for use during the tests on the 100- and 400-ft² fires. The concentric circles were constructed of 10-gage sheet steel in two circular segments. Each segment had a 90 degree opening. The larger circular segment was placed outside the smaller segment with the openings at opposite sides. These openings were braced in order to prevent the circular segments from deforming excessively. Both circles were placed directly on the bottom of the pit.

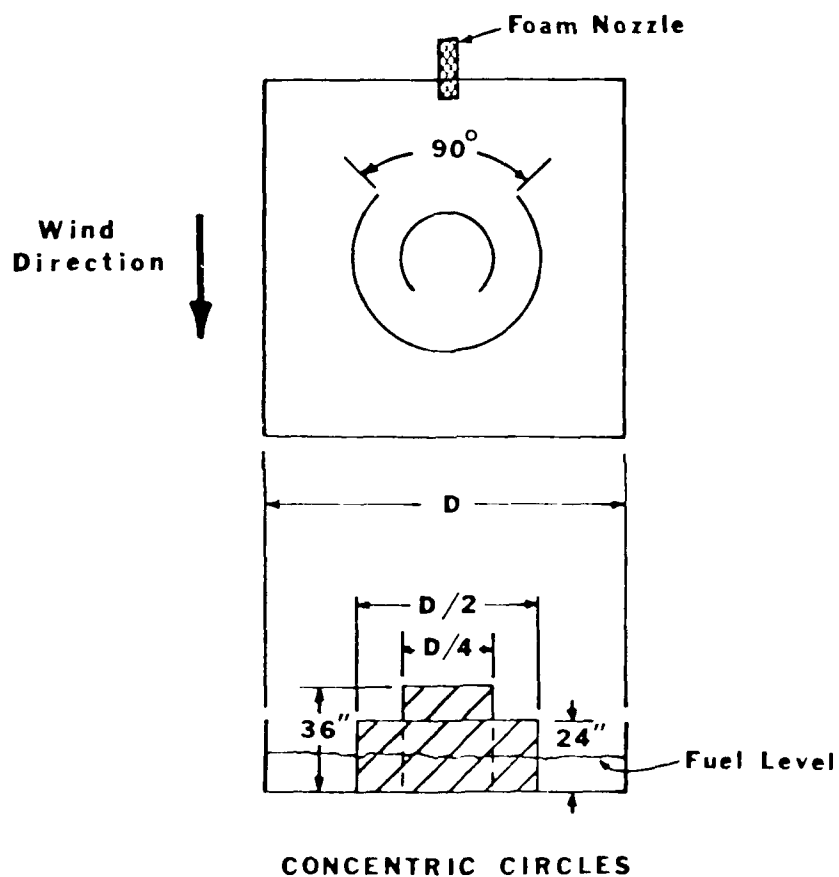


FIGURE B-1. DESIGN OF CONCENTRIC CIRCLE OBSTRUCTION.

APPENDIX C

DRY CHEMICAL DISTRIBUTION SYSTEM

The dry chemical distribution system consisted of four nozzles placed 6 inches below the top of the pit wall and located at the center of each wall. Figure C-1 shows the nozzle arrangement. This arrangement was used for three reasons:

- 1) powder consistently reached the center of the pit
- 2) all of the dry chemical entered the fire zone
- 3) the wind had little effect on the dry chemical distribution

The dry chemical nozzles used in the carbon disulfide tests were of the type shown in Figure 7.

In the dry chemical system, the distribution piping networks were designed to be symmetric, balanced systems with only small pressure losses due to the piping so that each nozzle would receive the same powder flow rate and would have sufficient pressure (i.e., 25 to 75 psig) available to provide adequate range. The piping network used for the dry chemical distribution system is illustrated in Figure C-2. Obviously, each pit size required a different piping system. Additional piping networks were necessary if the dry chemical flow rate was to be varied over a wide

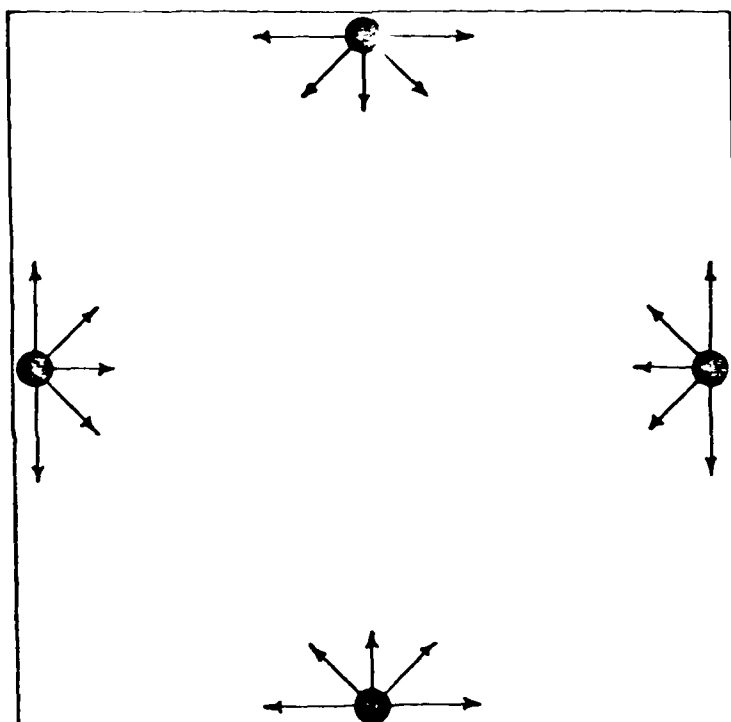
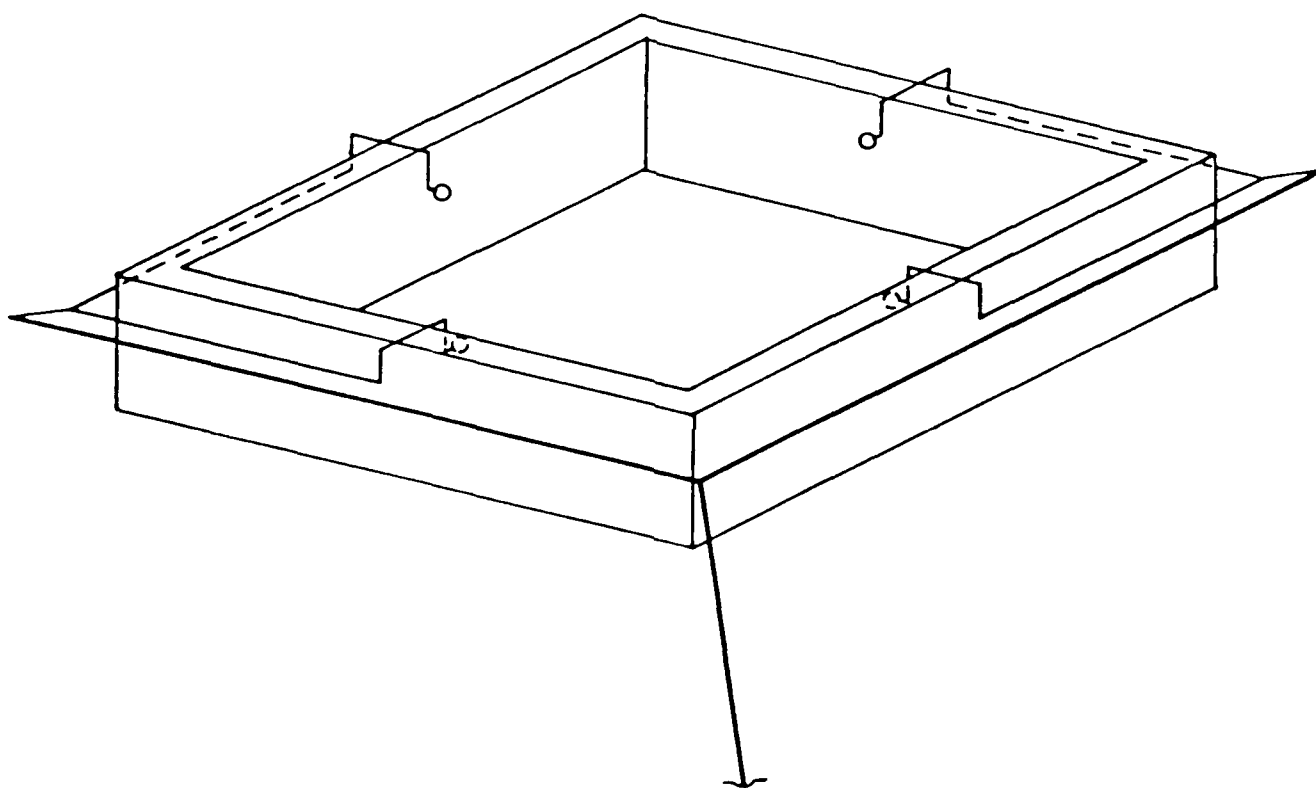


FIGURE C-1. LOCATION OF DRY CHEMICAL DISCHARGE NOZZLES.



From Dry Chemical Unit

FIGURE C-2. DRY CHEMICAL DISTRIBUTION PIPING SYSTEM.

range; different pipe sizes are required in order to keep the velocity of the nitrogen/powder mixture sufficiently high so that the powder did not settle out, yet low enough so that the pressure drop was not excessive.

APPENDIX D

FOAM GENERATORS

The nozzles used for generating low expansion foam for this series of fire control and extinguishment tests were manufactured by National Foam Systems, Inc. Eleven nozzles, ranging in capacity from 2 to 120 GPM, were available for use during the tests. Three of these were test nozzles (i.e., not intended for use in actual fire protection systems). The other eight were intended for use inside flammable liquid storage tanks. The flow rates and operation pressures for the various nozzles are listed in Table D-1.

TABLE D-1. FLOW RATES AND OPERATING PRESSURES
OF LOW EXPANSION FOAM NOZZLES

Number of Nozzles Available	Flow Rate (gpm)	Operating Pressure (psig)
2	2*	100
1	6*	100
1	10	60
1	15	60
1	20	60
1	40	60
1	80	60
1	100	60
2	120	60

* Test nozzles

AD-A098 552

APPLIED TECHNOLOGY CORP NORMAN OK F/8 13/12
FIRE CONTROL AGENT EFFECTIVENESS FOR HAZARDOUS CHEMICAL FIRES: --ETC(U)
JAN 81 D W JOHNSON, W D CAVIN, H P LAWSON DOT-C8-841340-A

UNCLASSIFIED AT-116-2

USC6-D-09-81

NL

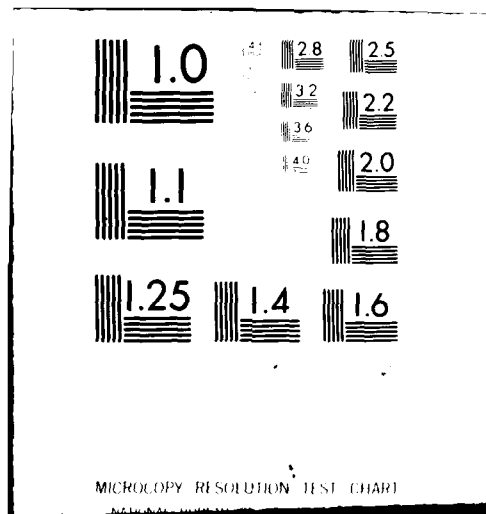
242

80

80



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By using two nozzles simultaneously, it was possible to obtain flow rates other than those available with any single nozzle (e.g., using the 10- and 20-gpm nozzles to get a 30-gpm flow rate). The only limitation on combinations was that the operating pressures of the two nozzles be the same. These nozzles were calibrated at the factory and proved to be nearly trouble-free in operation.

The high expansion foam generators used in this series of fire control and extinguishment tests were manufactured by Mine Safety Appliance Research. All of the generators used 110-volt electric motor driven fans to supply the necessary air flow. All but the three smallest generators had explosion proof motors. The nominal capacities of the eight generators ranged from 130 to 6000 cfm of 500:1 expansion ratio foam. The nominal capacities, solution flow rates, and operating pressures (all assuming 500:1 foam) are listed in Table D-2.

TABLE D-2. NOMINAL OPERATING PARAMETERS FOR HIGH EXPANSION FOAM GENERATORS

Number of Generators Available	Capacity (cfm)	Solution Flow Rate (gpm)	Operating Pressure (psig)
3	130	2	40
1	1200	18	100
2	2600	39	40
2	6000	90	100

Measuring the expansion ratio and foam production rate for a high expansion foam generator requires a large enclosure of known volume that can be filled with foam. Such an enclosure was not available at the test site. Therefore, the decision was made to report the application rate in terms of solution flow rate (i.e., gpm/ft²). This also made comparisons among the four types of foam much easier.

APPENDIX E

PHYSICAL AND CHEMICAL DATA FOR CARBON DISULFIDE

The high purity carbon disulfide used as fuel for the fire tests had a purity of almost 100 percent. A maximum residue of only 0.003 percent is allowed by the manufacturer*. Pertinent physical constants for carbon disulfide are:

Molecular Weight	76.13
Boiling Point	115.3 F
Flash Point	-22. F
Auto Ignition Temp.	194. F
Liquid Density (60 F)	78.8 LB/CU FT
Vapor Specific Gravity	2.63
Vapor Pressure (68 F)	5.8 PSIA
Refractive Index (64 F)	1.6295
Explosive Limits in Air (Vol %)	1.3 to 50

*PPG Industries, Inc. Chemical Division

APPENDIX F

KEY ELEMENTS OF THE BASIC TEST METHOD

The basic test method used in this series of tests consisted of a few key elements which were developed under contract DOT-CG-42, 355-A, Task 6. These elements were followed as closely as possible in order to allow comparison with previous results.

- a) Fire Pits - Square pits of concrete or steel (no earthen pits), 2 ft deep.
- b) Obstructions - If an obstruction is to be used, it should be the concentric circle described in Appendix B.
- c) Dry Chemical Nozzle Locations - Nozzles must be placed within the pit, midway between the corners and approximately 6 inches below the top of the pit wall. If possible, four nozzles should be used. In order to reduce application rate, fewer nozzles can be used, but only for smaller fires, i.e., 100 sq ft and less. If two nozzles are used, they should be placed opposite each other on the upwind and downwind sides of the pit. If one nozzle is used, it should be placed on the upwind side of the pit.
- d) Dry Chemical Nozzle Type - The nozzles should be of the type shown in Figure 7. Slit sizes are optional, but must be large enough to preclude plugging.
- e) Dry Chemical Distribution System - The piping system should be designed and constructed to deliver equal amounts of agent to each nozzle.
- f) Foam Generator Location - The foam generator(s) should be placed so that the foam is introduced at the center of the upwind wall of the pit and applied gently.

- g) Foam Solution - The foam solution should be pre-mixed to insure accurate dilution. If premixing is not practical, both water and concentrate flow rate must be accurately measured and controlled to insure accurate dilution. The foam system must not allow water to enter the fire zone before solution reaches the foam generator.
- h) Agent Application Rates - Agent flow rates must be measured accurately to insure that the application rate can be calculated accurately.
- i) Fuel Burning Rate - The burning rate of the fuel must be measured accurately so that any effect of burning rate can be determined.
- j) Preburn Time - The fuel should be allowed to burn a sufficient period of time to allow the burning rate to reach its steady-state value before agent flow is started.
- k) Weather Conditions - Wind should be less than 20 mph.
- l) Control time - Fire control is defined as the time required to reduce the radiant flux at one pool diameter crosswind from the pool to 5 percent of the free burning value. Radiometers must be used to monitor the heat flux.

*U.S.G.P.O. 725-957/1302-1239

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