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EFFECTIVENESS OF FIRE CONTROL AGENTS ON CHEMICAL FIRES

PHASE I: TEST METHODOLOGY AND BASELINE HEXANE TESTS

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FINAL REPORT

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16. Abstract

A basic test method for comparing relative effectiveness of fire control agents on fires from liquid chemicals was set and modified through developmental tests. The methodology was then demonstrated in a test series intended to produce baseline data for comparison with future test data using other chemicals as fuels. Fuel for the baseline test series was high purity hexane. Tests were run in concrete pits with and without sheet steel wall linings and with and without steel obstructions. Pit (fuel) surface areas were 25 ft^2, 100 ft^2, 400 ft^2, and 1600 ft^2. Foam fire control agents used were low expansion protein, AFFF, and alcohol and a saltwater high expansion foam. Dry chemical agents were used in the three smaller pit sizes and were sodium bicarbonate and potassium bicarbonate, and a urea-potassium bicarbonate reaction product. Agents were applied through fixed systems, with a few manual tests for comparison. Data collected include burning rates; fuel, wall and obstruction temperatures; radiant fluxes; agent flow rates and nozzle pressures; preburn, control, and extinguishment times; and meteorological information. Times were taken by instrumentation or observation and stopwatch. Tentatively, the best data element for comparison appears to be a plot of application rate versus control time for foams and versus extinguishment time for dry chemical agents. Future tests should establish scaling parameters to allow use of smaller surface areas for the comparative effectiveness tests.

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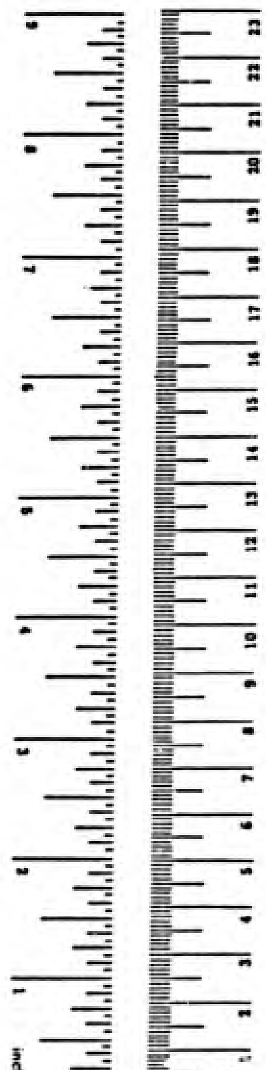
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

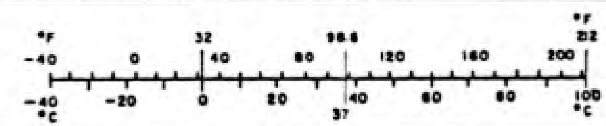
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2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

*1 in = 2.54 (exactly). 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	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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SUMMARY OF RESULTS

This is a report of results of fire control and extinguishment tests using four foam agents and three dry chemical agents on hexane fires. The basic test methodology adopted for conducting the tests is also presented. The work was conducted for the U. S. Coast Guard under Contract DOT-CG-42,355-A. The objective of the test program was to set a basic, uniform method for measuring the response of fires to various fire control agents and to demonstrate the methodology in a baseline series of tests using hexane as the baseline fuel.

Dry chemical fire extinguishing tests were conducted on 25-ft^2, 100-ft^2, and 400-ft^2 hexane fires with and without obstructions. Extinguishment equipment included 150- and 350-lb wheeled engine fire extinguishers and a 2000-lb stationary unit. Several different agent distribution systems and discharge nozzles were tried. Most of the tests used fixed nozzle systems. A few tests used manual agent application (dry chemical hoselines) on unobstructed fires. Agents tested were sodium bicarbonate ($NaHCO_3$), potassium bicarbonate ($KHCO_3$), and a urea-potassium bicarbonate reaction product (urea-$KHCO_3$). Agent application rates ranged from 0.021 to 0.222 lb/sec-ft^2.

Low and high expansion foam tests were conducted on 25-ft^2, 100-ft^2, 400-ft^2, and 1600-ft^2 hexane fires with and

without obstructions. Several foam generators of different types and capacities were used in the tests. Most of the tests used a fixed nozzle system wherein the foam was applied gently at the center of the upwind edge of the fire. A few tests used manual application of low expansion foam on unobstructed fires. Agents tested were protein, AFFF, and alcohol low expansion foams and one high expansion foam. Application rates ranged from 0.014 to 0.40 gpm/ft^2.

The results of the dry chemical tests show that if the fire extinguishing effectiveness of a dry chemical is defined as the ability to extinguish fires at low application rates, then the urea-$KHCO_3$ is the most effective, $NaHCO_3$ is least effective, and $KHCO_3$ is intermediate. At application rates greater than about 0.10 lb/ft^2-sec, there is very little difference in extinguishment times among the three dry chemicals.

Obstructions in the test fires had little effect on extinguishment time for $NaHCO_3$ and urea-$KHCO_3$ in 100-ft^2 tests. In larger fires and in 100-ft^2 fires using $KHCO_3$, dry chemicals did not extinguish the fires because the powder range was too small. Those fires could be extinguished with properly designed systems.

Several attempts were made to extinguish the 100-ft^2 and 400-ft^2 fires manually using one or two hoselines from the dry chemical units. When the fuel surface was only a few inches below the top of the pit wall, the attempts were successful and the extinguishment times were approximately the same as for fixed system tests at the same application rates.

Results of the foam tests show that high expansion foam is the most effective of the foam agents tested on the hexane 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, alcohol foam produced the shortest fire control times for any given application rate. It is followed in effectiveness by AFFF and protein foam. For fire extinguishment, the alcohol foam again was the most effective low expansion foam.

Fire control time (defined as the time at which the radiant flux to a radiometer located one pool diameter 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 from one day to the next 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.

Obstructions had varying effects on the ability of the foams to control the fire. The available data indicate that an I-beam cross and a sheet metal cross had no significant effect on the foam control times. A concentric circle obstruction increased control times for the three low expansion foams but did not show any effect on the high expansion foam control times.

Control times for manually applied low expansion foam were about equal to those for fixed nozzle tests, but extinguishment times were much shorter for the manual tests.

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 types of combustible materials in living quarters and machinery spaces are generally common materials and fire fighting methods are 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 fumes 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.

These problems with cargo fires prompted the USCG to investigate methods for controlling fires for the 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. This report presents the results of a baseline test series using hexane as the fuel.

Ideally the way to develop a standardized test method would be to duplicate every applicable test method that has validity and some history of use, devise a few others, and through processes of comparison, select an appropriate method for each agent type. This approach is not economically feasible. Consequently, the test method used had to be selected prior to beginning the test series. The test methods finally chosen were selected after reviewing (and subsequently rejecting) test methods currently used by various organizations (e.g., Underwriters Laboratories Standard UL 711 and Military Specification 0-F-555C).

The UL 711 test method was rejected because it is designed only as a means of rating the fire extinguishing capability of a certain extinguisher on an n-heptane fire. Fire sizes from 2.5 to 1600 ft^2 are allowed for but all tests used manned equipment. In order to prevent the variability of the operator (i.e., skill level) from entering into the tests it was decided that all extinguishing systems should be of the fixed-in-place type with manual extinguishments used in only a few tests. The UL standard also calls for a 60-second waiting period (preburn) between ignition of the fuel and commencement of the extinguishment attempt. The judgment was made that a longer preburn would yield data more applicable to the needs of the Coast Guard (i.e., how effective the agent is in extinguishing the fire when hot metal surfaces are involved). The data taken in the UL test is limited to the total time of discharge, the amount of agent used, weather conditions, and whether or not the fire is extinguished. These data are insufficient for engineering or evaluating a system for a given hazard. Data on flow rate, burning rate, and extinguishment time are also necessary if the results are to be meaningful in terms of engineering design.

The federal specification 0-F-555C, Foam Liquid, Fire Extinguishing, Mechanical, calls for testing foam on a 10-ft by 10-ft gasoline fire after a 60-sec preburn. A 6-gpm nozzle is fixed in place at the middle of one side of the 3-ft deep metal test pan so that the foam stream strikes the opposite side 12 in above the fuel level. Coverage, control, and extinguishment times are recorded. The relatively small size (100 ft^2) and short preburn (60 sec) may be insufficient if the agent effectiveness is to be assessed at the peak mass burning rate and in the presence of hot surfaces. Also, only one application rate is called for. A range of application rates and fire sizes must be used in order to provide meaningful data for systems engineering and evaluation.

DESCRIPTION OF TEST FACILITIES

Location

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.

Structures

There are presently two structures located at the Newcastle test site: a 10-ft by 20-ft portable building and a 24-ft by 32-ft preformed concrete building. These buildings are located as shown in Figure 1.

The portable building serves as an office and visitors' center. It is located near the site entrance and contains telephone and sanitary facilities.

The concrete building houses the shop, storage area, foam solution piping and valving, and instrument room. The interior of the building is partitioned into a work-storage area and an instrument room. The instrument room is roofed and insulated. It contains the analytical instrumentation used in the tests and also provides storage space for motion picture and video equipment. The entire building is equipped with a central heating system. The instrument room is air

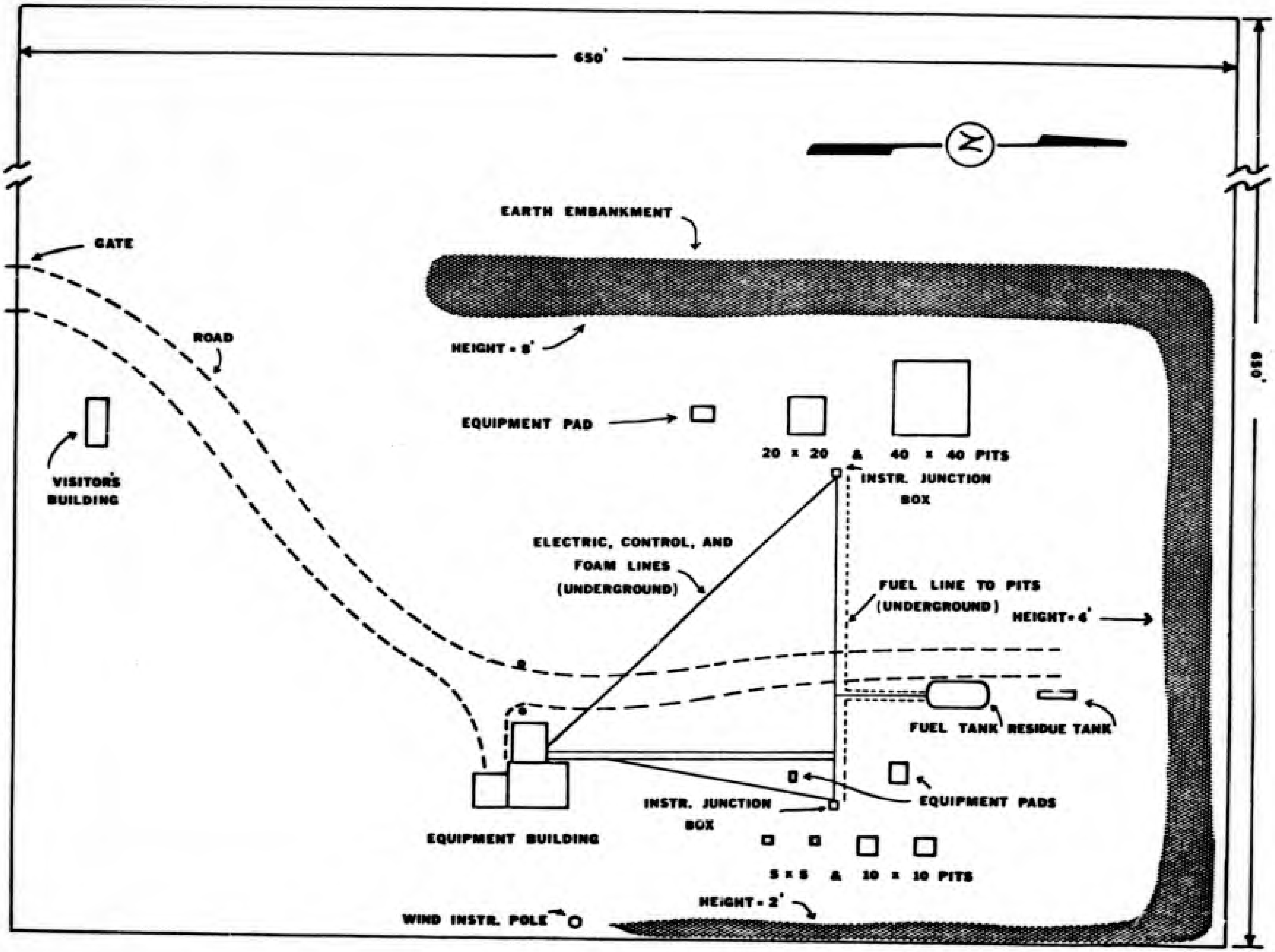


FIGURE 1. FIRE TEST FACILITY LAYOUT.

conditioned and contains additional heating equipment. The roof of the building is accessible by an outside stairway and is used as a platform for observing, photographing, and otherwise monitoring the fires.

Concrete pads adjacent to the storage and instrument building are used for additional off-ground storage and provide foundations for the water storage tank, foam holding tanks, and firewater pump. Figure 2 details the concrete building and associated concrete pads.

Fire Pits

The fire extinguishment tests were conducted in four sizes of square concrete pits constructed to give approximate burning areas of 25, 100, 400, and 1600 ft^2. All pits were 2 ft deep and were sunk into the ground so that the top of the pit wall was near ground level. The inner surfaces and tops of the concrete walls were covered with approximately 1/4 inch of insulating refractory to aid in protecting the concrete from the severe heating/cooling cycles.

A metal pit liner of 10-gage sheet steel was placed in the 25- and 100-ft^2 pits for some of the tests. Each liner covered the inner surface and tops of the walls. The liner pieces were welded together to provide a continuous structure that was open only at the bottom and around the outer edge at the top of the walls.

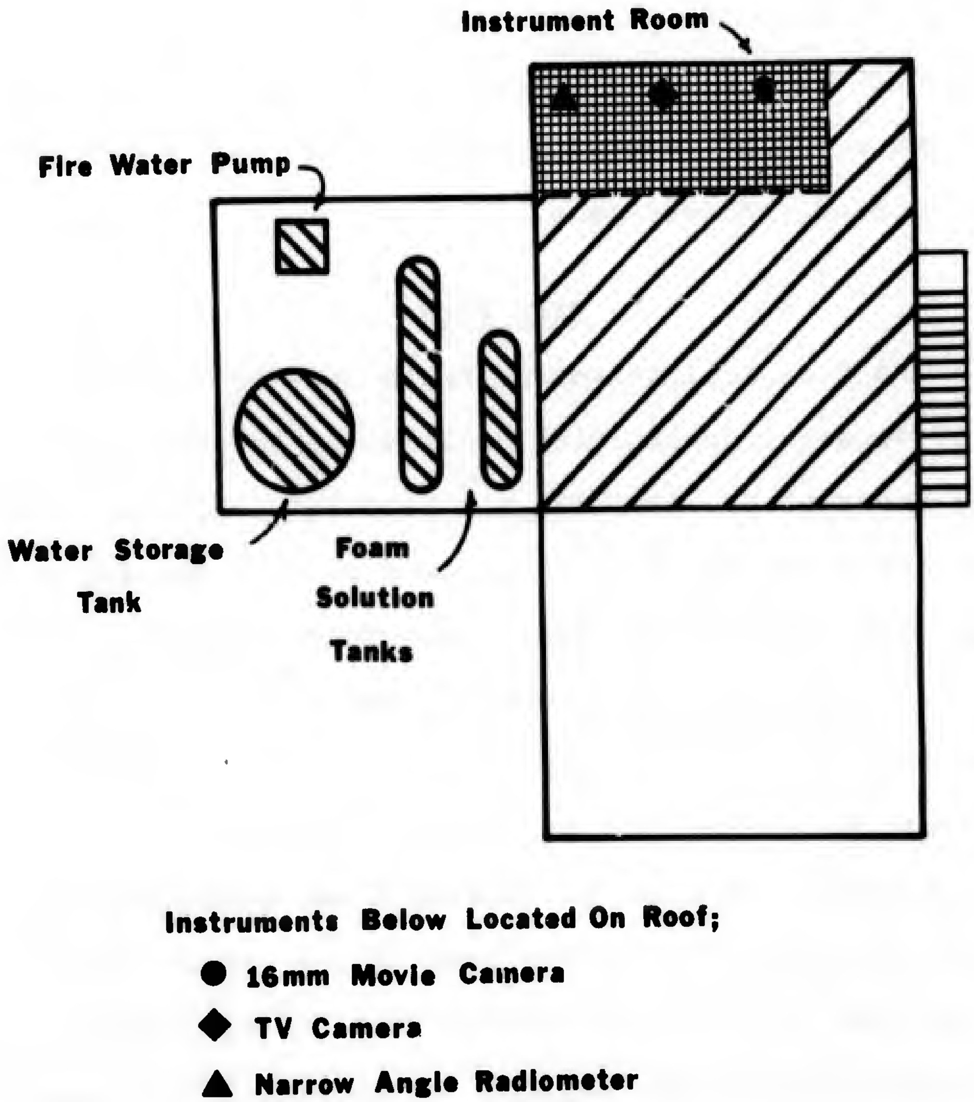


FIGURE 2. LAYOUT AT INSTRUMENTATION BUILDING SHOWING TYPICAL ROOFTOP EQUIPMENT LOCATION.

During pit construction, a 10-mil PVC liner was placed beneath each pit to act as a secondary containment system in the event that the concrete pit leaked. Figure 3 is a cross section of a typical pit and shows the locations of the metal inner-liner and the PVC outer-liner.

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 whose inner surface is protected by an epoxy coating. Nominal dimensions of the tank are 8.5 ft diameter by 13 ft high. The foam holding tanks are standard 500- and 1000-gallon LPG storage tanks with 250-psig working pressure. The water storage tank and foam holding tanks are located on a concrete pad adjacent to the storage and instrument building

The fuel tank has a capacity of approximately 10,000 gallons and a working pressure of 50 psig. It is a horizontal tank 9 ft in diameter and 20 ft long. The tank is constructed of steel and has no internal coating. All connections are through the top portion of the tank.

The horizontal residue tank has a capacity of 4,000 gallons and is rated for atmospheric pressure only. All connections are through the top portion of the tank.

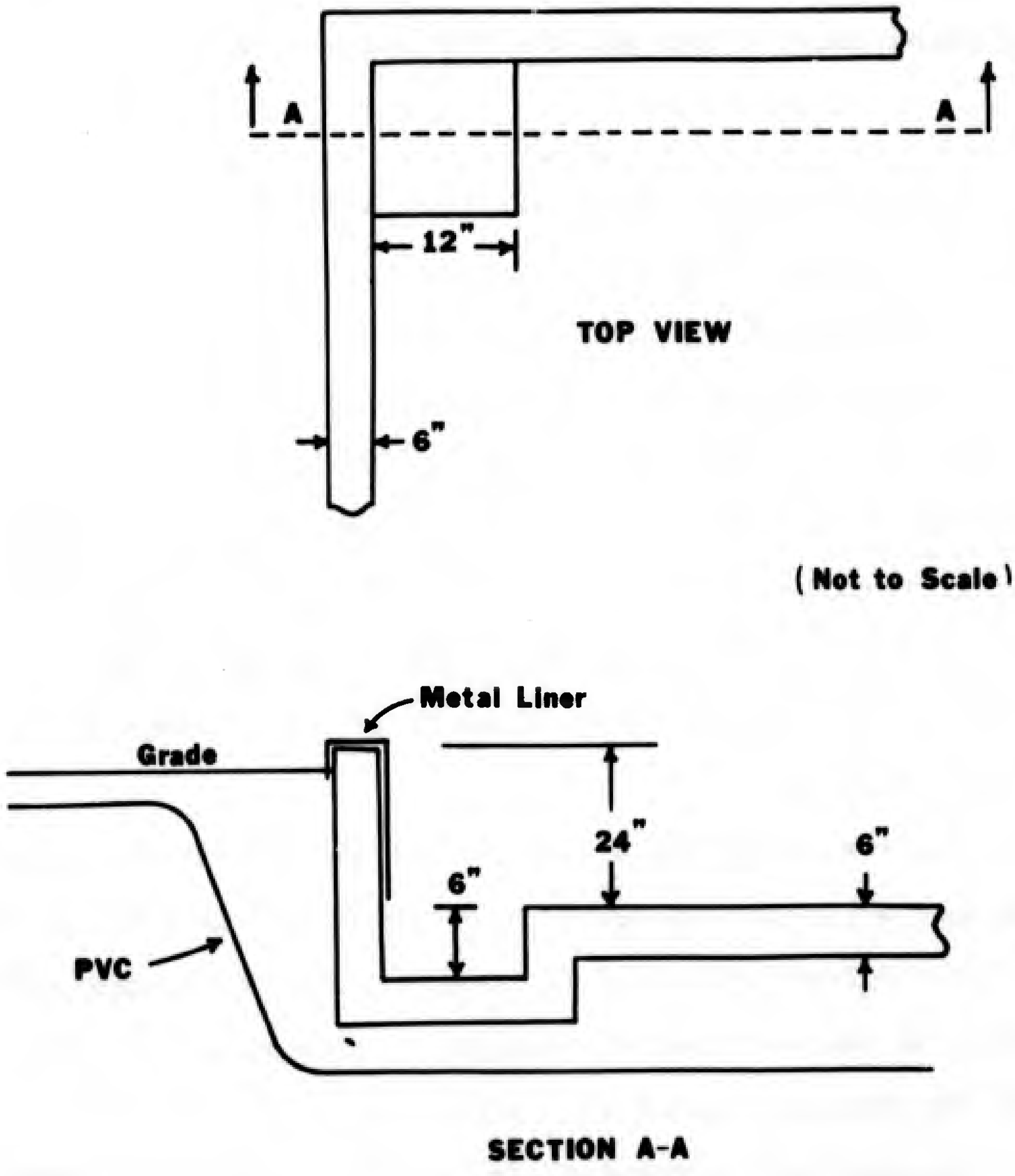


FIGURE 3. DETAIL OF TEST PIT CONSTRUCTION.

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 is constructed of schedule 40 steel. Below ground and indoor piping is schedule 40 PVC piping.

Fuel Delivery System

The fuel delivery system, shown in Figure 4, consists of the 10,000-gallon, nitrogen-padded fuel storage tank (previously described) and necessary piping and valving so that fuel can be routed to any fire pit. Fuel is transferred from the tank to the desired pit by using nitrogen pressure to force the fuel from the tank, through the appropriate buried steel pipe, to the air operated valve on a pipe riser near the instrumentation junction box. From this valve to the pit the fuel flows through a flexible hose and steel pipe transfer line. The air operated valves are operable from within the control room so that once the appropriate valves have been opened at the tank and the transfer line is in place, the actual process of transferring fuel can be accomplished remotely. Once the desired amount of fuel has been added to the pit, all fuel piping from the tank to the pit is purged with nitrogen. The transfer line is then disconnected and moved to a safe distance from the pit.

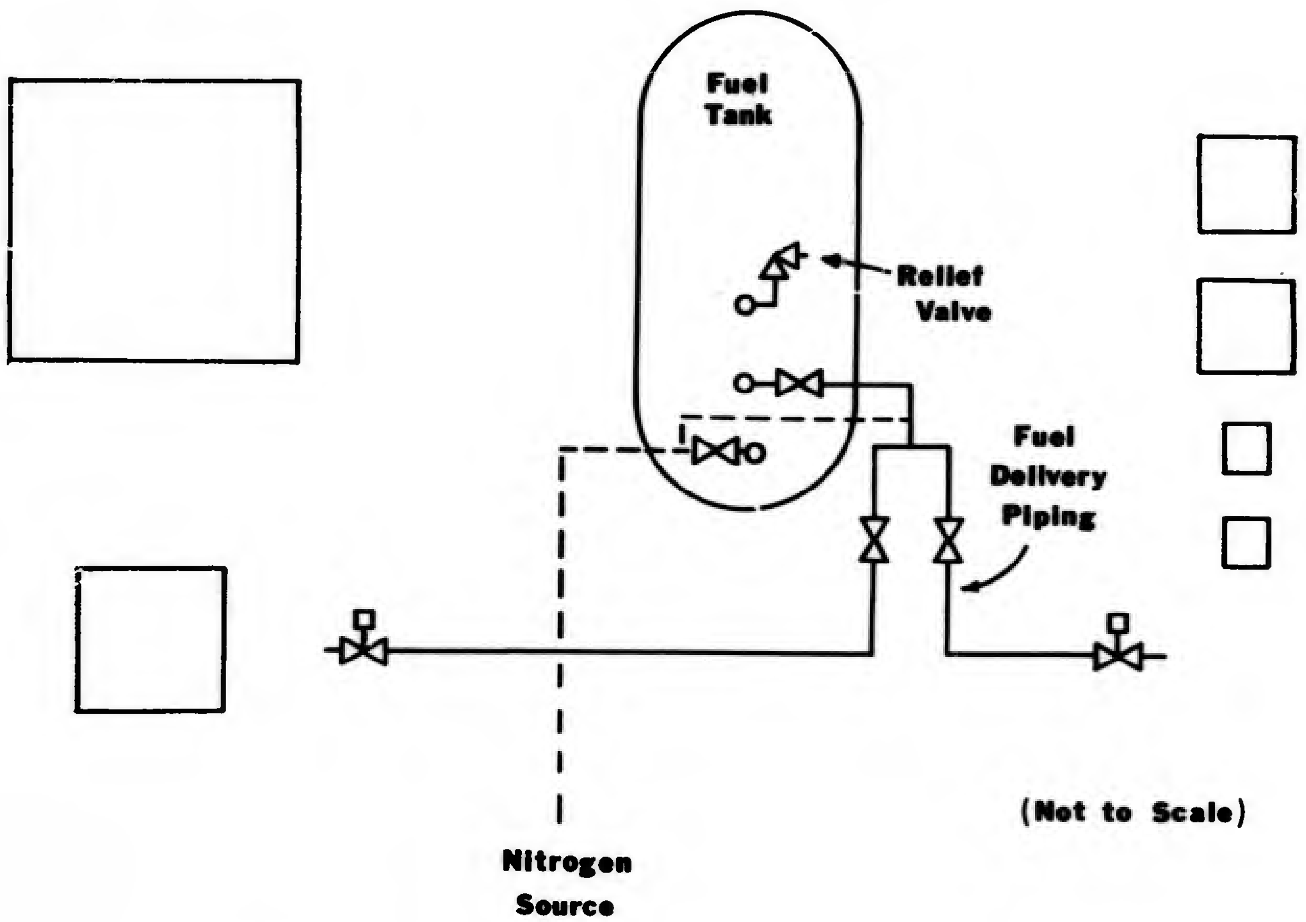


FIGURE 4. SCHEMATIC OF FUEL DELIVERY SYSTEM.

When refilling the tank, it is necessary to vent the tank. This is done by allowing vapors within the tank to flow through a hose to a safe venting location (location depends on wind conditions). Due to the nitrogen atmosphere being maintained in the tank, no flammable mixture can occur in the tank.

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 premixing of foam concentrate and water for most of the tests and also allows for direct injection of foam concentrate into the water stream if required for the larger tests.

The overall foam system is shown in Figure 5. For those tests requiring foam solution flow rates up to 10 gpm, the system works as follows. Foam concentrate is dumped by hand into the premix tank and is mixed with a quantity of water drawn from the water storage tank. This solution is pumped into the 500-gal holding tank using pump P1. Additional water required to give the correct concentration ratio is added to the tank in the same manner. Pump P2 is then used to circulate and thoroughly mix the solution in the tank by drawing off solution from the bottom connection and reinjecting it through the side connection. After about

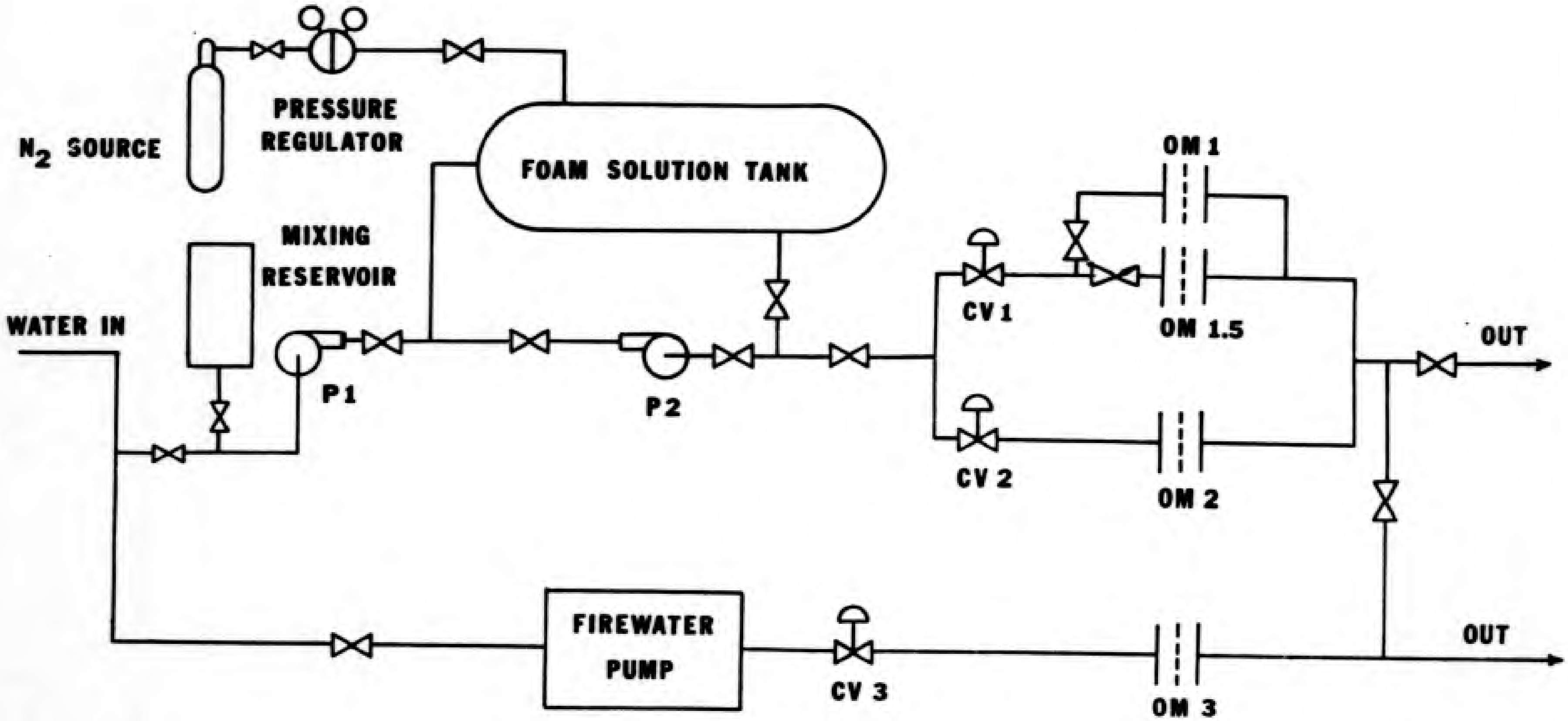


FIGURE 5. SCHEMATIC OF FOAM DELIVERY SYSTEM.

10 minutes of recirculation, the pump is shut off, the valves are closed, and the tank is pressurized to the desired pressure with nitrogen from high pressure cylinders.

During a test, the solution is forced out of the tank by nitrogen pressure, flows through the automatic control valve CV1, through the orifice meter OM1, through underground PVC piping to the pipe riser near the instrumentation junction box. It then flows through a hose, aboveground, to the foam nozzle(s) or generator(s). The pressure at the entrance to the foam making device is monitored by a pressure transducer. The output from this transducer is used to set the control valve, CV1, so that the foam solution is supplied to the foam maker(s) at the proper pressure.

Tests requiring foam solution flow rates between 10 and 40 gpm are done in a similar fashion but use the next larger orifice meter, OM1.5. For flow rates from 40 to 150 gpm, the 1000-gal holding tank, the 2-inch control valve, CV2, and 2-inch orifice meter, OM2, are used. It is also possible to use both holding tanks simultaneously in order to provide up to 10-minutes supply of foam at the highest flow rates (150 gpm).

For those tests requiring foam solution flow rates in excess of 150 gpm, a 500-gpm gasoline engine powered water pump is used to supply the necessary water under pressure. Foam concentrate is pumped into the 500-gal holding tank before the test. During the test the concentrate is forced out of the tank by nitrogen pressure, flows through the 1-inch control valve, CV1, and either the 1- or 1 1/2-inch orifice meter as required. The foam concentrate is then injected into the waterline downstream from the water pump. The water flow rate is adjusted by a 3-inch automatic control valve, CV3, and metered by a 3-inch orifice meter, OM3, to provide the proper flow rate. The control valve CV3 is controlled by a pressure transducer that monitors the foam solution pressure at the entrance to the foam maker(s). The control valve for the foam concentrate, CV1, is controlled manually to provide the proper concentrate flow rate.

Nitrogen Distribution System

The nitrogen system, as shown in Figure 6, provides dry nitrogen for transferring foam and fuel, and for the fuel tank liquid level (bubbler) system. Nitrogen is supplied from 32 standard "T" bottles of pressurized nitrogen. Each bottle contains about 300 standard cubic feet of gas for a total capacity of 9600 scf. The bottles are mounted to a manifold in a trailer which can be moved for refilling when necessary. High pressure nitrogen from the trailer manifold is reduced to the pressure required by the foam delivery system by a Victor Model SME 700 regulator. Further nitrogen pressure regulation for the fuel tank pressurization and fuel tank bubbler system is provided by 0 to 125 psi standard air regulators. The nitrogen supply is large enough to provide fuel delivery and foam pressurization for a 40-ft by 40-ft fire test.

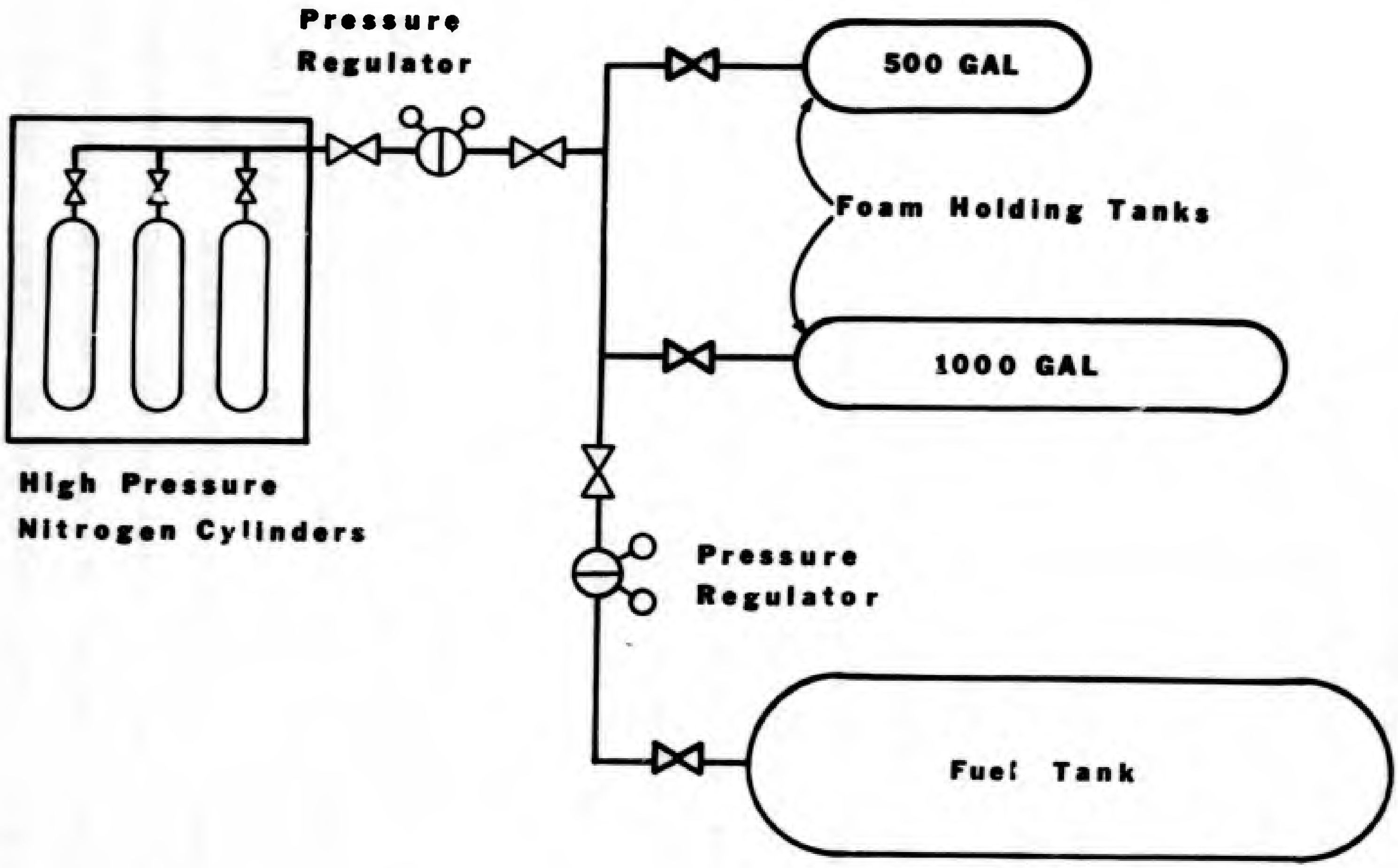


FIGURE 6. SCHEMATIC OF SYSTEM FOR SUPPLYING NITROGEN TO FOAM AND FUEL TANKS.

Foam Generators

Two types of low expansion foam nozzles were used. The 2-gpm and 6-gpm nozzles are test nozzles (i.e., not intended for actual fire protection systems). The larger capacity nozzles (10 to 120 gpm) are "tank side nozzles" (i.e., they are intended to be used inside of 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 7).

The high expansion foam generators, shown in Figure 8, produce foam by spraying the foam solution onto a metal screen while simultaneously blowing air through the screen. These generators all included 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 were used 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

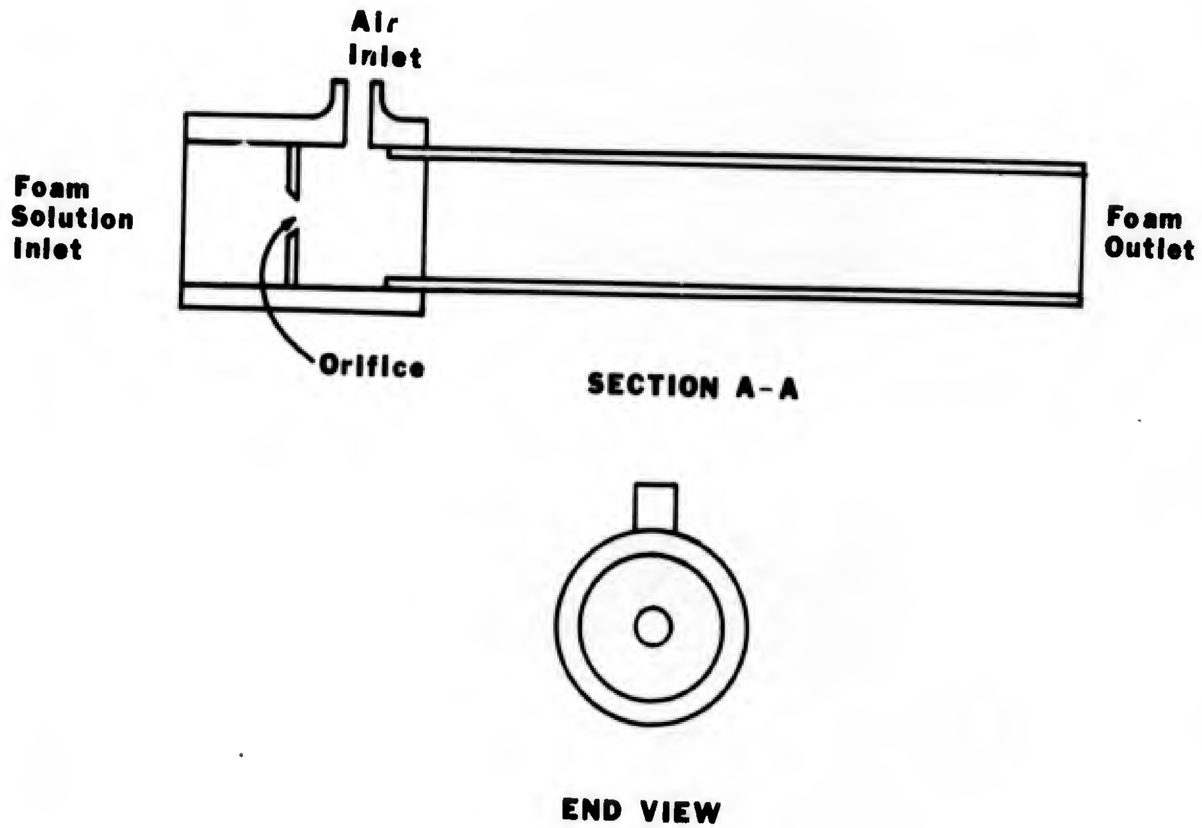


FIGURE 7. DESıGN OF TANK SIDE LOW EXPANSION FOAM NOZZLES.

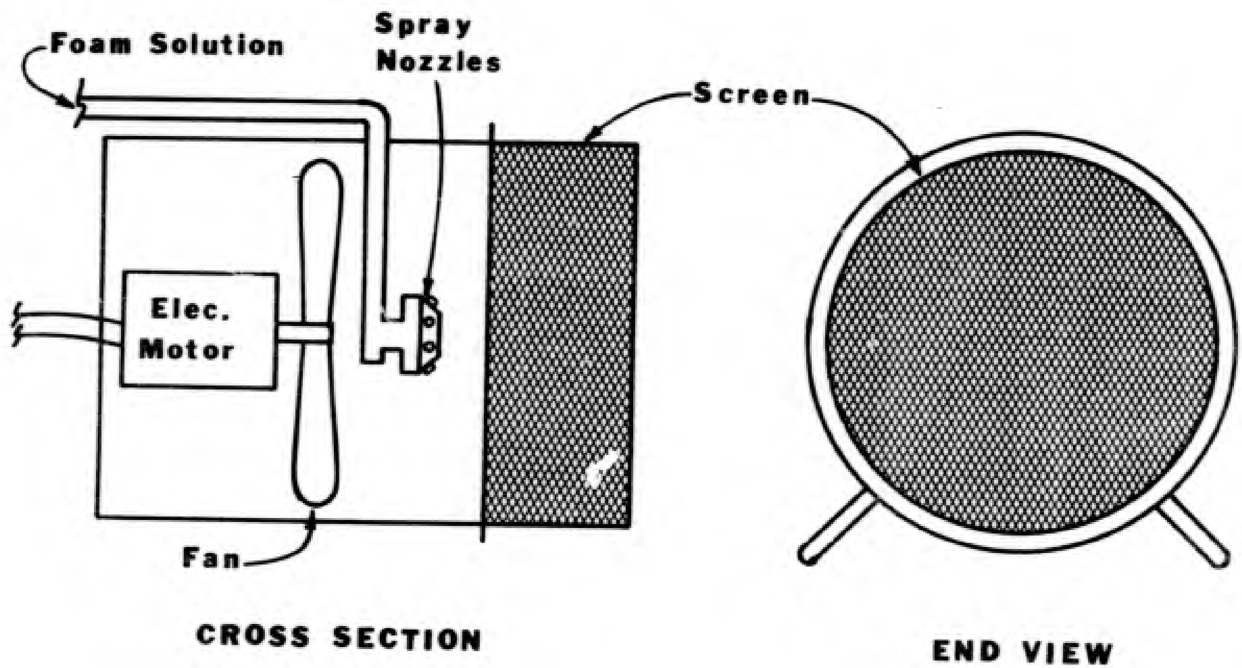


FIGURE 8. DESIGN OF HIGH EXPANSION FOAM GENERATORS.

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 combination of flexible hoses and steel pipes. A schematic diagram of a dry chemical system is shown in Figure 9.

Two basic types of nozzles were used in the dry chemical extinguishment tests. The first type that was tried is a non-proprietary nozzle intended mainly for water service. These nozzles, shown in Figure 10a, produce a flat, fan-shaped spray pattern approximating a 70-80° segment of a circle.

The second type of nozzle incorporates a narrow slit through which the powder is dispersed into a flat, fan-shaped spray approximating a 180° segment of a circle. As shown in Figure 10b, one variation of this nozzle type discharges in the direction of the axis of the nozzle body. During the testing, this style was quickly abandoned in favor of the nozzles that discharge the powder perpendicular to the nozzle axis (Figure 10c and 10d).

Instrumentation and Control

Obtaining the necessary test data and providing adequate control of certain variable test parameters requires a

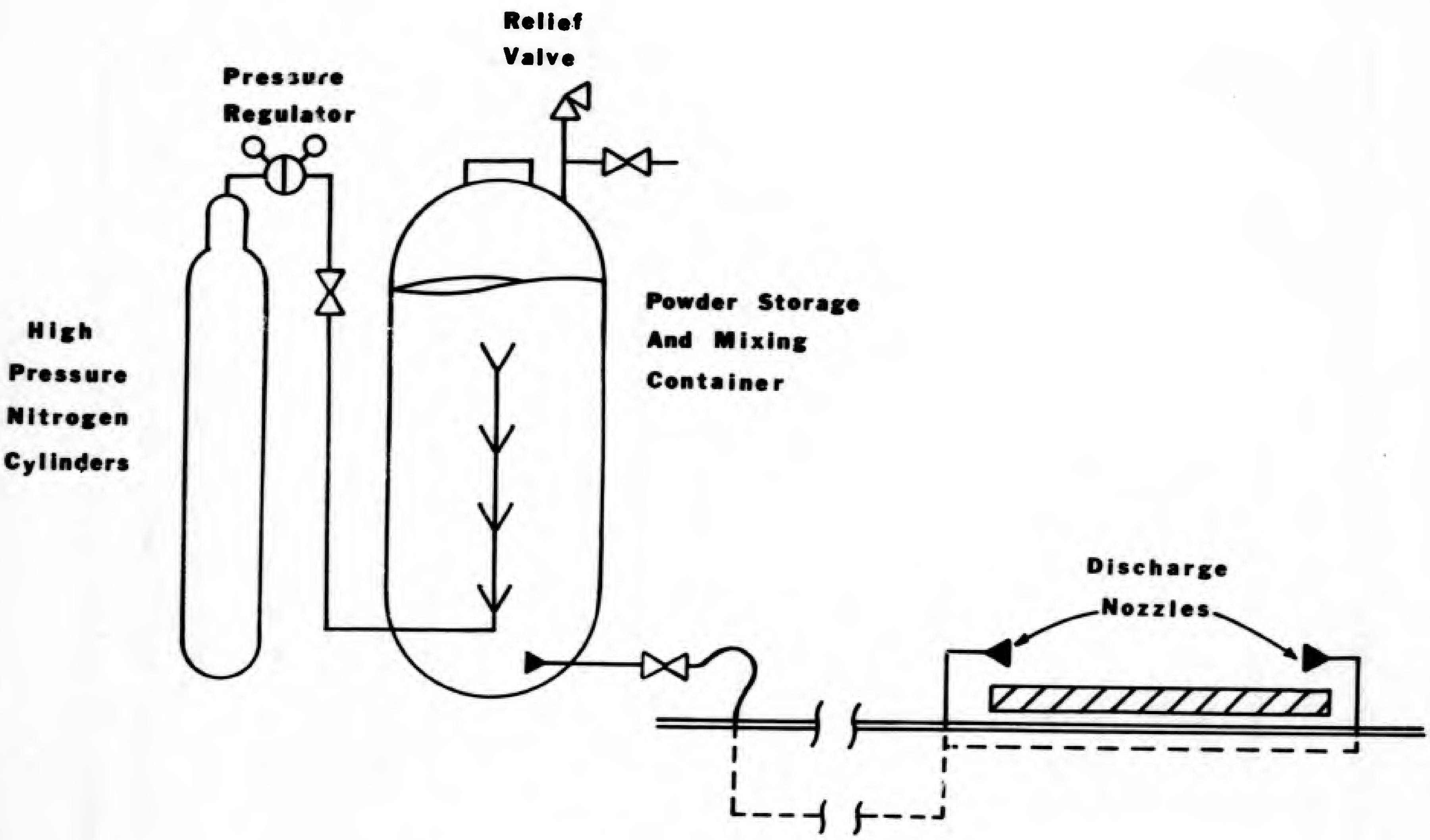


FIGURE 9. SCHEMATIC OF THE DRY CHEMICAL DELIVERY SYSTEM.

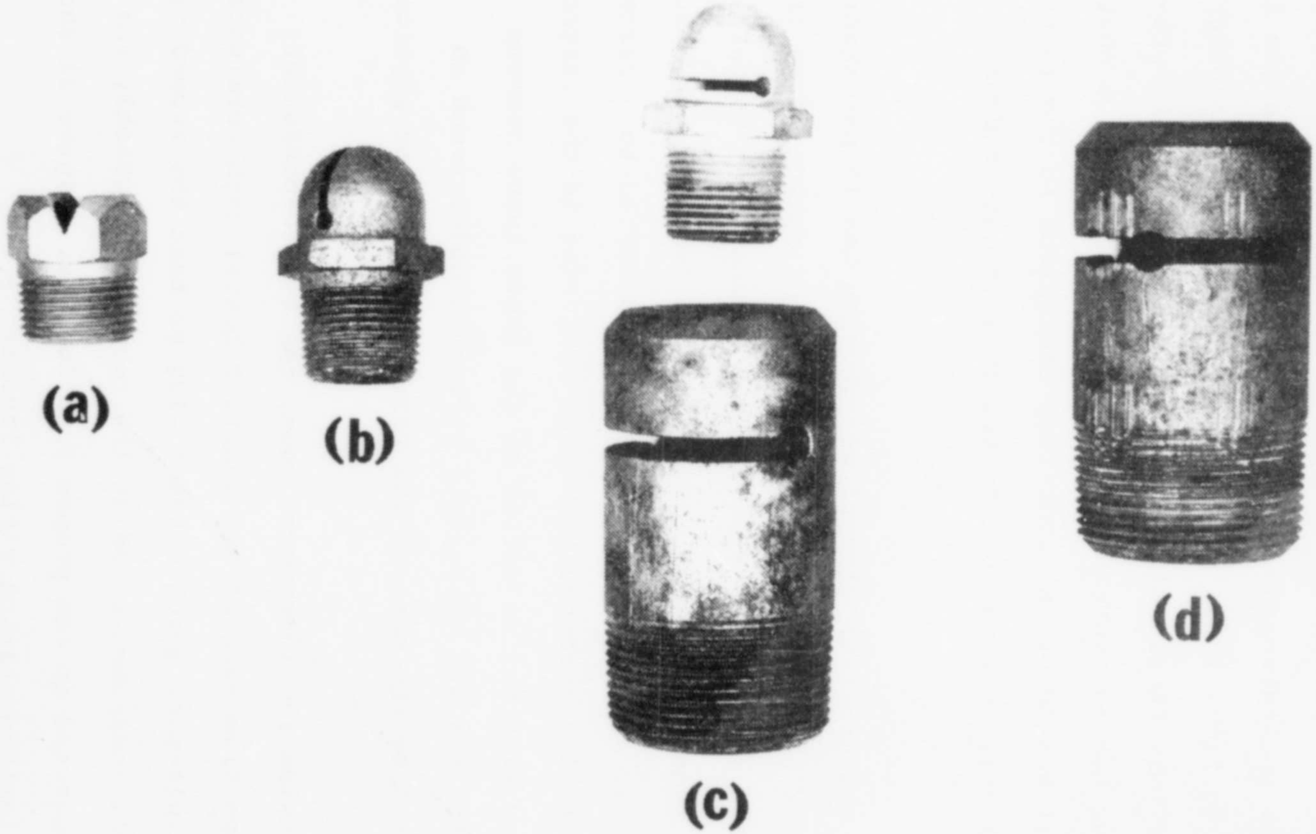


FIGURE 10. PHOTOGRAPH OF DRY CHEMICAL DISCHARGE NOZZLES.

wide range of test and control instruments. The entire test instrumentation package must also be flexible enough to allow for changes in instrument locations called for by changes in fire pit location, local weather conditions, etc. 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

A weatherproof electrical junction box is permanently mounted near each group of pits. Input and output wires from the moveable instruments (i.e., those located near the pit in use), are temporarily laid to the closest junction box. Inside the box, the instrument wires are connected to a permanently installed 30-conductor cable that runs to the instrument room. With the exception of the short space between the junction box and grade, all wiring is underground to protect it from the heat of the fire and from other physical damage.

Inside the instrument room, the two 30-conductor cables (one from each of two junction boxes) each terminate in a multiple-pin, quick-connect plug so that the recording and control instruments inside the room can be quickly and easily connected to the proper junction box. Figure 11 shows the main instrumentation wiring layout.

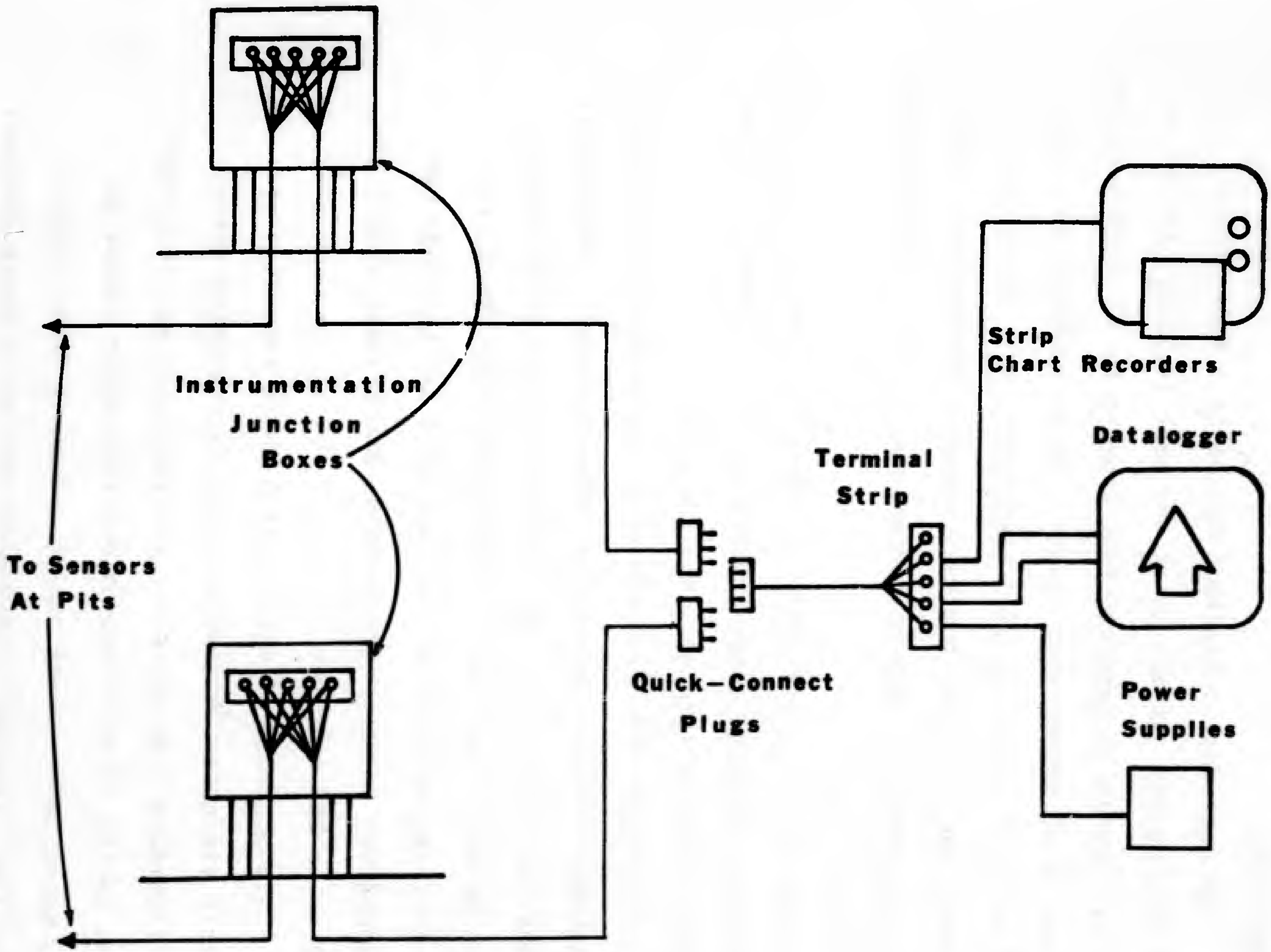


FIGURE 11. SCHEMATIC OF DATA COLLECTION AND RECORDING SYSTEM.

Data Recording

The main data collection device is a Fluke Model 2240 B datalogger. As set up at the test facility, the datalogger is capable of handling data from up to 40 input sources at a rate of 15 sources per second. Input voltages can range from 4 mv to 40 v full scale. Resolution is $\pm$ .001 mv on a 4-mv range and $\pm$ 1 mv on the 40-v range. Thermocouple inputs can be converted directly to temperature units if thermocouple lead wire is used.

During a typical test, 15 channels of data are scanned; the scanning sequence takes approximately 1.8 seconds due to the speed of the datalogger tape recorder.

Digitized data from the Fluke datalogger are recorded on a Kennedy 1600/360 incremental tape recorder. The Kennedy 1600/360 is a nine track, odd parity recorder which stores data on magnetic tape that is IBM compatible. Thus, the tapes that are recorded at the test site can be read, the data converted to engineering units, and printed output obtained on an IBM computer.

Six channels of analog strip chart recording are available via three Omniscribe Model 5217 two-pen strip chart recorders. As equipped, the recorders are very versatile, having 18 chart speeds and full scale inputs of from 1 mv to 10 v. These analog recorders were selected because their feedback transducers (pen positioning devices) operate without directly contacting any other recorder parts. Therefore, they are very rugged and relatively immune to dust and dirt.

For those instruments that require an input voltage, regulated DC voltage can be provided by 0-20- and 0-40-v Lambda Model LL power supplies. These power supplies provide line regulation within 0.01% plus 1 mv and load regulation within 4 mv. Ripple and noise are within 0.250 mv rms. The power supplies have adjustable current limiters. With the use of appropriate zener diodes, voltages can be limited to well defined maximums, thereby affording excellent overvoltage protection.

Wind Speed and Direction

Wind speed and wind direction are monitored using a Weathertronics Micro Response Wind System. The system consists of a micro response wind vane and micro response anemometer located 10 ft above grade east of the concrete building, and wind speed and wind direction translators located in the instrument room. As installed, the anemometer has a usable range of 0.5 to 100 mph and an accuracy of ± 1% ± 0.15 mph. The wind vane has an accuracy of 2 degrees and the threshold wind speed of 0.5 mph. The translators serve as power supplies, signal conditioners, and calibrators for the micro response instruments. Outputs from the translators are 0-1-volt signals that are directly proportional to the wind speed and wind direction.

Foam System Control

The foam generators are calibrated to give the desired flow rate at a certain foam solution inlet pressure. Therefore, one method of controlling the foam solution flow rate is to use an automatic valve to throttle the flow so that the inlet pressure to the foam generator is the same as that used during calibration. This is done as shown in Figure 12. A Setra 0-250-psig pressure transducer (Model 205) is used to monitor the foam solution inlet pressure to the foam generator. The transducer is connected to the foam generator inlet with 0.25-inch tubing. The tubing and transducer are both covered with earth before each test to protect them from the heat of the fire. Connections are available at the transducer that enable it to be calibrated in-situ. The output from this transducer is converted to a pneumatic signal by a Foxboro voltage to pneumatic converter (Model 33B). The pneumatic signal is the input to a Honeywell Pneumatic Tel-O-Set, two-pen, recorder/controller which in turn controls the pneumatically operated flow control valve.

Foam Flow Rate

The foam flow rate is controlled as previously described. However, 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 monitored by a Honeywell pneumatic differential

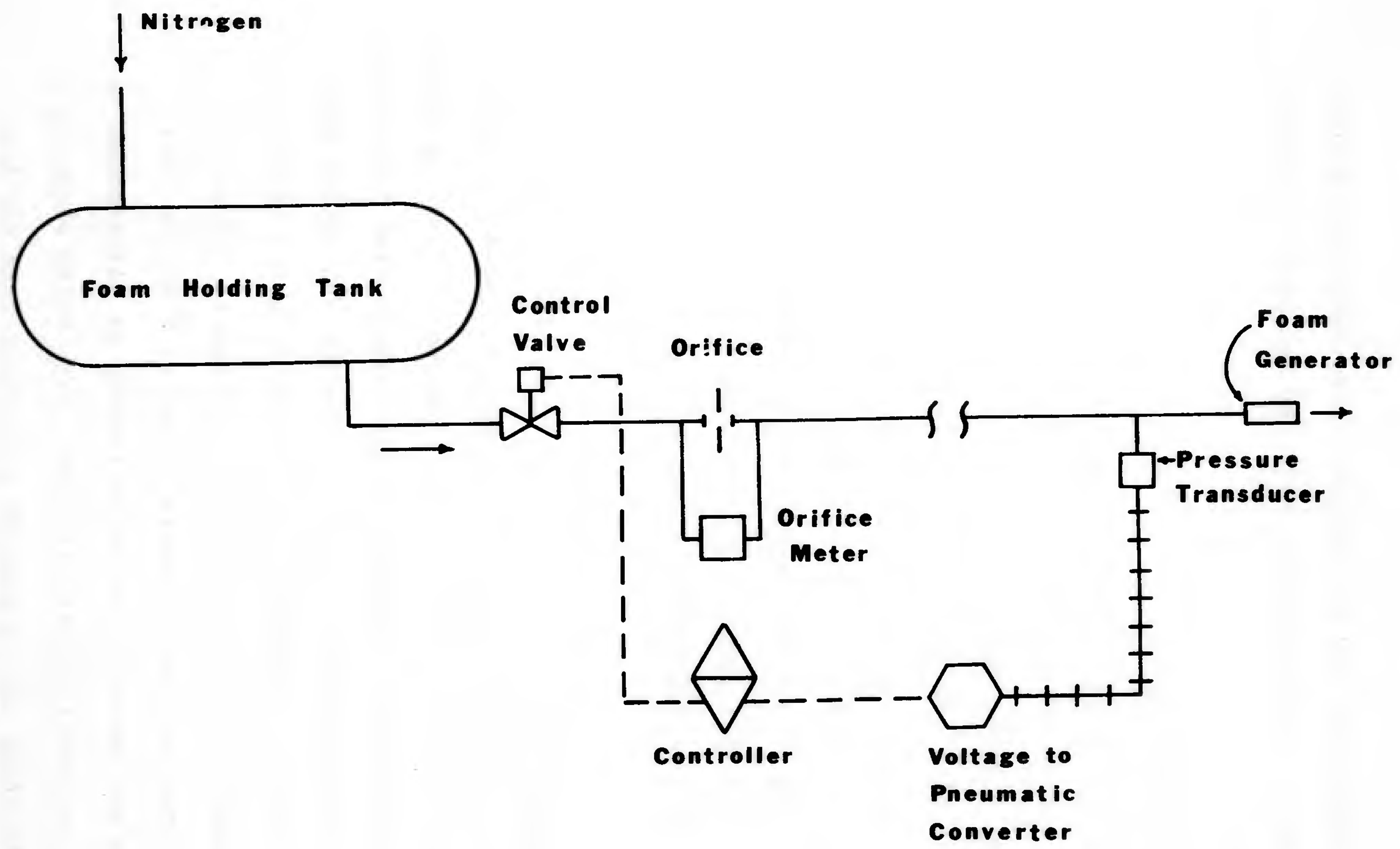


FIGURE 12. SCHEMATIC OF THE FOAM CONTROL SYSTEM.

pressure transmitter and its output is recorded by a noncontrolling pen on the previously mentioned Honeywell recorder/controllers.

Temperature Measurement

Chromel-alumel thermocouples are available to measure the upwind and downwind metal sleeve temperatures, obstruction temperature, and the fuel temperature. The EMF signals from the thermocouples are transmitted via copper wiring to the control room. A thermocouple utilizing chromel-alumel lead wires is placed at the copper wire/thermocouple wire junction (located underground a few feet from the pit) to obtain the reference junction temperature. The sleeve and obstruction thermocouples are "strapped" to the metal parts by metal strips.

Heat Flux Measurement

Two Medtherm wide angle radiometers (150-degree view angle) and two Hy-Cal narrow angle radiometers (7-degree view angle) are available for measuring the radiant heat flux from the fires. The radiometers are water cooled and employ sapphire or calcium fluoride windows so that only the radiant flux is measured. The narrow angle radiometers (shown in Figure 13) were mounted on simple tripods. The wide angle radiometers are housed in portable stands, as illustrated in Figure 14, to facilitate re-alignment after being moved to a different location and to provide protection from the heat of the fire.

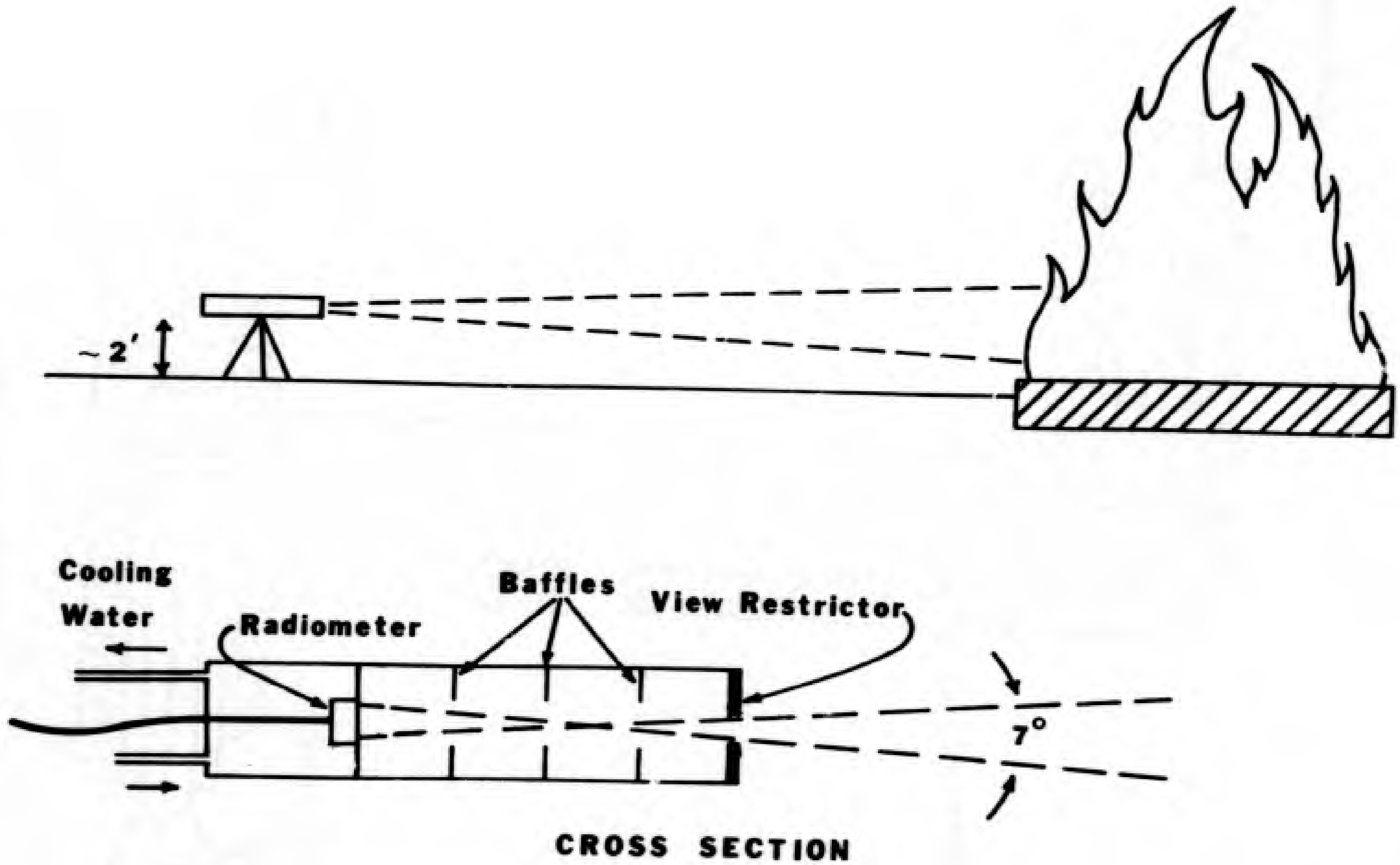


FIGURE 13. NARROW ANGLE RADIOMETER AND TYPICAL AIMING POINT AT OPTICALLY THICK FIRE AREA.

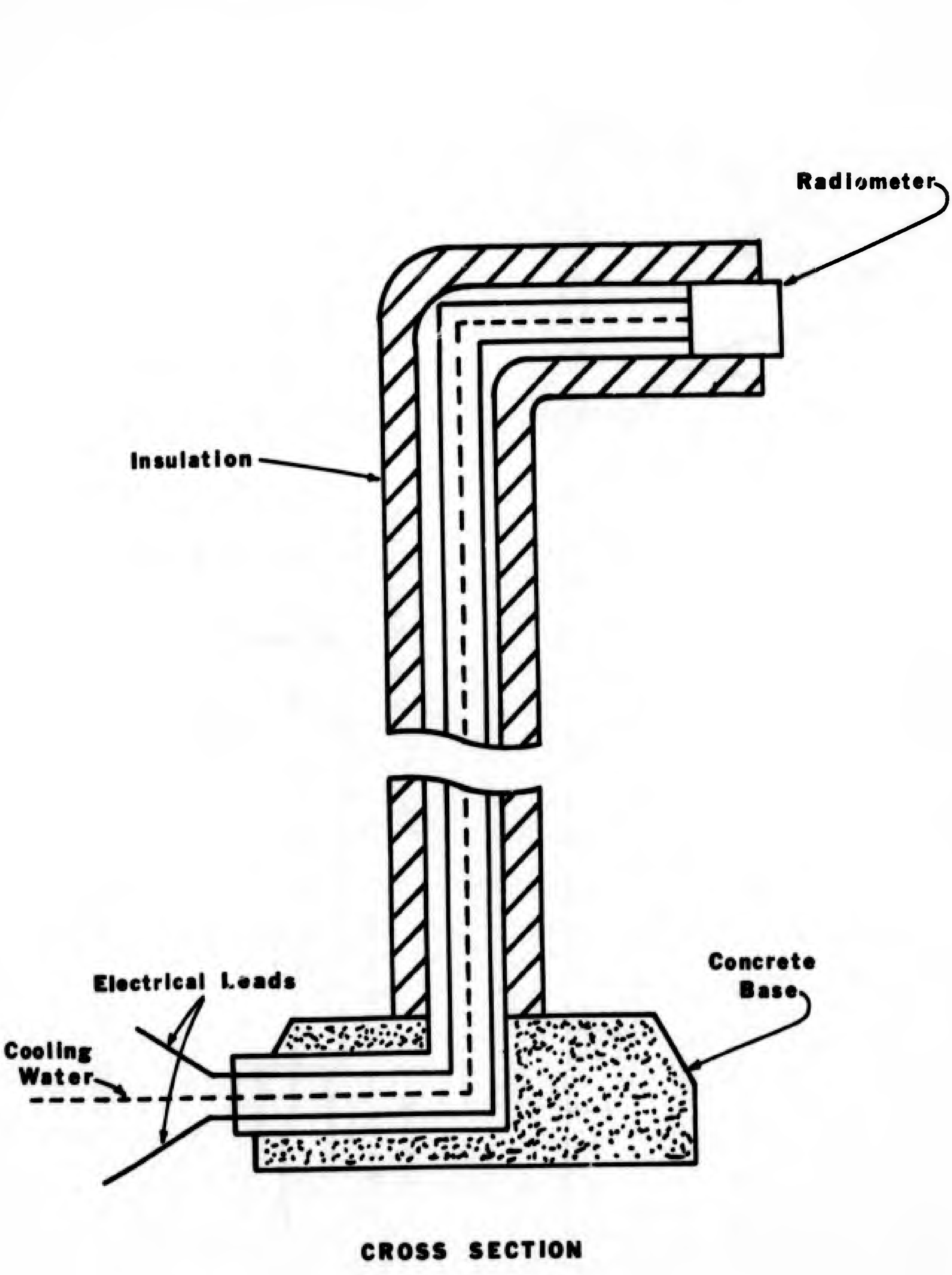


FIGURE 14. DESIGN OF PORTABLE STAND FOR WIDE ANGLE RADIOMETERS.

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 usually located on top of the instrument building. It incorporates a telescopic sight to aid in properly orienting it toward the fire.

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 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. The system, shown in Figure 15, consists of a small tank containing pressurized dry nitrogen; a pressure regulator and a throttling valve for controlling the flow of nitrogen; a reservoir/restriction combination to smooth out pressure fluctuations caused by bubble separation; a small tube (the end of which is held firmly at a fixed location near the bottom of the pit) through which the nitrogen is bubbled; and a Setra 0-0.5 psid pressure transducer (Model 236) to measure the nitrogen pressure. Once calibrated, this system allows accurate measurement of changes in liquid level.

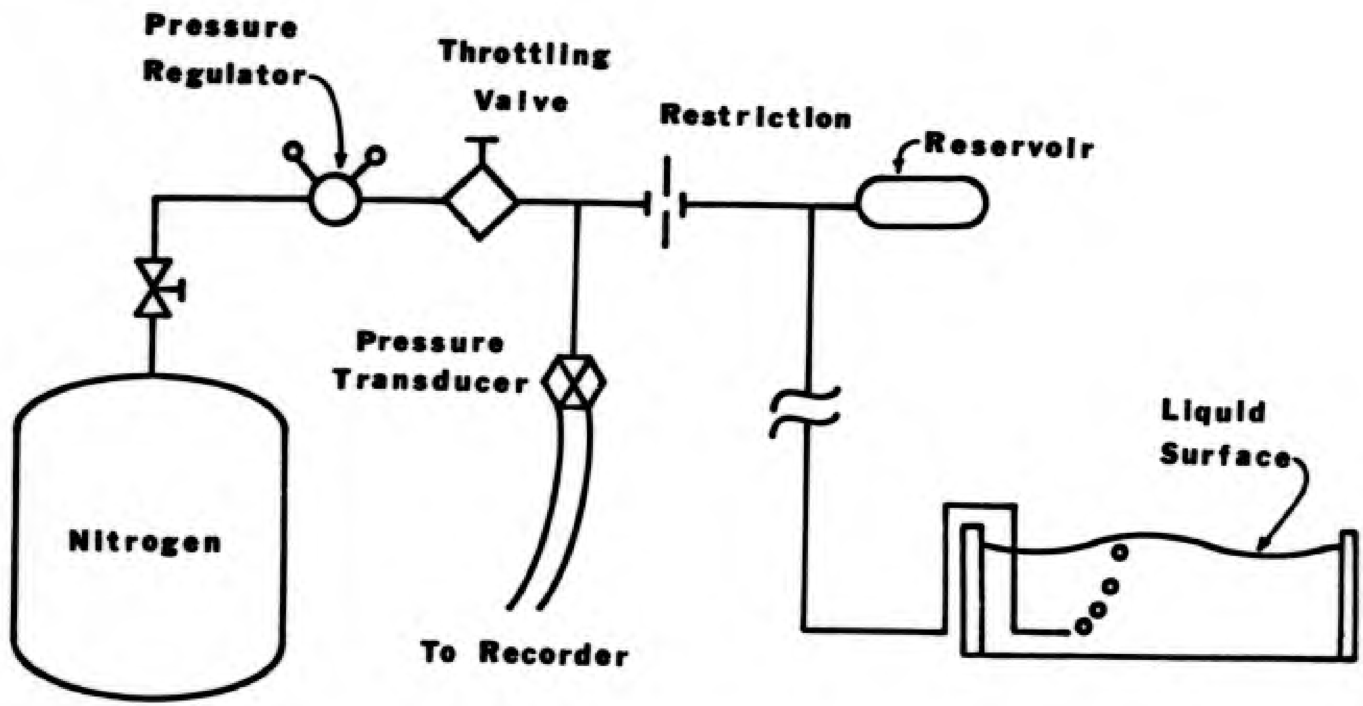


FIGURE 15. SCHEMATIC OF LIQUID-DEPTH SENSING SYSTEM FOR FIRE PITS.

Dry Chemical Flow Rate 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 Statham UC-3 universal transducing cell (with load cell accessory) 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 (see Figure 16). 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. Each time a unit is loaded with dry chemical, the weighing system is also calibrated.

Dry Chemical Nozzle Pressure

The pressure at the dry chemical nozzles is measured with a Setra 0-250-psig pressure transducer (Model 205), as shown in Figure 17. The arrangement is basically the same as used for measuring foam generator inlet pressure except that a sintered metal filter is used in the line between the nozzle and the transducer to prevent dry chemical powder from entering the transducer. During in-situ calibration, the connecting tubing can be blown free of obstructions.

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 tests. The 16-mm camera is a Bell and

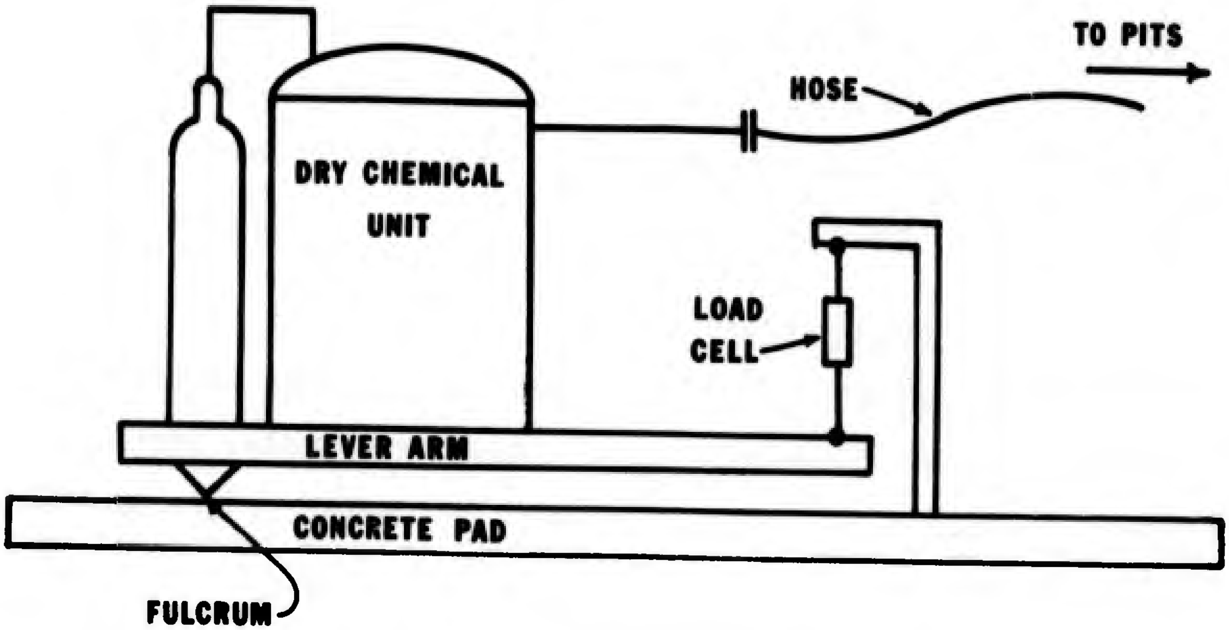


FIGURE 16. DRY CHEMICAL UNIT WEIGHING SYSTEM TO OBTAIN FLOW RATE DATA.

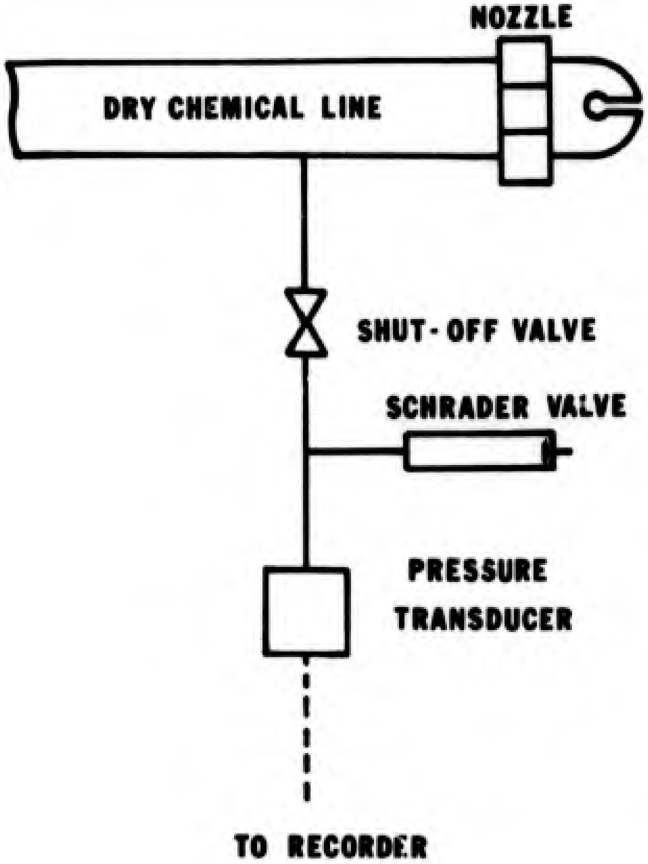


FIGURE 17. DRY CHEMICAL NOZZLE PRESSURE MONITORING SYSTEM.

Howell Model 70 HR equipped with a 110-volt motor drive and 400-foot film magazine. It is fitted with a Berthiot zoom lens with a 17- to 70-mm focal length. A close-up lens and digital watch have been adapted so that the time of day can be superimposed in one quadrant of the camera frame to allow synchronization of film and data from other sources for analysis. An in-line switch is used so that the camera can be started and stopped from the instrument room.

Video coverage is available through use of a Panasonic Model WV-3700 EN color video camera and a Panasonic Model PV-1000A video tape recorder. The camera is equipped with an extra long cable so that it can be remotely positioned (the recorder and camera control unit remain in the instrument room). A Vi-on Instruments Model V240T time generator is used to place date and time of day information on the video tape. A small color television is used to monitor the video recording.

A Canon AT-1 35-mm SLR camera equipped with a motor winder and 35-90-mm zoom lens is used for still photography. The camera is equipped with a pneumatic shutter release which allows remote operation (up to 250 ft) from the instrument room.

TYPICAL FOAM FIRE EXTINGUISHMENT SETUP AND TEST PROCEDURE

The experimental equipment used to perform a fire extinguishment test utilizing foam (either low expansion or high expansion) consists of the following equipment:

- a pressurized foam delivery system
- orifice meters, transmitters, and pneumatic recorders to measure, control, and record foam solution flow rates
- foam generator(s)
- narrow angle and wide angle radiometers to measure fire radiation flux
- liquid level sensor to measure fuel burning rate
- pressure transducer to measure foam nozzle pressure
- thermocouples to measure pit wall and obstruction temperatures
- 16-mm, 35-mm, and color video cameras to record the test
- wind speed and wind direction measuring instruments
- fuel delivery system
- data recording system

The radiometers, liquid level system, cameras, and thermocouples are placed as shown in Figure 18. The wind speed and direction sensors are permanently installed so no additional setup is required for them. The desired foam generator(s) is connected to the foam solution piping (using

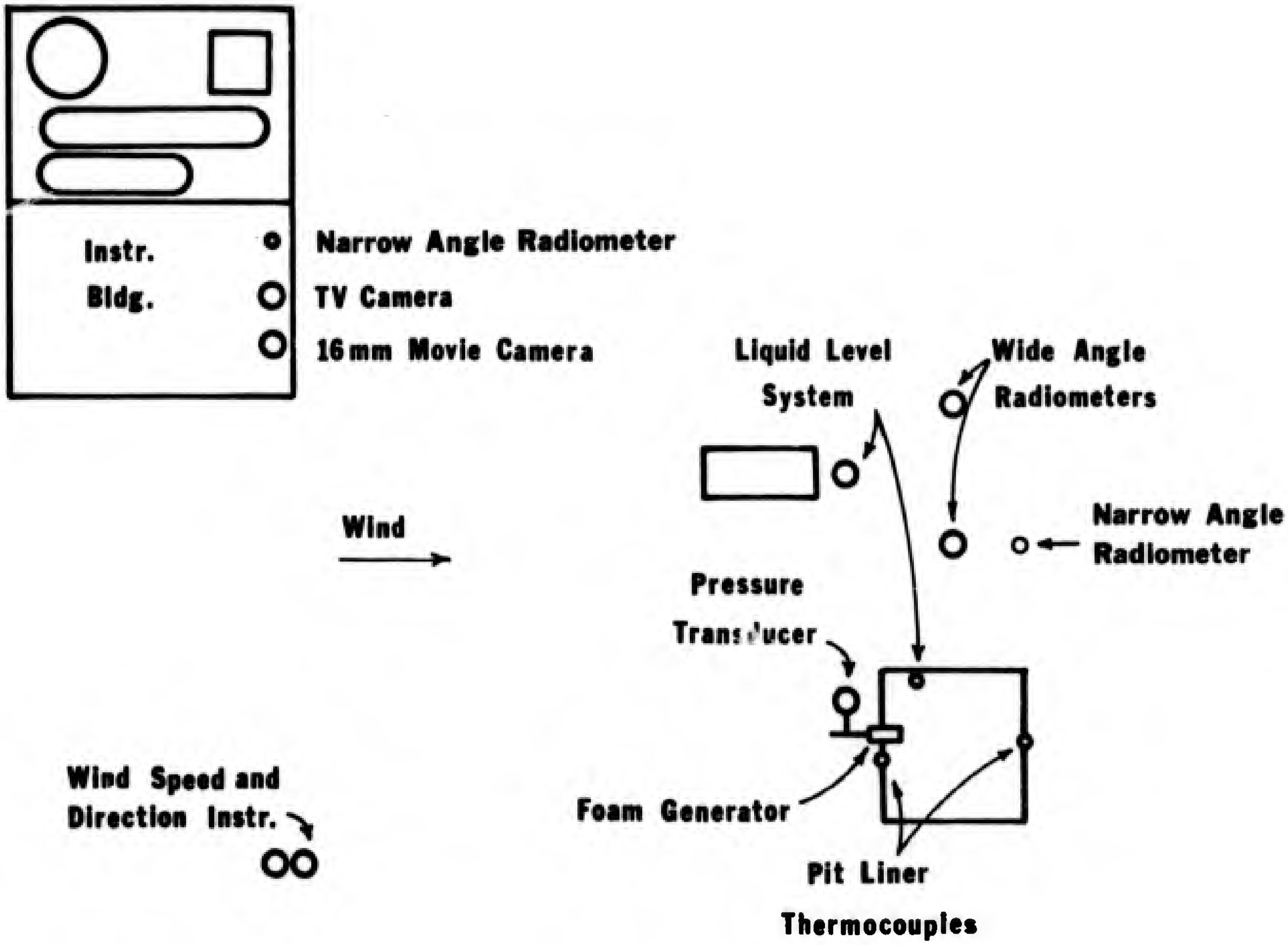


FIGURE 18. EQUIPMENT PLACEMENT FOR TYPICAL FOAM TEST.

1.5-inch fire hose) and is placed on the upwind side of the pit. Low expansion nozzles are located at the center of the upwind side, as shown in Figure 19, and are equipped with a curved metal deflector to prevent the foam from plunging into the fuel. High expansion foam generators are either placed in a similar location or are placed about 10 ft back from the pit (to protect them from the heat), in which case foam chutes are used to direct the foam from the generator to the edge of the pit (see Figure 20).

Once all cameras, foam generators, sensing instruments, etc. are properly positioned, the necessary electrical connections are made to the nearest junction box, the water lines for the radiometers are connected, the data recording devices are turned on, and the foam generator inlet pressure transducer is calibrated. All exposed hoses, tubing, electrical lines, etc. near the pit are then buried.

Prior to the start of a foam extinguishment test, the following preliminary operations are performed:

- all instrumentation turned on and allowed to warm up
- clocks on the datalogger, movie camera, and video recorder synchronized
- foam solution mixed and placed in the appropriate holding tank (or tanks)
- test titles filmed on motion picture and video tape
- radiometer cooling water turned on
- obstructions (if used) are placed in the pit

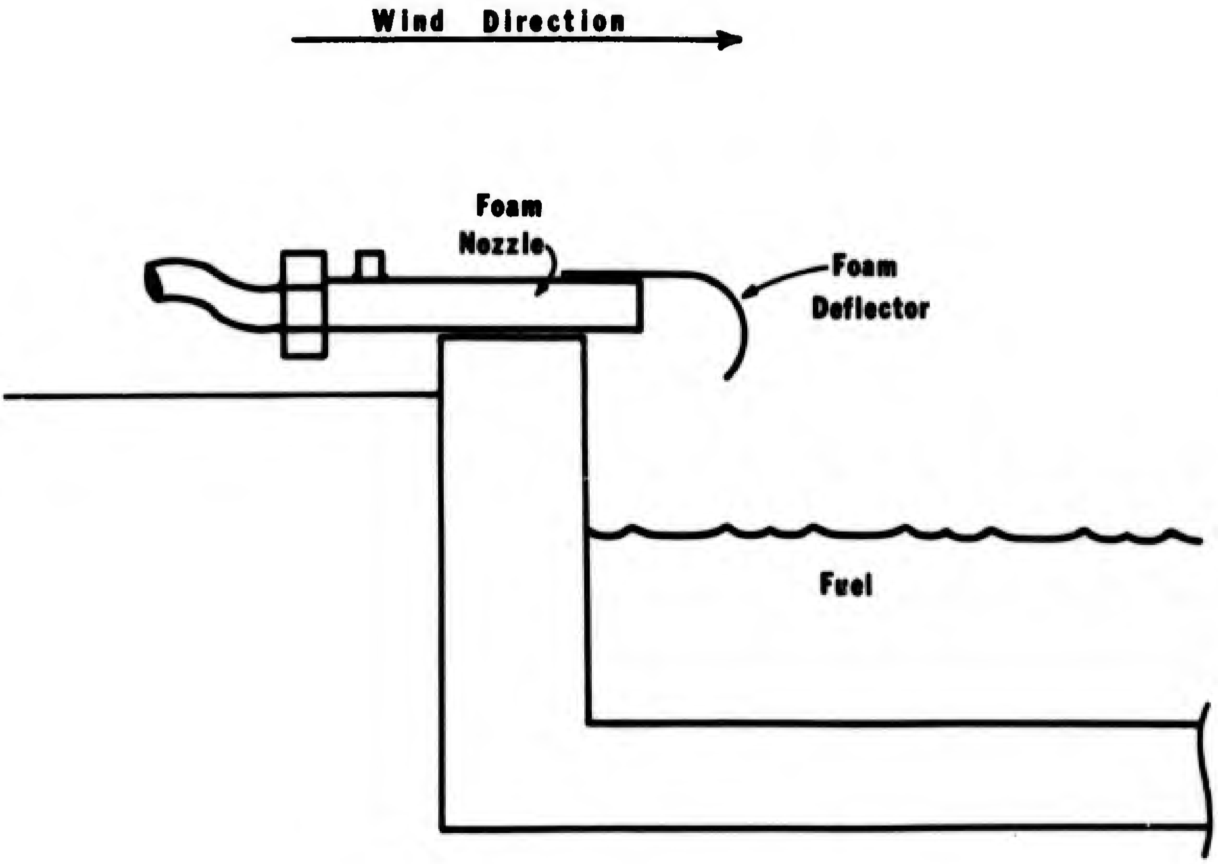


FIGURE 19. CROSS SECTION OF PIT SHOWING PLACEMENT OF LOW EXPANSION FOAM NOZZLE AND DEFLECTOR.

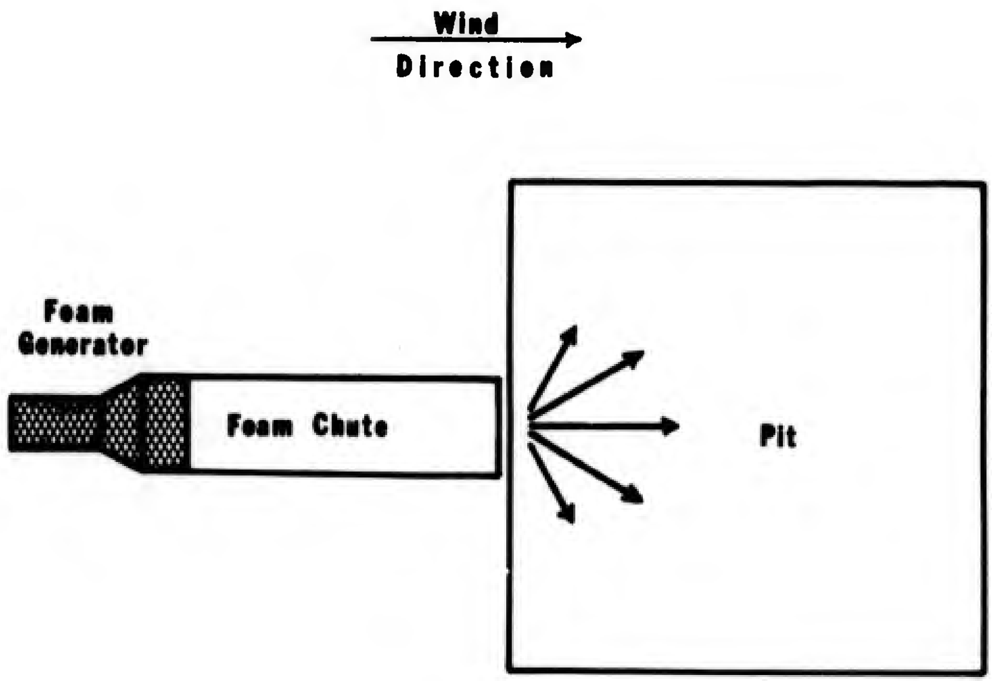


FIGURE 20. PLAN VIEW OF PIT SHOWING PLACEMENT OF HIGH EXPANSION FOAM GENERATOR AND FOAM CHUTE.

- liquid level system nitrogen flow turned on

- appropriate valving opened to route the foam solution through the desired control valve and orifice meter

- water added to pit (if necessary) (This step is omitted if there is reason to believe that the water will react with the fuel or otherwise hinder the test.)

- desired amount of fuel added to the pit

- fuel line blown clear of liquid and moved a safe distance away

- fuel depth above bubbler location measured manually (This step can be omitted if the liquid level system is calibrated prior to the test.)

- zero (i.e., beginning) readings taken on all sensing instruments

- foam solution piping prefilled with solution

Fuel is ignited after all data recording devices are started. After ignition, the fuel is allowed to burn for approximately 8-10 minutes or until steady state temperature in the metal liner is reached. Personnel with stop watches are then dispatched to areas near the burning pit. The motion picture camera and video recorder are turned on. The foam solution flow is started and the foam generator inlet pressure manually brought up to the desired value. As soon as the correct pressure is achieved (usually < 10 sec), the pressure controller is placed on automatic. Foam delivery is continued until extinguishment or until the pit is filled with foam. At the end of the test, foam production is stopped and recorders and cameras are shut off.

If sufficient fuel remains in the pit, it is cleared of foam and readied for the next test. When the same type foam solution is used for several consecutive tests, the only change necessary is to change the foam generator(s). If a different foam solution is to be used, the foam tank and delivery lines are flushed several times with water and new foam solution made up. After prefilling the delivery lines, the next test can be started and carried out as previously described.

If the fuel level is insufficient for another test, the pit is allowed to cool. Additional fuel is then added to the pit and preparations for the next test proceed as before.

TYPICAL DRY CHEMICAL FIRE EXTINGUISHMENT

SETUP AND TEST PROCEDURE

The experimental equipment used to perform a fire extinguishment test utilizing dry chemical powder consists of the following equipment:

- dry chemical fire extinguisher of 150, 350, or 2,000 lb capacity
- dry chemical unit weight measuring apparatus
- dry chemical nozzles and distribution piping system
- narrow and wide angle radiometers to measure fire radiation flux
- liquid level sensor to measure fuel burning rate
- pressure transmitter to measure dry chemical nozzle pressure
- thermocouples to measure pit wall and obstruction temperatures
- 16-mm, 35-mm, and color video cameras to record the test
- wind speed and wind direction measuring instruments
- fuel delivery system
- data recording system

The operation of most of these systems has been discussed previously and will not be repeated here. The discussion will be limited to the dry chemical distribution system, the location of the sensors, and the sequence of events.

The dry chemical distribution system consists of a fixed piping system designed to divide the total dry chemical flow stream into a number of smaller streams with equal flow rates; a set of 2 or 4 identical nozzles for dispensing the dry chemical into the fire; and a flexible hose for connecting the dry chemical unit to the fixed pipe system. One distribution system configuration is shown in Figure 21. Other configurations that can be used are discussed in Appendix C.

The radiometers, liquid level system, cameras, and thermocouples are placed in the same locations as they are for foam tests (see Figure 18). The wind speed and direction sensors are permanently installed so no additional setup is required for them.

Once all cameras, sensing instruments, etc. are properly positioned, the necessary electrical connections are made to the nearest junction box, the water lines for the radiometers are connected, the data recording devices are turned on, and the dry chemical nozzle inlet pressure transducer is calibrated. All exposed hoses, tubing, electrical lines, etc. near the pit are then buried.

Prior to the start of a dry chemical extinguishment test, the following preliminary operations are performed:

- all instrumentation turned on and allowed to warm up
- clocks on the datalogger, movie camera, and video recorder synchronized

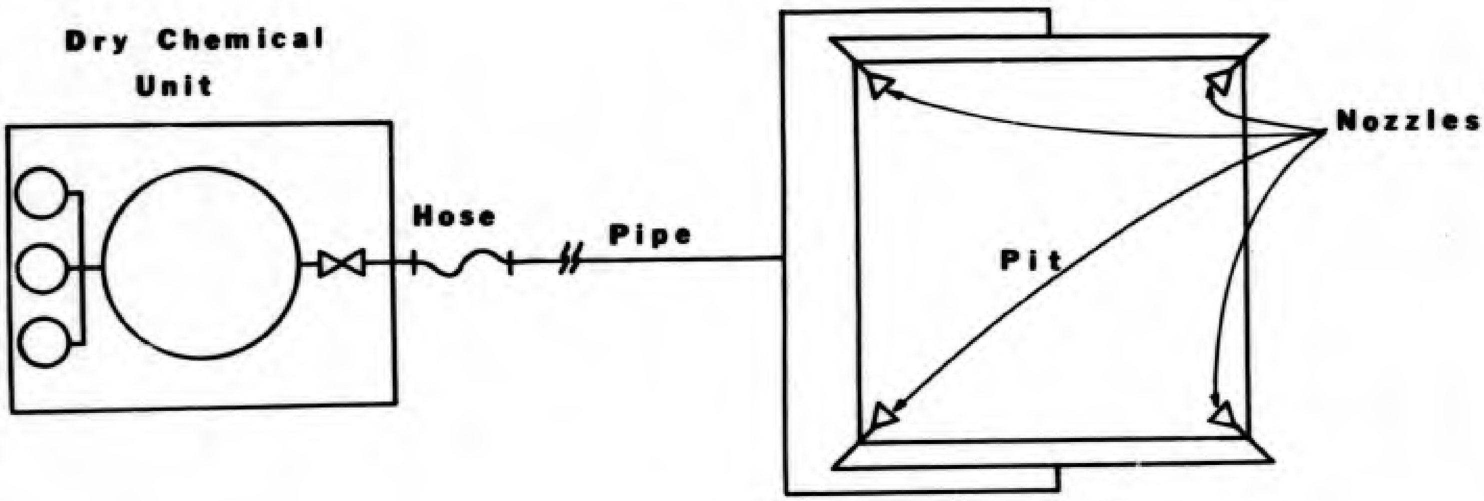


FIGURE 21. PLAN VIEW OF ONE DRY CHEMICAL DISTRIBUTION SYSTEM.

- change high pressure nitrogen cylinder(s) (if necessary) on the dry chemical unit

- adjust dry chemical unit nitrogen supply regulator setting (if necessary)

- load dry chemical unit with proper amount of agent (also serves as calibration)

- test titles filmed on motion picture and video tape

- radiometer cooling water turned on

- obstructions (if used) are placed in the pit

- liquid level system nitrogen flow turned on

- water added to pit (if necessary) (This step is omitted if there is reason to believe that the water will react with the fuel or otherwise hinder the test.)

- desired amount of fuel added to the pit

- fuel line blown clear of liquid and moved a safe distance away

- fuel depth above bubbler location measured manually (This step can be omitted if the liquid level system is calibrated prior to the test.)

- zero (i.e., beginning) readings taken on all sensing instruments

Fuel is ignited after all data recording devices are started. After ignition, the fuel is allowed to burn for approximately 8-10 minutes or until steady state temperature in the metal liner is reached. Personnel with stop watch are then dispatched to areas near the burning pit. The motion picture and video cameras are turned on. The dry chemical unit operator opens the valve and allows the unit to pressurize. As soon as the correct pressure is achieved, the operator opens the dry chemical discharge valve to start the flow of powder. Dry chemical application is continued until a few seconds after the fire is extinguished or until the unit runs out of powder. If the fire is not extinguished, low expansion foam is sometimes applied to extinguish the fire, thereby conserving fuel. Cameras and recording equipment are turned off after the fire is extinguished.

If sufficient fuel remains in the pit, it is readied for the next test. First, the dry chemical distribution system is blown clear of powder. Then changes may be made to the dry chemical unit nitrogen regulator setting, nozzles can be replaced (once the pit has cooled sufficiently), the unit is refilled with powder, and the nitrogen cylinders are replaced (if necessary). If a change in dry chemical type is called for, the unit is emptied completely and blown free of the old powder before the new powder is loaded. Following these changes, the next test can be started and carried out as before.

If the fuel level is insufficient for another test, the pit is allowed to cool. Additional fuel is then added to the pit and preparations for the next test proceed as before.

DATA COLLECTION DURING TESTS

The datalogger can be programmed to collect and display the data in various ways. For the foam and dry chemical test series, it was set to sample and record 15 channels of data approximately every 1.8 seconds. These 15 channels were assigned to the following:

- 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. Any channels that were not used on a particular test were set equal to zero.

The data tapes were computer processed with a program that used the calibrations for the various sensing instruments in order to provide a printout of all the data in standard engineering units.

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

- wind speed
- wind direction
- liquid level
- dry chemical weight
- one radiometer
- one pit wall thermocouple

A pneumatic recorder/controller was used to control the foam system and to record (on its own strip chart) the foam system parameters:

- foam solution flow rate
- foam generator inlet pressure

SUMMARY OF TEST DATA

A total of 210 fire extinguishment tests (112 foam tests and 98 dry chemical tests) were conducted on hexane fires. The fire fighting agents used for the tests included four foams: 1) protein foam, 2) aqueous film forming foam (AFFF), 3) alcohol foam, and 4) high expansion foam; and three dry chemicals: 1) sodium bicarbonate ($NaHCO_3$), 2) potassium bicarbonate ($KHCO_3$), and 3) a powder which is the reaction product of urea and potassium bicarbonate, trade named Monnex.

Selected data from these tests are listed in Tables 1 through 7. More 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 interval from one minute after ignition to the time when the extinguishment attempt began, divided by the time interval. The burning rate listed is an average rate for all but the first minute of preburn time. Within the accuracy of measurements, the burning rate for an individual test was about constant after the first minute of burning.

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

- For high expansion foam tests, the application rate is equal to the unexpanded foam solution flow

TABLE 1. SUMMARY OF PROTEIN FOAM DATA

Test ID	Pit Size (ft^2)	Obstruc.[a]	Burning Rate (in/min)	Application Rate (gpm/ft^2)	Control Time (sec)	Exting. Time (sec)	Wind Speed (mph)	Preburn Time (sec)
1	25		0.15	0.376	43	44	13	540
2	25		0.14	0.224	60	93	10	600
3	25		0.14	0.148	87	134	9	560
4	25		----	0.08	97	207	4	---
5	100		----	0.137	51	126	11	---
6	100		----	0.09	99	162	9	565
7	100		----	0.086	117	331	8	---
8	100		0.24	0.182	76	152	7	530
9	100		0.27	0.055	186	396	7	220
10	100		----	0.014	NC	NE	--	300
11	100		----	0.40	49	125	7	---
12	100		0.31	0.40	52	118	8	---
13	100		0.36	0.27	52	218	8	510
14*	100		0.31	0.145	60	183	18	750
15	100		0.31	0.40	45	120	15	490
16	100		0.24	0.119	52	144	20	425
17	100		0.24	0.058	141	448	15	425
18	100		0.29	0.016	NC	NE	16	250
19	100	CC	0.26	0.144	160	510	12	410
20	100	IB	0.23	0.140	70	278	16	720
21	100	SC	0.37	0.142	109	435	7	775
22	100	CC	0.33	0.140	68	180	11	600
23	400		0.33	0.194	50	96	14	190
24	400		0.38	0.092	135	NE	17	185
25	400		0.32	0.049	110	177	17	180
26	400	CC	0.36	0.097	NC	NE	--	380
27	400	CC	0.36	0.097	330	NE	--	386
28*	400		0.25	0.097	120	NE	--	120
29	1600		0.33	-----	---	---	2	390
30	1600		0.38	0.10	100	341	8	120

(a) Obstruction design shown in Appendix B.

*Manual test.

TABLE 2. SUMMARY OF AFFF DATA

Test ID	Pit Size (ft^2)	Obstruc.[(a)]	Burning Rate (in/min)	Application Rate (gpm/ft^2)	Control Time (sec)	Exting. Time (sec)	Wind Speed (mph)	Preburn Time (sec)
1	25		0.18	0.352	27	36	4	435
2	25		0.16	0.228	48	92	7	720
3	25		0.18	0.144	37	64	5	525
4	25		0.17	0.068	63	81	5	575
5	100		0.24	0.400	28	73	14	525
6	100		0.38	0.178	39	NE	10	710
7	100		0.26	0.120	43	NE	10	840
8	100		0.30	0.058	74	701	12	845
9	100		0.30	0.036	116	NE	12	660
10*	100		0.31	0.037	60	263	11	760
11	100		0.33	0.277	45	140	15	610
12	100		0.39	0.155	67	---	16	535
13	100		0.35	0.178	50	190	14	570
14	100		0.34	0.088	63	537	11	785
15	100		0.35	0.088	63	187	14	680
16	100		0.47	0.134	43	229	14	700
17*	100		0.41	0.150	---	103	10	640
18	25		---	0.080	45	100	--	1160
19	25		---	0.080	---	---	--	1030
20	100		0.25	0.40	34	909	8	500
21	100		0.29	0.120	32	925	6	490
22	100		0.35	0.058	67	993	6	505
23	100		0.31	0.016	220	775	6	575
24	100	CC	0.27	0.144	95	364	13	460
25	100	IB	0.25	0.138	68	306	18	690
26	100	SC	0.31	0.143	69	---	7	550
27	100	CC	0.28	0.140	64	109	--	300
28	400		0.25	0.194	30	NE	7	180
29	400		0.36	0.097	64	NE	5	180
30	400		0.27	0.049	170	NE	4	180
31*	400	CC	0.32	0.097	90	207	--	120
32	400	CC	0.27	0.097	120	315	5-15	180
33*	400		0.36	0.097	35	137	10	---
34	1600		0.32	0.100	64	222	5	80

(a) Obstruction design shown in Appendix B.

*Manual test.

TABLE 3. SUMMARY OF ALCOHOL FOAM DATA

Test ID	Pit Size (ft^2)	Obstruc.[a]	Burning Rate (in/min)	Application Rate (gpm/ft^2)	Control Time (sec)	Exting. Time (sec)	Wind Speed (mph)	Preburn Time (sec)
1	25		0.20	0.336	30	480	4	560
2	100		0.42	0.135	42	82	7	---
3	100		----	0.057	47	180	6	---
4	100		----	0.036	90	NE	8	---
5	100		----	0.400	43	1200	13	60
6	100		0.26	0.290	30	466	12	540
7	100		0.34	0.132	39	528	15	615
8	100		0.30	0.077	47	587	15	675
9*	100		0.22	0.128	<60	107	14	480
10	100	CC	0.26	0.137	72	506	13	540
11	100	IB	0.27	0.133	42	360	21	635
12	100	SC	0.28	0.138	50	282	9	445
13	400		0.25	0.049	85	200	13	180
14	400		0.34	0.097	60	150	12	180
15	400		0.24	0.194	28	88	12	270
16	400	CC	0.27	0.097	114	228	--	300
17*	400		0.26	0.097†	50	235	--	90
18	1600		0.31	0.100	45	533	8	120

[a] Obstruction design shown in Appendix B.

*Manual test.

†3% Solution.

TABLE 4. SUMMARY OF HIGH EXPANSION FOAM DATA

Test ID	Pit Size (ft^2)	Obstruc.[a]	Burning Rate (in/min)	Application Rate (gpm/ft^2)	Control Time (sec)	Exting. Time (sec)	Wind Speed (mph)	Preburn Time (sec)
1	100		----	0.18	28	65	18	551
2	100		0.24	0.18	19	30	17	342
3	100		0.34	0.18	21	39	5	416
4	100		0.34	0.036	NC	NE	7	330
5	100		0.32	0.108	47	73	15	335
6	100		0.37	0.108	66	65	13	390
7	100		0.35	0.18	20	28	13	270
8	100		0.37	0.18	23	21	18	84
9	100	CC	0.32	0.18	33	45	12	338
10	100	CC	0.36	0.18	24	25	12	60
11	25		----	0.048	45	113	7	519
12	25		0.26	0.048	40	87	7	446
13	25		----	-----	--	---	3	---
14	25		0.17	0.096	24	75	9	360
15	25		0.20	0.048	36	100	9	382
16	400		0.36	0.078	NC	NE	16	66
17	400		----	0.078	132	250	19	20
18	400		0.33	0.066	88	96	11	120
19	400		0.33	0.056	58	74	11	120
20	400		0.38	0.066	35	59	10	120
21	400		0.28	0.056	42	60	11	120
22	400		0.30	0.136	30	30	10	120
23	400		0.35	0.129	30	53	10	60
24	400		0.40	0.107	23	40	10	210
25	400		0.31	0.092	48	70	14	140
26	400		0.32	0.112	36	50	12	120
27	400		0.30	0.044	60	118	10	90
28	400	CC	0.31	0.066	62	113	5-15	300
29	400	CC	0.33	0.056	83	102	5-15	300
30	1600		0.34	0.088	81	120	6	60

[a] Obstruction design shown in Appendix B.

TABLE 5. SUMMARY OF $NaHCO_3$ DRY CHEMICAL DATA

Test ID	Pit Size (ft^2)	Obstruc.[a]	Burning Rate (in/min)	Application Rate ($lb/sec-ft^2$)	Exting. Time (sec)	Nozzle Type and Number	Wind Speed (mph)	Preburn Time (sec)
1	25		0.15	0.220	1.5	A (4)	13	485
2	25		0.12	0.167	5.9	A (4)	14	530
3	25		0.16	0.126	4.8	A (4)	9	525
4	25		0.14	-----	NE	A (4)	--	490
5	25		0.15	0.113	6.0	A (4)	5	710
6	25		0.17	0.037	NE	A (4)	3	1260
7	25		0.11	0.043	NE	A (4)	16	615
8	25		0.12	0.058	NE	A (4)	14	810
9	100		0.42	0.044	NE	A (4)	10	500
10	100		0.36	0.069	15.6	A (4)	6	595
11	100		0.34	0.041	NE	A (8)	10	590
12	100		0.27	-----	NE	A (8)	--	480
13	100		0.28	0.077	44	B (2)	16	525
14	100	IB	0.29	0.074	55	B (2)	18	479
15	100	IB	0.26	0.080	7.0	C (4)	15	409
16	100	IB	0.30	0.057	7.6	C (4)	20	485
17	100	IB	0.27	0.049	33.4	C (4)	20	372
18	100	CC	0.3*	0.080	7.5	C (4)	10	---
19	100		0.3*	0.040	17.6	C (4)	8	180
20	100		0.27	0.094	5.6	C (4)	9	195
21	100		0.18	0.061	NE	C (2)	15	208
22	100		0.16	0.058	NE	1 Hoseline	15	53
23	100		0.32	-----	NE	C (4)	10	48
24	400		----	-----	NE	-----	16	70
25	400		0.29	0.069	NE	D (4)	19	60
26	400		0.26	0.069	11	D (4)	11	148
27	400		----	0.054	15	D (4)	13	139
28	400		0.21	0.045*	12	2 Hoselines	12	90

[a] Obstruction design shown in Appendix B.

*Estimated values.

TABLE 6. SUMMARY OF $KHCO_3$ DRY CHEMICAL DATA

Test ID	Pit Size (ft^2)	Obstruc.[a]	Burning Rate (in/min)	Application Rate ($lb/sec\text{-}ft^2$)	Exting. Time (sec)	Nozzle Type and Number	Wind Speed (mph)	Preburn Time (sec)
1	25		0.18	0.137	5.3	A (4)	4	510
2	25		0.16	0.110	5.6	A (4)	4	525
3	25		0.17	0.070	7.0	A (4)	4	800
4	25		0.12	-----	NE	A (4)	14	695
5	100		0.29	0.033	NE	A (4)	9	710
6	100		0.30	0.062	NE	A (4)	6	555
7	100		0.31	0.064	NE	A (4)	7	700
8	100		0.29	0.042	NE	A (8)	9	605
9	100		0.27	-----	NE	-----	15	551
10	100		0.28	0.058	49	B (2)	19	472
11	100	IB	0.31	0.020	NE	B (2)	20	438
12	100	IB	0.26	0.049	NE	B (2)	15	531
13	100	IB	0.27	0.089	27	C (4)	15	471
14	100	IB	0.31	-----	NE	C (4)	15	56
15	100	IB	0.28	0.036	NE	C (4)	22	391
16	100	IB	0.28	0.044	NE	C (4)	9	532
17	100	IB	0.30	0.037	NE	C (4)	8	420
18	100	CC	----	0.081	NE	C (4)	8	390
19	100		0.23	0.076	NE	C (4)	23	234
20	100		0.27	0.067	22	C (4)	11	255
21	100		0.32	0.053	7.8	C (4)	16	300
22	100		0.30	0.041	NE	C (4)	18	296
23	100		0.30	0.050	NE	C (4)	20	331
24	100		0.27	0.049	33.2	C (4)	10	157
25	100		0.31	0.075	4.8	C (4)	5	161
26	100		0.41	0.038	NE	1 Hoseline	15	91
27	100	CC	----	0.047	NE	C (4)	10	366
28	100	CC	0.17	0.090	NE	C (4)	25	60
29	100	CC	0.25	0.074	NE	C (4)	12	48
30	25		0.11	0.190	4.4	C (2)	10	386

[a] Obstruction design shown in Appendix B.

TABLE 6. SUMMARY OF $KHCO_3$ DRY CHEMICAL DATA (continued)

Test ID	Pit Size (ft^2)	Obstruc.[a]	Burning Rate (in/min)	Application Rate ($lb/sec-ft^2$)	Exting. Time (sec)	Nozzle Type and Number	Wind Speed (mph)	Preburn Time (sec)
31	25		0.17	0.097	5.0	C (1)	9	418
32	400		0.29	0.068	14	D (4)	5	150
33	400		0.32	0.057	12	D (4)	5	124
34	400	CC	0.25	0.094	NE	D (4)	15	137
35	400	CC	0.24	0.069	NE	D (4)	10	122
36	400		0.36	0.025	NE	2 Hoselines	5-10	120
37	400		0.22	-----	NE	2 Hoselines	5-10	126
38	400		0.25	0.03	NE	2 Hoselines	5-10	131
39	400		0.26	0.025	NE	2 Hoselines	12	306
40	400		0.23	0.036	17	2 Hoselines	13	124

[a] Obstruction design shown in Appendix B.

TABLE 7. SUMMARY OF UREA - $KHCO_3$ DRY CHEMICAL DATA

Test ID	Pit Size (ft^2)	Obstruc.[a]	Burning Rate (in/min)	Application Rate ($lb/sec-ft^2$)	Exting. Time (sec)	Nozzle Type and Number	Wind Speed (mph)	Preburn Time (sec)
1	25		0.12	0.076	4.5	A (4)	19	645
2	25		0.11	0.058	7.0	A (4)	13	615
3	25		0.11	0.033	NE	A (4)	11	840
4	25		0.10	0.037	7.7	A (4)	14	780
5	100		0.27	0.052	28	B (2)	20	454
6	100	IB	0.29	0.055	NE	B (2)	15	341
7	100	IB	0.28	0.059	4.5	C (4)	25	443
8	100	IB	---	---	9.5	C (4)	22	---
9	100	IB	0.33	0.056	31	C (4)	11	346
10	100	IB	0.30	0.039	18	C (4)	6	290
11	100	CC	0.33*	0.069	13	C (4)	6	450
12	100		0.36	0.040	7.5	C (4)	6	337
13	100		0.33	0.067	4.2	C (4)	5	278
14	100		0.35	0.033	NE	C (1)	6	182
15	100		0.27	0.049	NE	C (2)	10	142
16	100		0.29	0.049	6.9	C (4)	11	105
17	100		0.33	0.037	NE	1 Hoseline	16	64
18	25		0.13	0.222	3.5	C (2)	13	480
19	25		0.13*	0.147	3.5	C (1)	15	---
20	25		0.13	0.136	6.6	C (2)	8	439
21	25		0.11	0.178	3.0	C (2)	9	362
22	25		0.13	0.099	3.9	C (1)	10	384
23	25		0.15	0.049	6.9	C (1)	7	362
24	400		0.34	0.058	9	D (4)	7	123
25	400		0.28	0.033	20	D (4)	8	125
26	400		0.25	0.063	NE	D (4)	10	120
27	400		0.27	0.049	6.9	2 Hoselines	13	126
28	400		0.26*	0.021	12	1 Hoseline	13	30
29	400		0.25	0.022	9.2	1 Hoseline	10	120
30	400		0.26*	0.021	10.7	1 Hoseline	10	30

[a] Obstruction design shown in Appendix B.

*Estimated values.

rate divided by the area of the pit. This allows direct comparisons to be made between the low and high expansion foams.

- For dry chemical tests, the application rate is determined from the slope of the straight-line portion of the dry chemical unit weight vs. time curve which is recorded on a strip chart recorder.

Control Time - The radiant heat flux on the wide angle radiometer nearest the fire was averaged over the one minute time period immediately preceeding the application of foam. The time required to achieve a 95 percent reduction in heat flux is the control time.

Extinguishment Time - The time given is the average of the times recorded by at least two observers using stopwatches. Extinguishment time was the time at which the fire was completely out, with no sign of flame, regardless of flame size. Extinguishment times for foam tests were erratic, as explained later.

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

Hexane Burning Rates

As Tables 1 to 7 show, burning rates (in inches of hexane per minute) were obtained for a majority of the tests. The burning rate for hexane (see Appendix E for composition) is almost completely dependent on the radiant and convective energy transmitted from the fire to the hexane pool since the evaporation rate for hexane was determined to be only about 0.0044 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 22) 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 comditions. The "calm wind" burning rate for the 25-ft^2 pit is 0.19 in/min. The 100-ft^2, 400-ft^2, and 1600-ft^2 pits all have a "calm wind" burning rate of 0.36 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 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.

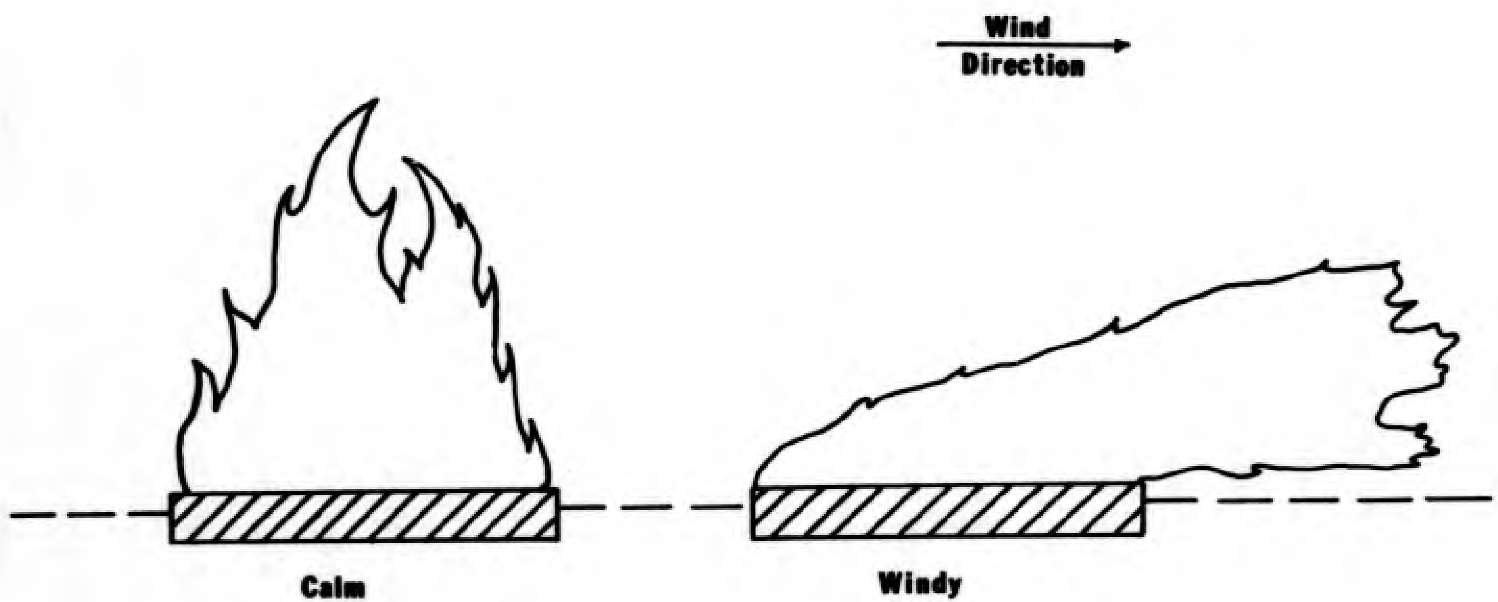


FIGURE 22. REDUCTION IN RADIANT HEATING OF FUEL DUE TO THE EFFECT OF WIND ON FLAMES.

This minimum pool size at which the burning rate reaches its maximum is influenced by the optical character of the flame. In comparison to clean-burning fires, smoky fires generally become "optically thick" at a smaller pool size due to the presence of the particulate matter, principally carbon particles. For hexane fires, the maximum burning rate is reached at a fairly small pool size (~100 ft^2) because the flame is quite smoky.

High and Low Expansion Foams

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

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

where: t = control or extinguishment time, sec

t_m = minimum control or extinguishment time, sec

A_r = agent application rate, gpm/ft^2

A_m = minimum application rate for fire control, gpm/ft^2

a, K = constants

This equation was developed to accommodate the following assumptions:

a) Higher application rates result in shorter control and extinguishment times.

b) Minimum control and extinguishment times 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.

$$q = B_r \rho_L \Delta H_v \qquad \text{Eq. 2}$$

where: q = radiant and convective heat flux, Btu/hr-ft^2

B_r = burning rate, ft/hr

ρ_L = density of burning liquid, lb/ft^3

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

Using a burning rate of 0.36 in/min (1.8 ft/hr), the value of q is calculated to be about 10,000 Btu/hr-ft^2. The minimum application rate is then calculated from

$$A_m = q/\rho_w \Delta H_w \qquad \text{Eq. 3}$$

where ρ_w 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 hexane. A_m is then 0.021 gpm/ft. This value cannot be easily confirmed experimentally, and is based on the burning rates for larger pits. The data for three low expansion foam agents show no fires controlled at rates lower than 0.021 gpm/ft^2. One AFFF test appeared to be controlled, but fuel was exhausted before the test was finished, making the test invalid.

No manual tests or tests using obstructions were included in the mathematical analysis of the data; neither were tests for which portions of the data were missing or tests not controlled or extinguished. In obstructed tests, control and extinguishment required the foam to flow around the obstruction. For sheet metal crosses and I-beam crosses, flow around the crosswind ends of the obstructions was uniform and fairly rapid, and no large increase in control or extinguishment time was noted. 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 required longer application time. Obstructed test data were excluded from the mathematical analysis in order to avoid biasing analysis. The data for control (and extinguishment) time analysis thus consisted of the results from tests in which an unobstructed fire was successfully controlled (and extinguished) by foam that was introduced into the pit at a fixed location.

Within the accuracy of the data, logarithmic plots of control or extinguishment times versus $(A_r - 0.021)^{-1}$ were linear and a straight line fit provided the remaining constants. Table 8 summarizes these constants.

Figure 23 shows a comparison of the calculated control time curve and the actual control times used in the analysis. This particular data set is for protein foam. For all four foams, the control times showed less scatter than extinguishment times. In particular, the AFFF and alcohol foams displayed much scatter in the extinguishment times versus $(A_r - .021)^{-1}$ plots. Figures 24 and 25 compare the correlation curves for the four foam types.

TABLE 8. SUMMARY OF CORRELATION CONSTANTS DEVELOPED FROM FOAM FIRE CONTROL AND EXTINGUISHMENT TEST DATA.

	Fire Control			Fire Extinguishment		
Type of Foam	t_m (sec)	K	σ (†) (sec)	t_m (sec)	K	σ (§) (sec)
Protein	33.1	4.70	16	52.4	11.89	41
AFFF	35.0	1.30	10	7.7	20.5	56
Alcohol	24.3	1.70	6	--*	--*	--*
High Expansion	23.0	1.12	15	33.0	1.79	15

† Standard deviation for fire control time.

§ Standard deviation for fire extinguishment time.

* Data scatter too great to correlate.

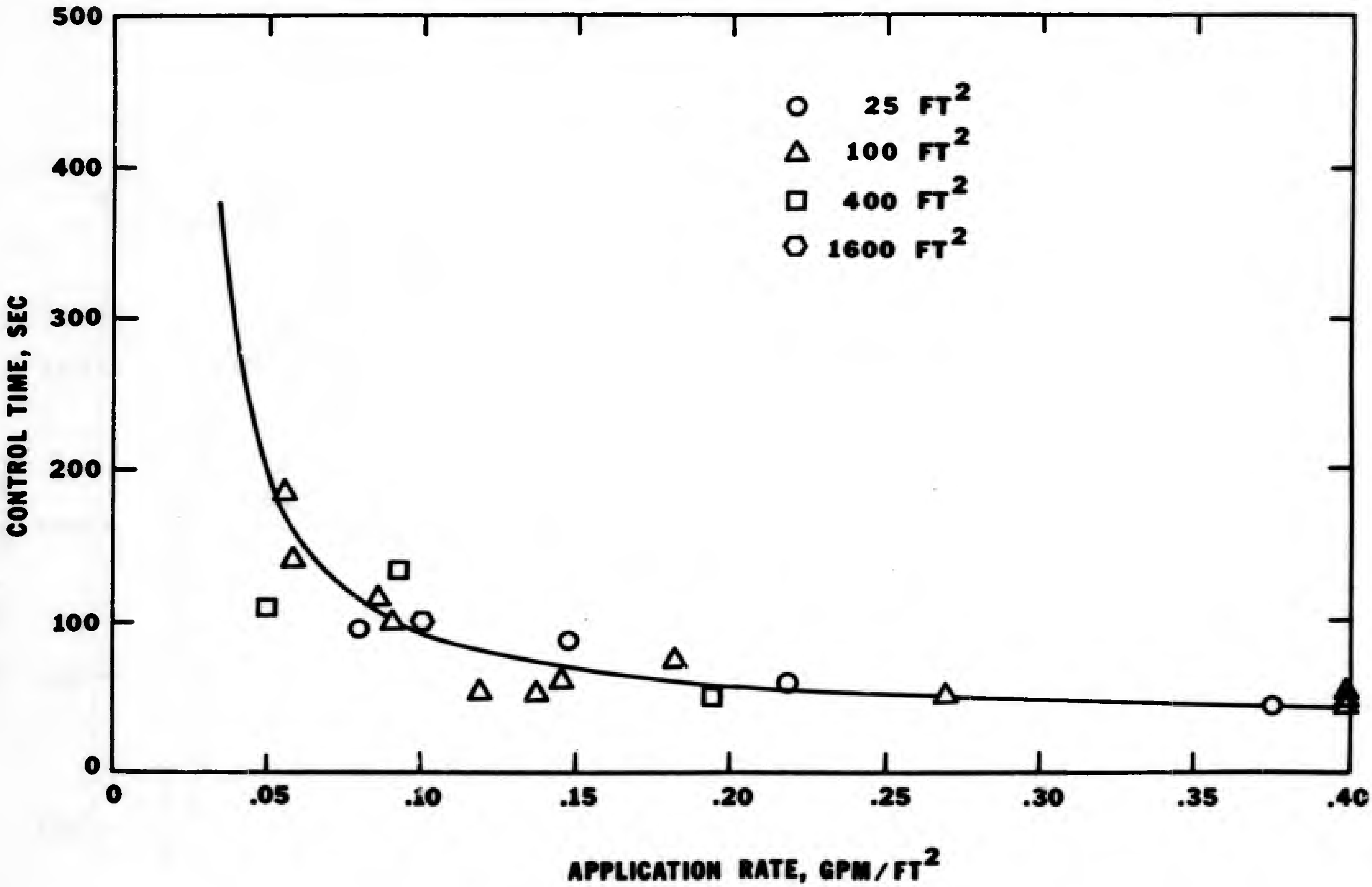


FIGURE 23. FIRE CONTROL TIME AS A FUNCTION OF PROTEIN FOAM APPLICATION RATE.

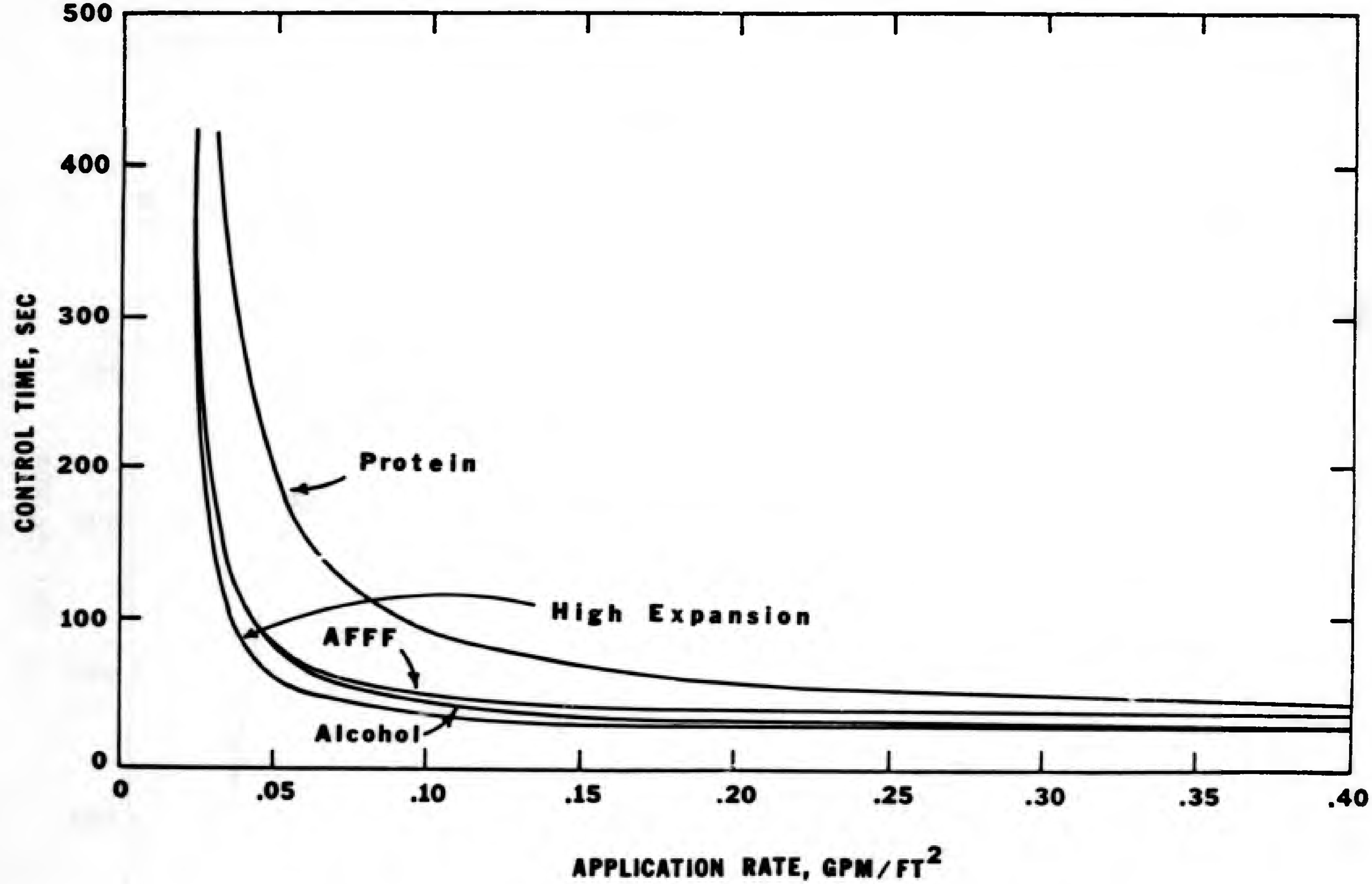


FIGURE 24. CALCULATED FIRE CONTROL TIMES AS A FUNCTION OF FOAM APPLICATION RATE.

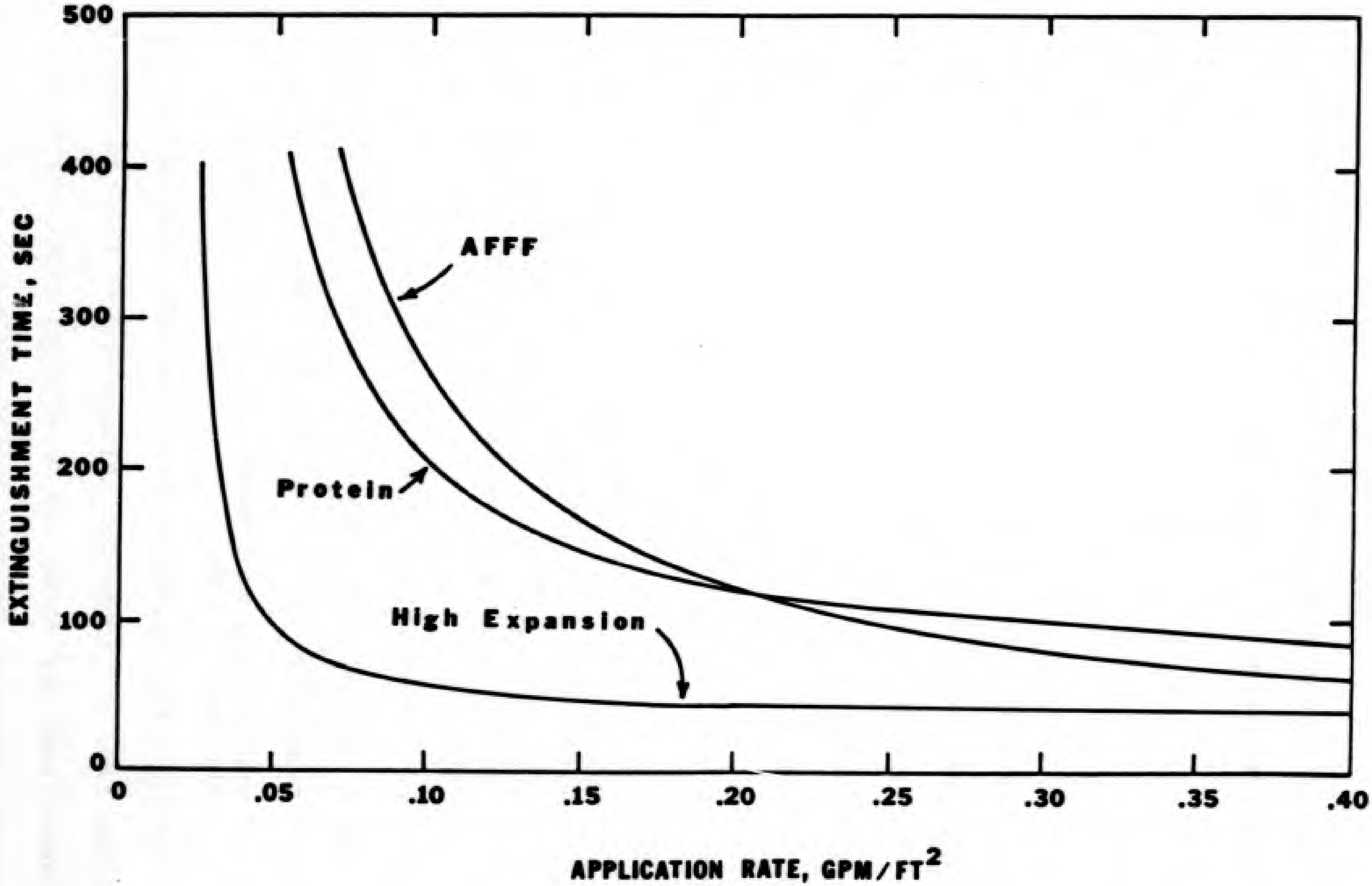


FIGURE 25. CALCULATED FIRE EXTINGUISHMENT TIMES AS A FUNCTION OF FOAM APPLICATION RATE.

Dry Chemicals

The extinguishment data for the three dry chemical agents were correlated using an equation of the form:

$$t_e - t_m = \frac{K}{\left(\dfrac{A_r - CB_r}{B_r}\right)^a} \qquad \text{Eq. 4}$$

where: t_e = extinguishment time, sec

t_m = minimum extinguishment time, sec

A_r = dry chemical application rate, lb/ft^2-sec

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 lower extinguishment times.

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.

Because this equation calls for both application rate and burning rate as inputs for calculating an extinguishment time, those tests for which one or both of these rates were not recorded could not be used in the analysis. Tests with obstructions, manual extinguishment tests, and those tests where extinguishment did not occur were also not used in the analysis. The data for the analysis thus consisted of the results of successful extinguishment attempts using fixed nozzle systems on unobstructed fires. The only exceptions to this were the tests which used Kidde 90° nozzles (this system performed so poorly, achieving only about 50% of the manufacturer-specified range, that all tests using it were excluded from the analysis) and Test 24, $KHCO_3$, in which the nozzles plugged during the test.

A multiple regression analysis of the remaining test data indicated that the exponent "a" was approximately equal to 0.5. Thus the equation becomes:

$$t_e - t_m = \frac{K}{\left(\dfrac{A_r - CB_r}{B_r}\right)^{.5}} \qquad \text{Eq. 5}$$

By rewriting to the form

$$t_e = t_m + \frac{K}{\left(\dfrac{A_r}{B_r} - C\right)^{.5}} \qquad \text{Eq. 6}$$

the equation can be expressed as

$$Y = A = B/X \qquad \text{Eq. 7}$$

where: $Y = t_e$

$A = t_m$

$B = K$

$X = \left(\dfrac{A_r}{B_r} - C\right)^{.5}$

A least squares fit of the linear transform of Equation 7 can then be performed and the constants "A" and "B" (i.e., t_m and K) can be determined. Unfortunately, in order to do this, a value must be chosen for C. Each dry chemical is expected to have its own value for C since it is known that certain agents can extinguish fires at lower application rates than other agents. The value of the constant "C" for each dry chemical was estimated based on a plot of A_r/B_r vs t_e. Least squares analyses were made using these C values and Equation 4. (Various values were tried for C for each dry chemical; the one for which the equation best fit the data was ultimately chosen). The equation that best fits the combined data for all three dry chemicals is:

$$t_e - 0.87 = \frac{3.62}{\left(\frac{A_r}{B_r} - C\right)^{.5}} \qquad \text{Eq. 8}$$

where: C = .02 for urea - $KHCO_3$

.07 for $KHCO_3$

.13 for $NaHCO_3$

Figure 26 shows all the data points that were used and illustrates how well Equation 8 fits the data. Figure 27 compares the correlation curves for the three dry chemicals tested.

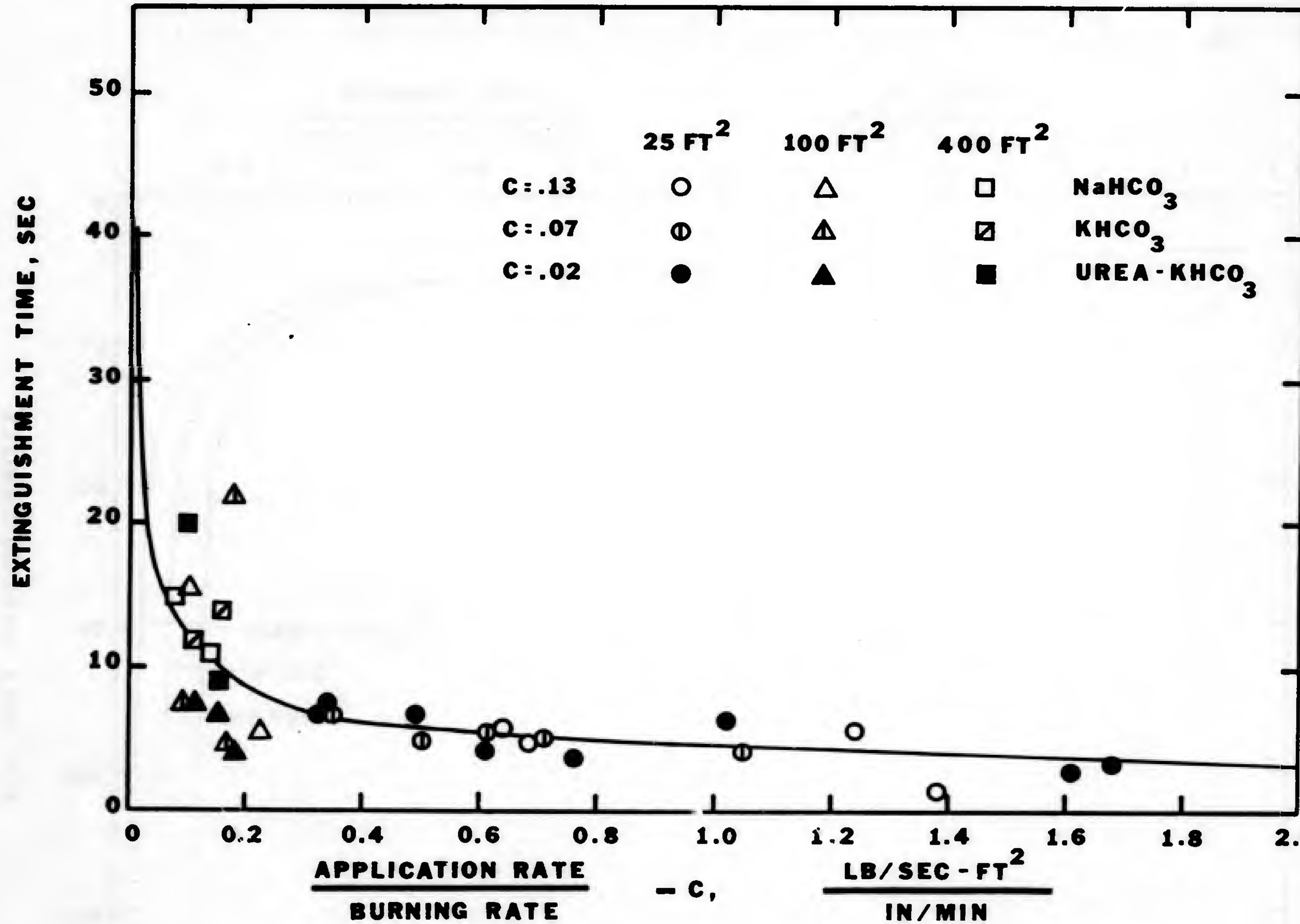


FIGURE 26. COMPARISON OF TEST DATA AND THE FIRE EXTINGUISHMENT TIME VS A_r/B_r - C CURVE DETERMINED BY THE LINEAR REGRESSION ANALYSIS.

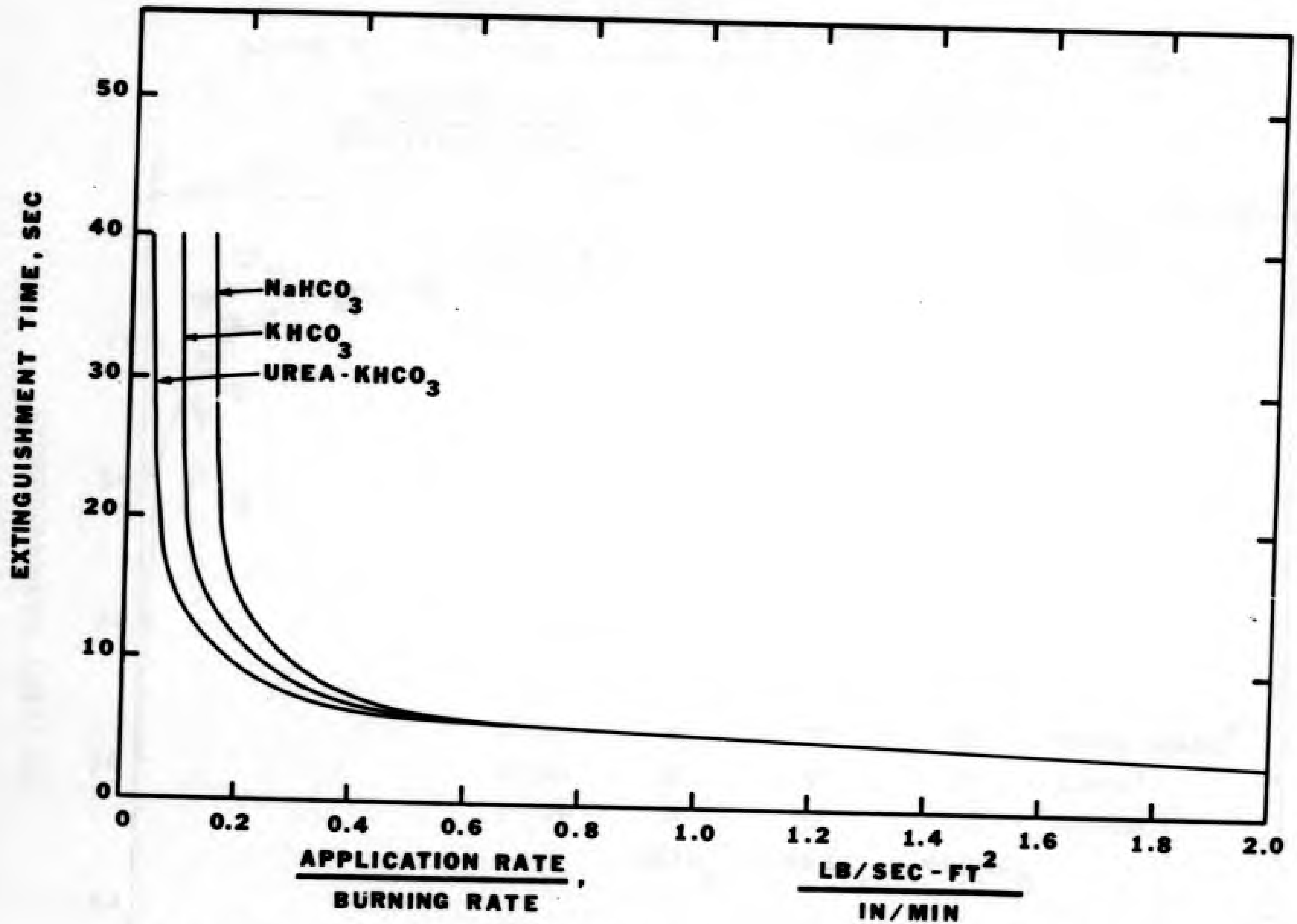


FIGURE 27. CALCULATED FIRE EXTINGUISHMENT TIMES AS A FUNCTION OF DRY CHEMICAL APPLICATION RATE AND HEXANE BURNING RATE.

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, alcohol foam produced the shortest fire control times for any given application rate. It is followed in effectiveness by AFFF and protein foam. For fire extinguishment, the alcohol foam again was the most effective low expansion foam. Protein foam was more effective than AFFF at low application rates (<0.20 gpm/ft^2) however, AFFF was somewhat more effective at higher rates. The difference was probably due to differences in foam sealing at the hot pit walls. It was not possible to correlate the results of the alcohol foam fire extinguishment tests due to the extreme data scatter present in the test results.

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 on a given day, it would also control a fire (at the same application rate) on another day. This statement could not be made for extinguishment times. Fire extinguishment would be possible for a given foam at a given application rate on one day, while on another day, the same agent at the same application rate would not extinguish the fire in the same time. It was felt that the cause of the poor extinguishment results could be attributed to the influence of the pit wall and pit liner. Any lessening of the foam's ability to seal at the wall surface, i.e., wall deterioration or use of metal liners, 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 "σ" between the test data and the correlating curves for the four foams (see Table 8) show that control times exhibited significantly less scatter than extinguishment times.

The effectiveness of a low expansion foam in controlling a hexane fire appeared to be directly related to the observed fluidity (ability to flow across the hexane surface) of the foam. The alcohol foam and AFFF appeared to have comparable ability in covering the fire surface. The protein foam, which was less effective (i.e., slower) in controlling the fires, appeared to be stiffer and more resistant to flow than the other two low expansion foams. The alcohol foam was used at a 10% concentration, its recommended dilution for use on polar liquids. One manual test was run using a 3% solution. The control time for this test was within 7% of the computed control time for the 10% solution.

Thus, for hexane fires, the use of a 10% alcohol foam concentration did not appear to produce significantly lower control times than the 3% concentration.

A definitive statement cannot be made concerning any observable foam property and the effectiveness of a foam in extinguishing a hexane fire. For application rates below 0.20 gpm/ft^2, the protein foam was more effective than AFFF (no comparison is available for alcohol foam). Above 0.20 gpm/ft^2, the AFFF produced shorter extinguishment times. The differences in extinguishment times between AFFF and protein foam were under 20 seconds at application rates above 0.20 gpm/ft^2 and approximately 70 seconds at an application rate of 0.10 gpm/ft^2 (see Figure 25). This would indicate that the protein foam was more effective in sealing the liquid at the pit edges. The sealing ability difference was apparently not as important at high application rates. In a large majority of the low expansion fire extinguishment tests, the area of the pit which burned the longest was located in the downwind corner of the pit, as shown in Figure 28, or, if no metal liner was used, occurred at cracks or fissures in the refractory coating.

Obstructions had varying effects on the ability of low-expansion foams to control the fire. As illustrated in Figures 29, 30, and 31, the available data indicate that the I-beam cross and the sheet metal cross had no significant effect on the foam control times. However, the concentric

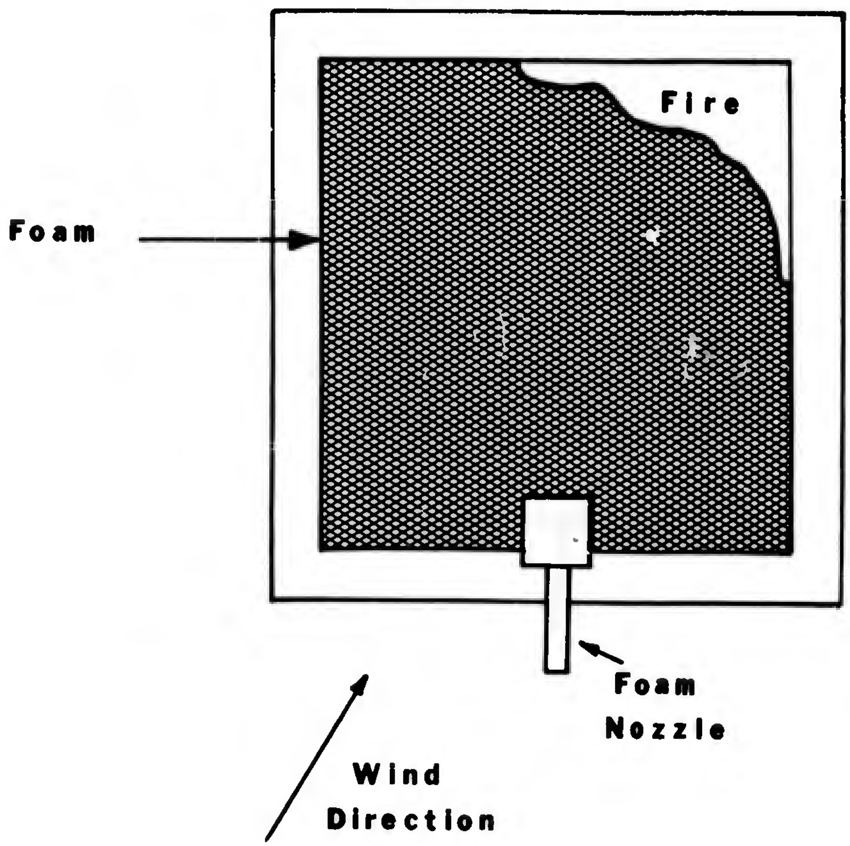


FIGURE 28. PLAN VIEW OF FIRE PIT SHOWING LOW EXPANSION FOAM COVERAGE AND LAST AREA OF FIRE TO BE EXTINGUISHED UNDER WINDY CONDITIONS.

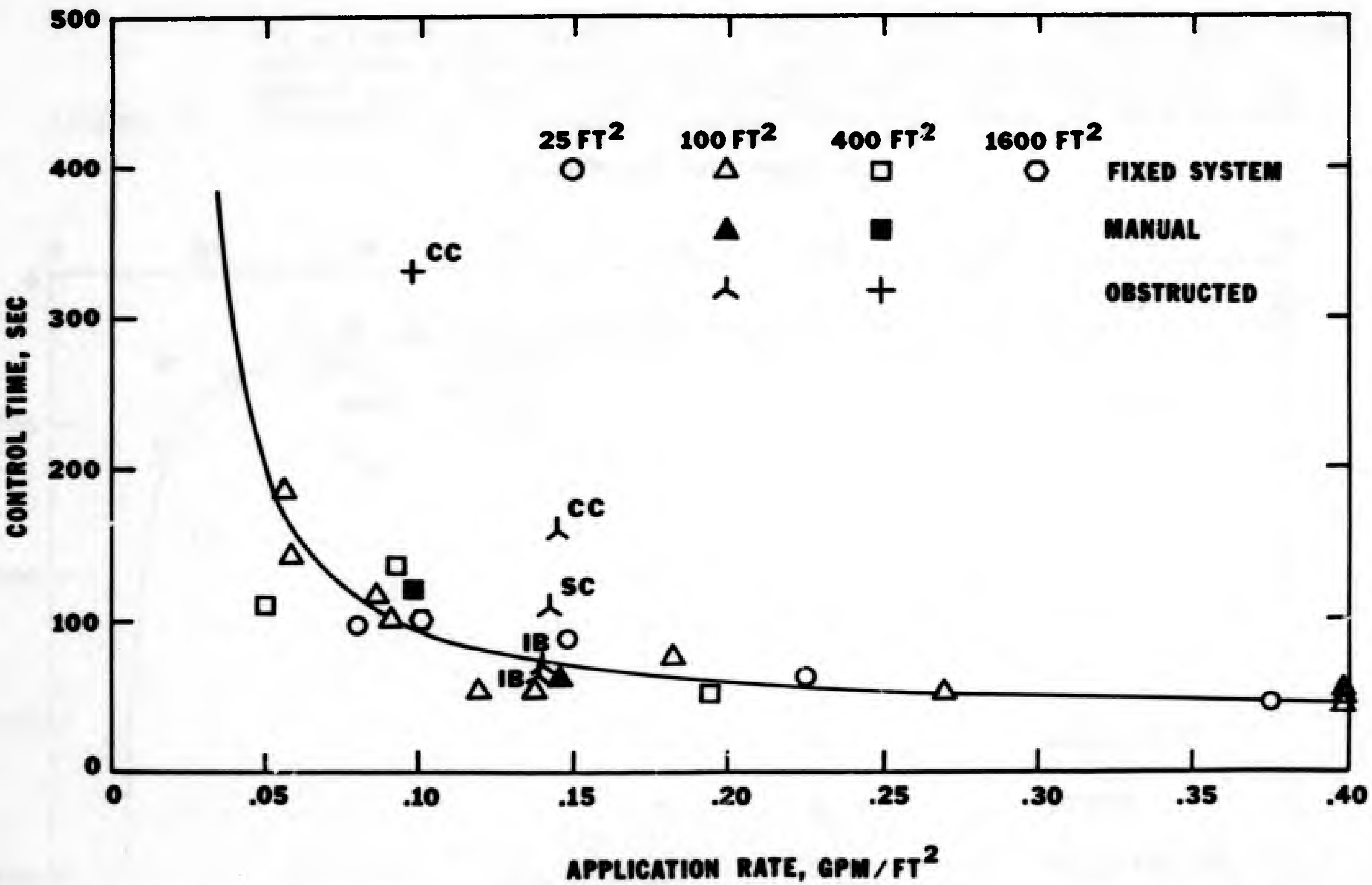


FIGURE 29. COMPARISON OF FIRE CONTROL TIMES FROM PROTEIN FOAM TESTS ON UNOBSTRUCTED HEXANE FIRES USING FIXED SYSTEM AND MANUAL FOAM APPLICATION, AND OBSTRUCTED HEXANE FIRES USING FIXED SYSTEM FOAM APPLICATION. (CC = CONCENTRIC CIRCLES, SC = SHEET METAL CROSS, IB = I-BEAM CROSS)

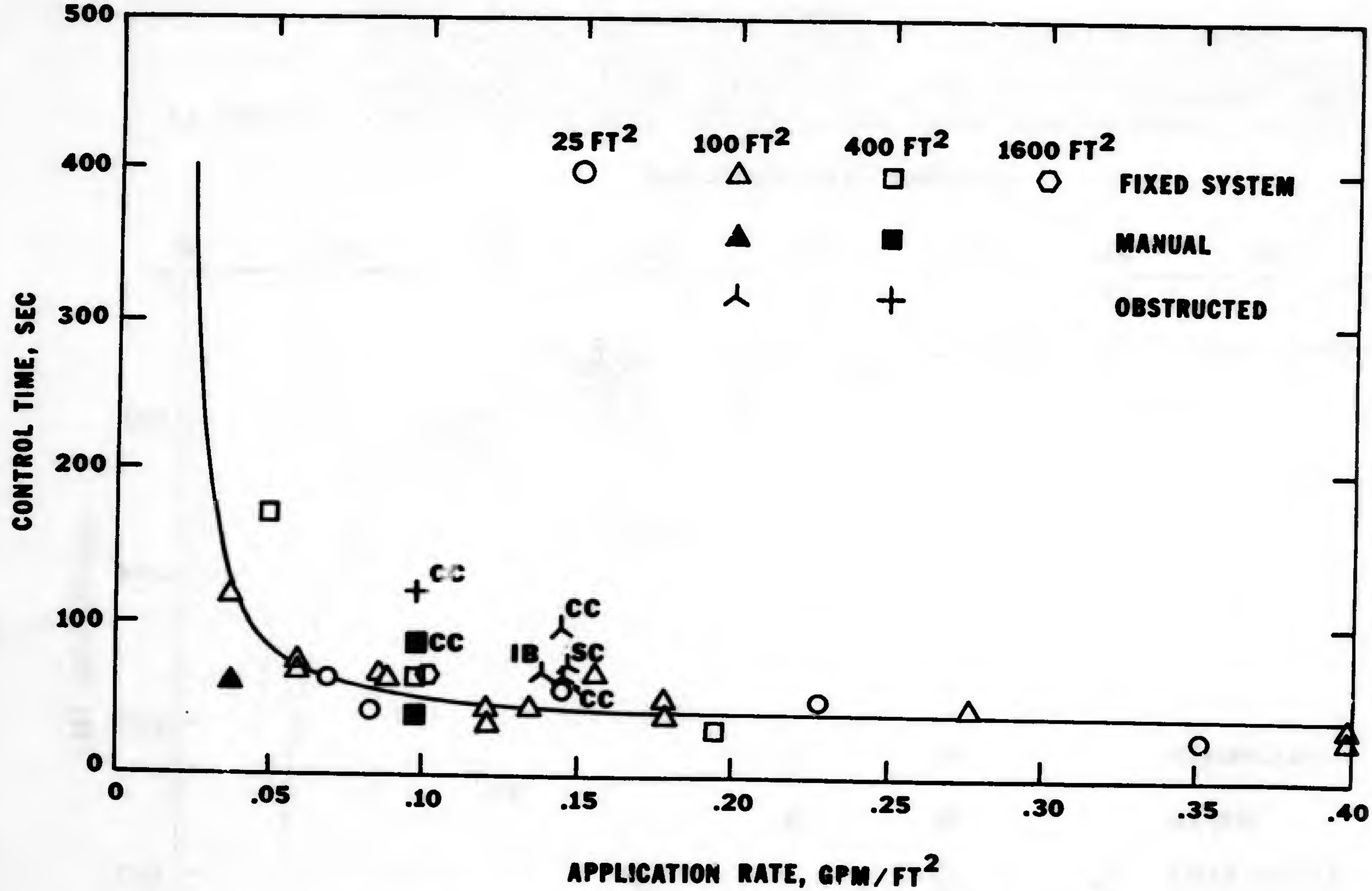


FIGURE 30. COMPARISON OF FIRE CONTROL TIMES FROM AFFF TESTS ON UNOBSTRUCTED HEXANE FIRES USING FIXED SYSTEM AND MANUAL FOAM APPLICATION, AND OBSTRUCTED HEXANE FIRES USING FIXED SYSTEM FOAM APPLICATION. (CC = CONCENTRIC CIRCLES, IB = I-BEAM CROSS, SC = SHEET METAL CROSS).

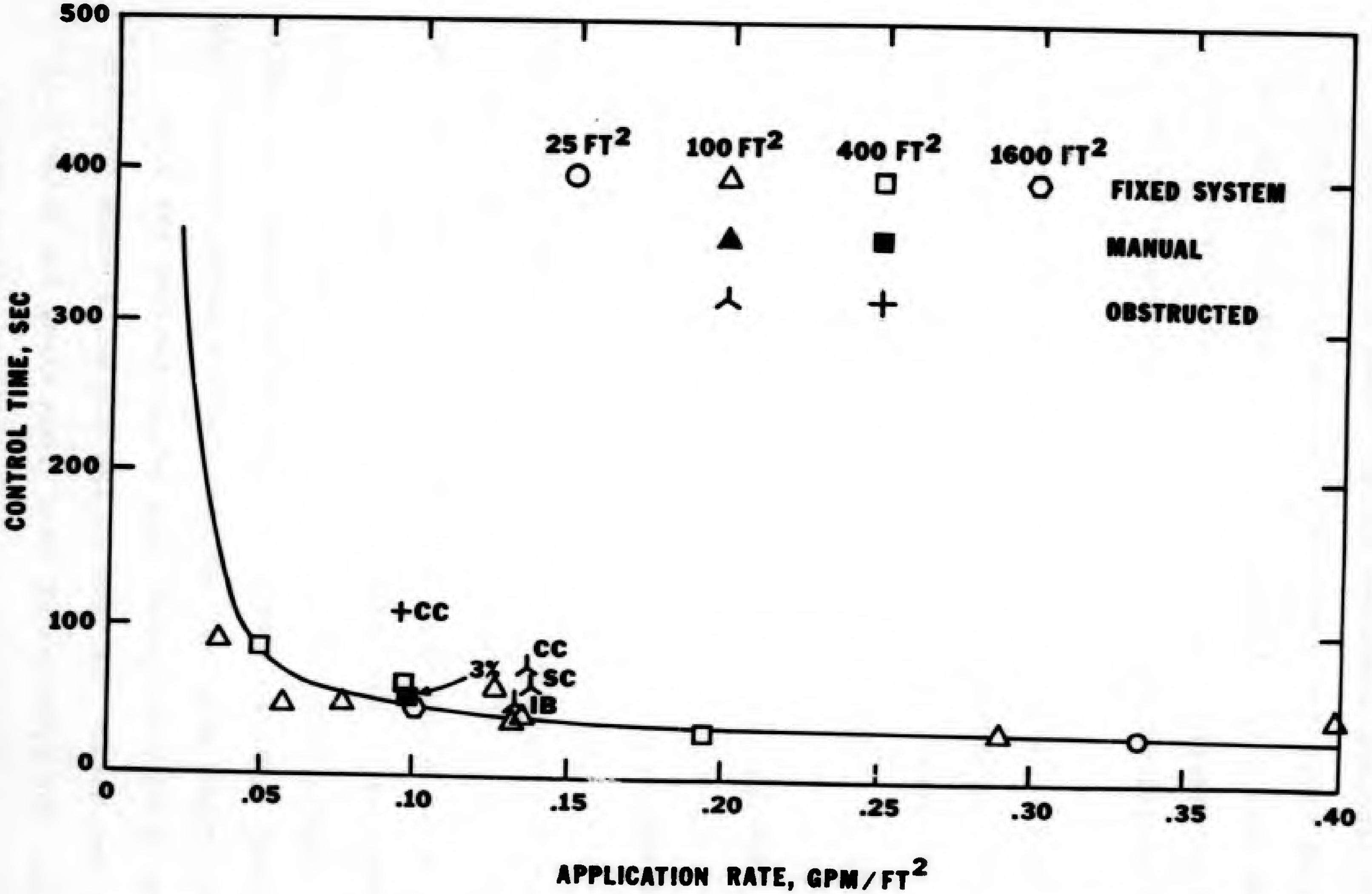


FIGURE 31. COMPARISON OF FIRE CONTROL TIMES FROM ALCOHOL FOAM TESTS ON UNOBSTRUCTED HEXANE FIRES USING FIXED SYSTEM AND MANUAL FOAM APPLICATION, AND OBSTRUCTED HEXANE FIRES USING FIXED SYSTEM FOAM APPLICATION. (CC = CONCENTRIC CIRCLES, SC = SHEET METAL CROSS, IB = I-BEAM CROSS)

circle obstruction increased control times in all cases. The control times for tests with the concentric circle obstruction were 2 to 3 times greater than for tests with no obstruction present. Since only meager data are available, these observations should be viewed as being qualitative in nature.

In the case of fire extinguishment, the test data provided no consistent behavior with regard to obstructions. In some instances, the obstructions increased the extinguishment time; in other cases, the extinguishment time was close to or less than the extinguishment time without obstructions.

Some general observations can be made concerning the behavior of the low expansion foams with the concentric circle obstruction present. The more fluid foams had little difficulty in controlling or extinguishing the fire within the concentric circle obstruction. Stiffer, less fluid foams were not capable of penetrating into the circles as easily and therefore were slower to control or extinguish a fire in inner portions of the concentric circle obstruction.

Manual foam application generally resulted in control times about equal to those for fixed nozzle tests, but extinguishment times were much shorter for the manual tests. This decrease in extinguishment time occurs because the fire fighter can direct the foam at the pit walls where the fire persists. The spraying of "new" foam along the walls helps to cool them and aids the foam blanket in sealing against them. If the range of the foam nozzle is insufficient to allow the operator to reach any desired part of the pit with foam, then the extinguishment time for the manual attack should be similar to the extinguishment time for a fixed system operating at the same application rate.

The low expansion foams showed no scaling effects. At the same application rate (in gpm/ft^2) 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 hexane pools.

High Expansion Foam

High expansion foam proved to be the most effective of the foam agents tested on the hexane fires, i.e., at a given application rate (expressed in gpm/ft^2), high expansion foam showed the fastest control and extinguishment times of all the foams tested. In addition, the concentric circle obstruction had virtually no effect on either control times (see Figure 32) or extinguishment times.

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

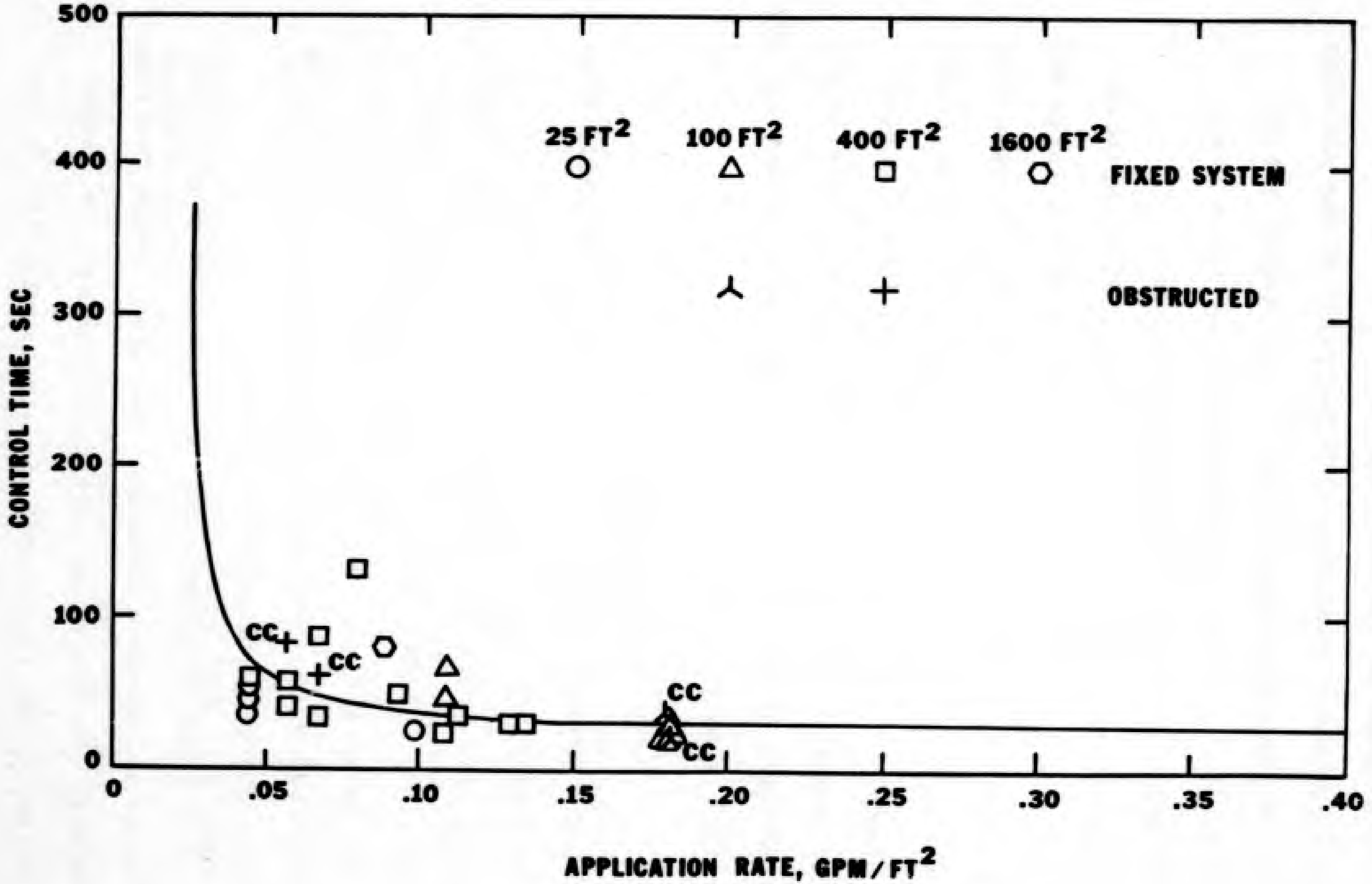


FIGURE 32. COMPARISON OF FIRE CONTROL TIMES FROM HIGH EXPANSION FOAM TESTS ON UNOBSTRUCTED AND OBSTRUCTED HEXANE FIRES USING FIXED SYSTEM FOAM APPLICATION. (CC = CONCENTRIC CIRCLES)

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. These reasons are felt to be most responsible for the excellent performance of the high expansion foam.

This is not to say that high expansion foam has no 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.

High expansion foam was the only foam which showed the same degree of correlation in both the control and extingiushment times. The standard deviation in the correlation curve was about 15 seconds for either control or extingiushment times.

The control and extinguishment times of the high expansion foam were not influenced by pit size or burning rate. However, wind speed and wind direction (in relation to the direction of foam application) did affect the results in a few tests. With the wind blowing at about 90° relative to the foam application direction, the foam was swept toward the downwind edge of the pit (see Figure 33). This resulted in a factor of two increase in the control and extinguishment times. The increase in control time may be misleading since,

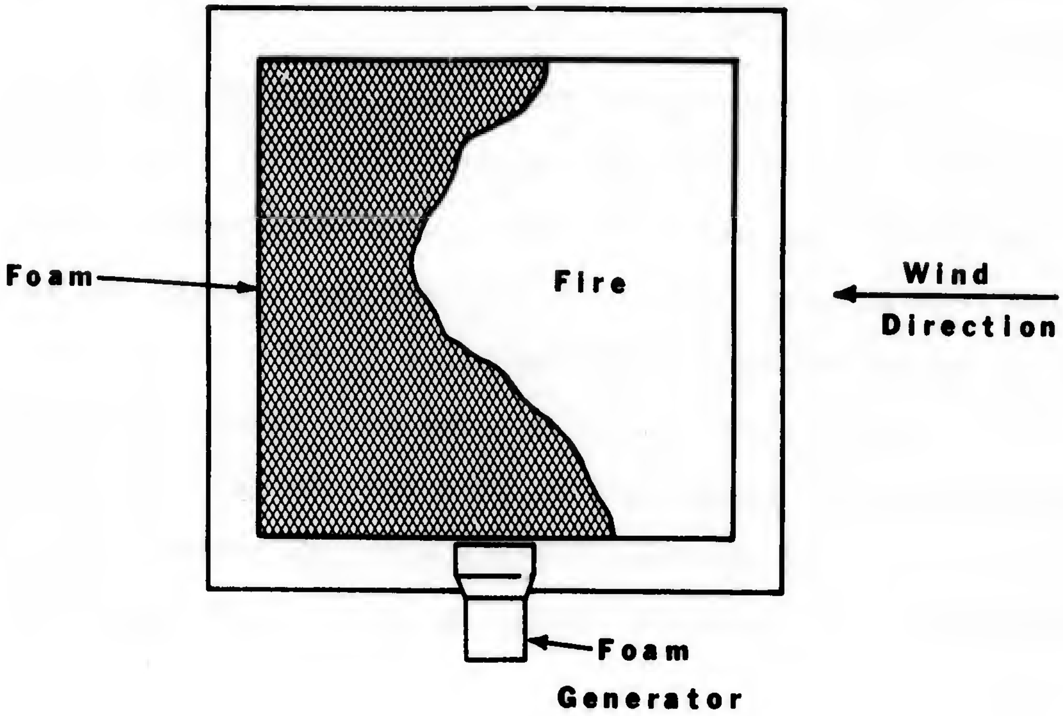


FIGURE 33. PLAN VIEW OF FIRE PIT SHOWING THE EFFECT OF CROSSWINDS ON HIGH EXPANSION FOAM DISTRIBUTION.

on those occasions when there was a crosswind, the last part of the fuel to be covered by foam was the part that was nearest the radiometer. Thus the incident heat flux at the radiometer did not decrease as fast as it would have if the wind had not been blowing or had been blowing from a different direction. This resulted in an "artificial" increase in control time. When the wind direction was parallel to the application direction, the wind speed did not adversly affect the foam's performance. The foam generators were placed upwind of the pit whenever possible and, barring unexpected wind shifts, most of the data showed no wind effects.

Dry Chemical Agents

Figure 27 illustrates that if the fire extinguishing effectiveness of a dry chemical is defined as the ability to extinguish fire at low application rates, then the urea-$KHCO_3$ is the most effective, $NaHCO_3$ is least effective, and $KHCO_3$ is intermediate. However, this definition of effectiveness is not universally accepted. Fixed nozzle fire extinguishing systems are generally designed to operate at application rates greater than the minimum in order to extinguish the fire in a reasonable period of time and provide a safety factor in case of windy conditions, etc. At application rates greater than about 0.10 lb/ft^2-sec, there is very little difference in extinguishment times for the hexane fires among the three dry chemicals. A case can therefore be made for selecting a dry chemical agent for use in fixed nozzle systems on the basis of which one will extinguish the fire for the lowest cost when applied at rates greater than 0.10 lb/ft^2-sec. Under these conditions, the order of the three dry chemicals is reversed since $NaHCO_3$ is much cheaper than urea-$KHCO_3$ and $KHCO_3$ is intermediate. If the dry chemical system is designed for manual application of the powder (e.g., hoselines, monitor nozzles, or portable units), then the choice of agents might be urea-$KHCO_3$ first and $NaHCO_3$ last since, for a given flow rate, the urea-$KHCO_3$ provides a greater safety factor.

Many of the tests resulted in nonextinguishment of the fires. For $NaHCO_3$, about 40 percent were not extinguished. For $KHCO_3$, about 60 percent and for urea-$KHCO_3$ about 25 percent were not extinguished. The inability of the dry chemical agents to extinguish a hexane fire can be attributed to one or more of the following reasons: inadequate application rate, uneven powder distribution, nozzle clogging, and powder surging. If application rates were below a certain minimum rate (the minimum rate varied depending upon the agent), extinguishment would not occur. Even with application rates above the required minimum, extinguishment attempts might not be successful if the powder distribution is uneven; some areas of the fire may receive inadequate agent and provide flame sites for subsequent reignition of the pool. Adequate powder distribution depends on proper nozzle location and selection and the type of agent used. For example, the urea-$KHCO_3$ agent tended to fan out from a nozzle in a shorter, bushier pattern than $NaHCO_3$ or $KHCO_3$, probably because the urea-$KHCO_3$ is less dense than the other two powders. Thus the urea-$KHCO_3$ was more effective in covering the area between nozzles but less effective in projecting agent across the pit. Nozzle clogging was influenced by the type of agent and the temperature of the dry chemical nozzles. Hot nozzles were potential sources of dry chemical melting, decomposition, and subsequent coating. The $KHCO_3$ powder used in these tests was more prone to nozzle plugging than the other agents. Powder surging was also a problem when the $KHCO_3$ powder was used; the fire would alternately receive adequate and then inadequate powder for extinguishment. Thus the fire would have a tendency to reform and extinguishment would be impossible or lengthened considerably.

In the 100-ft^2 fire tests, obstructions had little effect on the performance of either the $NaHCO_3$ or the urea-$KHCO_3$ agents (see Figure 34 and 35). The $KHCO_3$ agent perfoamed poorly with obstructions, extinguishing only 1 of 10 obstructed 100-ft^2 fires (see Figure 36). The poor performance of the $KHCO_3$ was probably due to lack of range and poor powder distribution. In general, the potassium bicarbonate ($KHCO_3$) was less reliable than the other two powders. It is not known if this is related to the chemical itself or if it is specific to the brand used in these tests.

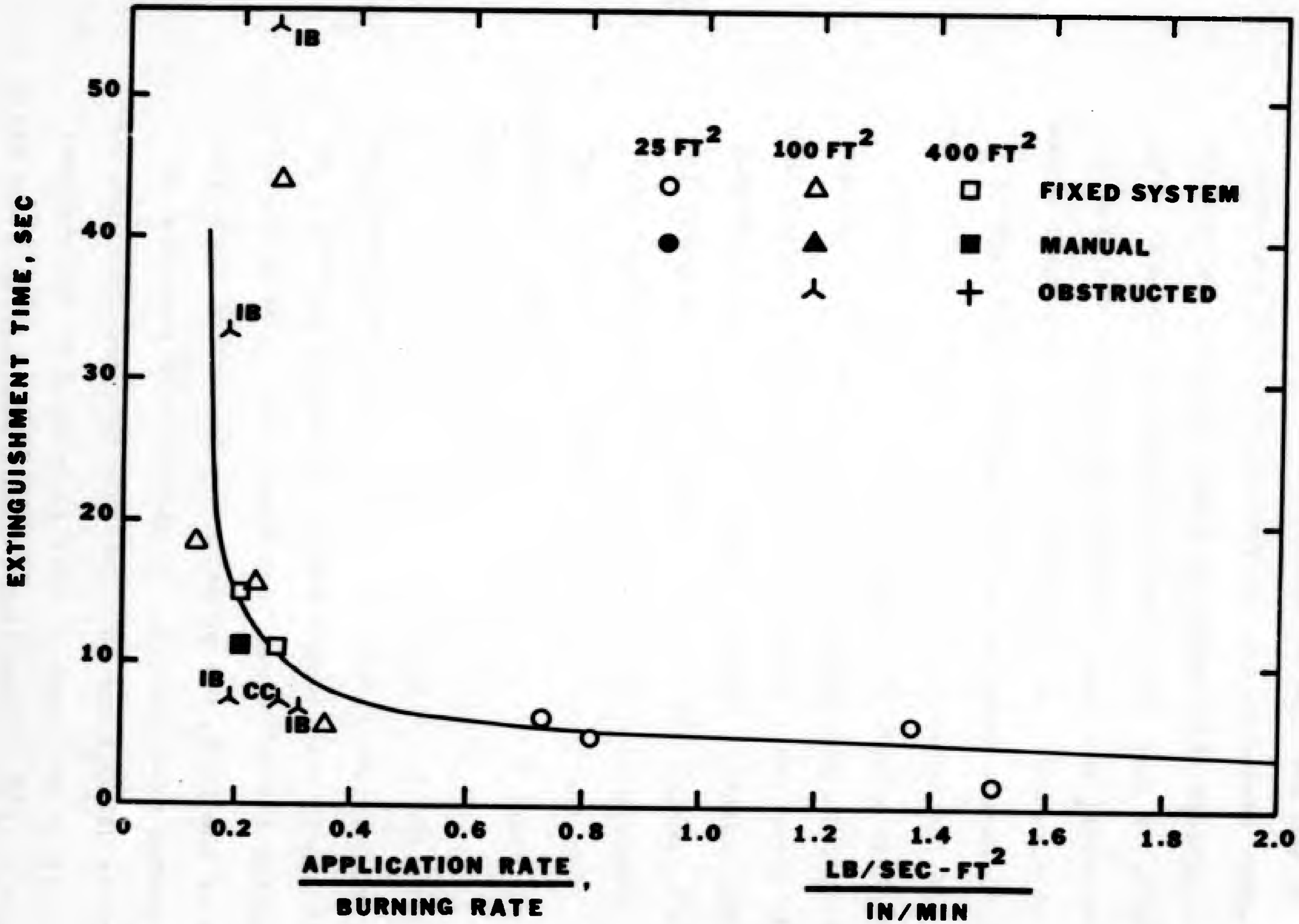


FIGURE 34. COMPARISON OF FIRE EXTINGUISHMENT TIMES FROM $NaHCO_3$ DRY CHEMICAL TESTS ON UNOBSTRUCTED AND OBSTRUCTED HEXANE FIRES USING FIXED SYSTEM DRY CHEMICAL APPLICATION. (IB = I-BEAM CROSS, CC = CONCENTRIC CIRCLES).

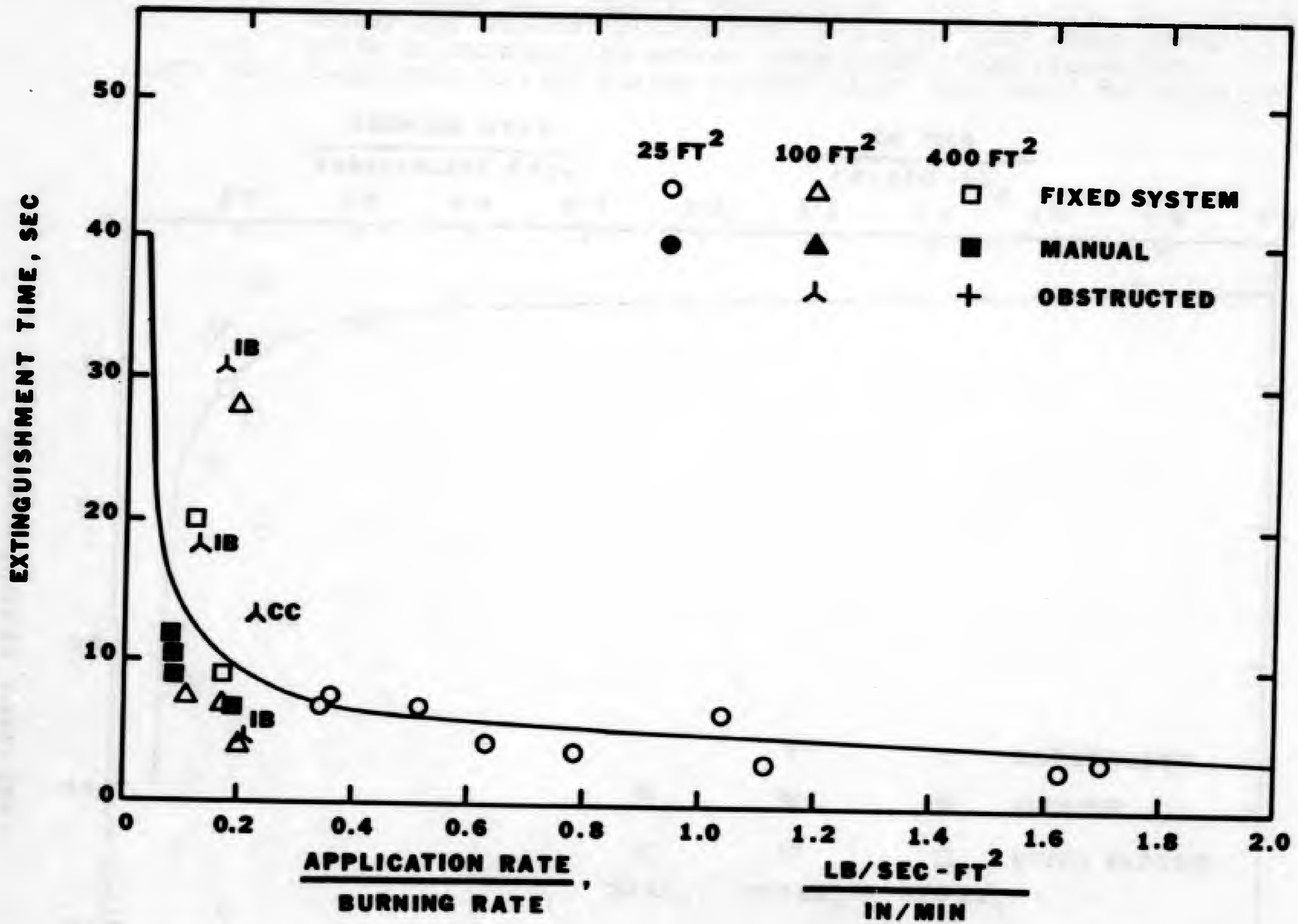


FIGURE 35. COMPARISON OF FIRE EXTINGUISHMENT TIMES FROM UREA-$KHCO_3$ DRY CHEMICAL TESTS ON UNOBSTRUCTED HEXANE FIRES USING FIXED SYSTEM AND MANUAL DRY CHEMICAL APPLICATION, AND OBSTRUCTED HEXANE FIRES USING FIXED SYSTEM DRY CHEMICAL APPLICATION. (IB = I-BEAM CROSS, CC = CONCENTRIC CIRCLES).

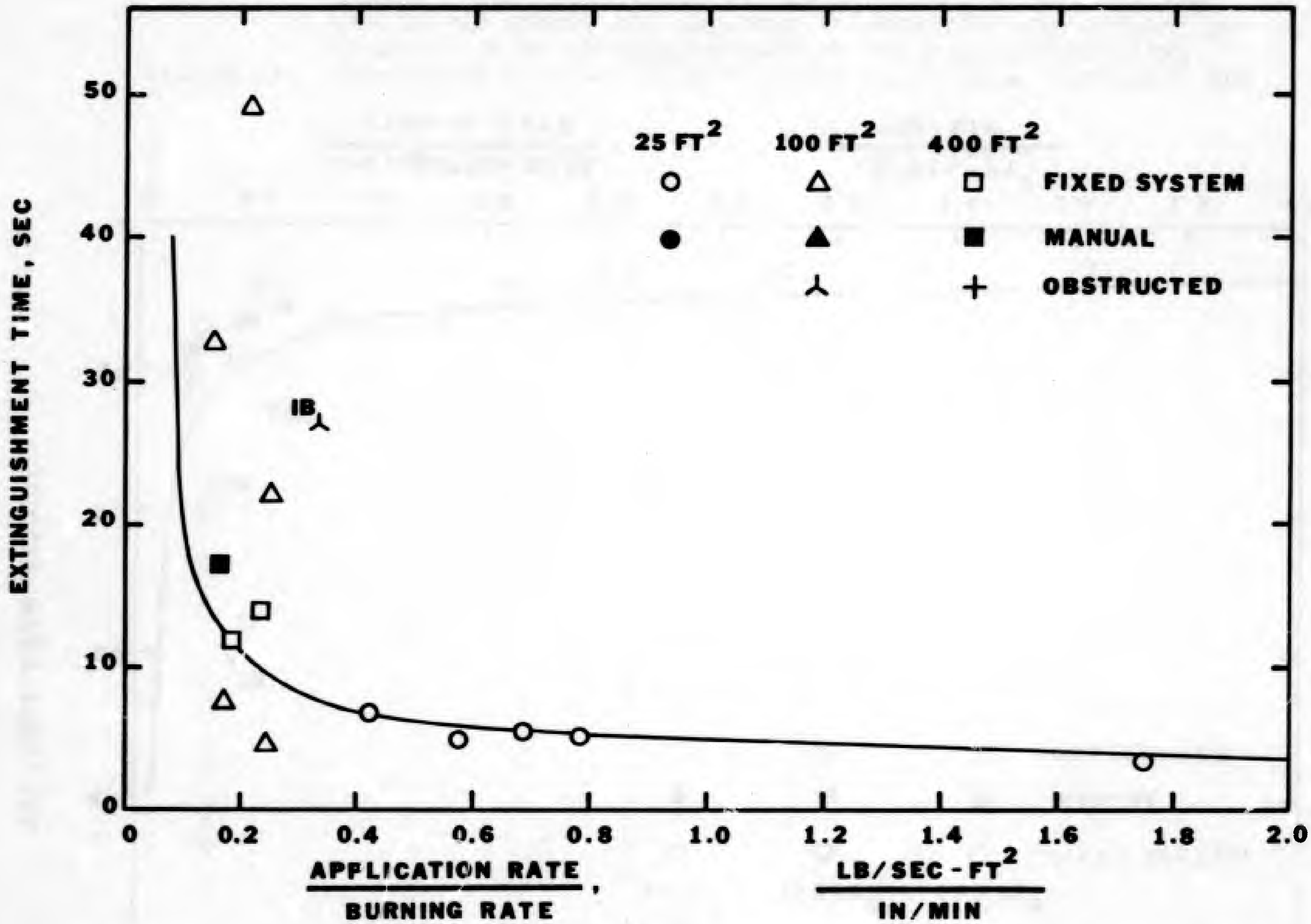


FIGURE 36. COMPARISON OF FIRE EXTINGUISHMENT TIMES FROM $KHCO_3$ DRY CHEMICAL TESTS ON UNOBSTRUCTED HEXANE FIRES USING FIXED SYSTEM AND MANUAL DRY CHEMICAL APPLICATION, AND OBSTRUCTED FIRES USING FIXED SYSTEM DRY CHEMICAL APPLICATION. (IB = I-BEAM OBSTRUCTION)

Three fire extinguishment attempts were made on 400-ft^2 fires with the concentric circles for obstructions. None of these was successful due to the inability of the dry chemical system to project sufficient powder to the center of the obstruction. A re-designed system with an overhead nozzle aimed at the center would most likely be capable of extinguishing these obstructed fires since obstructed fires should not be more difficult to extinguish than unobstructed fires if the dry chemical system is properly designed (i.e., designed so that adequate powder is supplied to all parts of the fire).

Several attempts were made to extinguish the 100-ft^2 and 400-ft^2 fires manually using one or two hoselines from the dry chemical units. The three attempts on the 100-ft^2 fire were unsuccessful. This was probably caused by the low level of the fuel in relation to the top of the pit wall which made it difficult to adequately reach all areas of the fire with the dry chemical from the single hoseline. For the manual extinguishment tests on the 400-ft^2 fires, water was added to the pit so that the fuel surface was only a few inches below the top of the pit wall. Once this change in test procedure was made, several manual extinguishment attempts were successful and their extinguishment times were approximately the same as for fixed system tests at the same application rates.

Other Observations

This section presents a discussion of observations made during the hexane fire tests. These observations are included either because they had an effect on the fire control or extinguishment time or because they might be useful in comparing results between different fuel types.

As previously mentioned, low expansion foam control times were far more repeatable than extinguishment times. This result was attributed to the effect of the pit wall on the sealing ability of the foam. The metal pit liners were potentially the most uniform wall surface since they would not crack or spall like the refractory coating. However, after several heating and cooling cycles the liners would buckle, twist, and begin to lift up from the pit bottom. This allowed burning to occur between the liner and the pit wall. As the foam covered the pit, the fire would be extinguished in the area bounded by the metal liner. However, the foam could not reach the space between the liner and pit wall and burning continued there. This allowed the fire to flash back into the main pit area causing erratic extinguishment times. This problem was solved by filling the pit with water to a level above the bottom of the pit liner. The water formed a seal that prevented hexane from entering the space between the liner and pit and thus eliminated the burning in that area.

Other fuels may not be amenable to this solution. For example, water soluble fuels or fuels denser than water could not be handled in this manner.

When metal liners were not used, the pit wall surface condition varied with time. This variation was the result of refractory flaking away from the concrete walls under the extreme heating/cooling cycles associated with the tests. At times, hexane would enter the refractory/concrete interface below the hexane level and exit, as vapor, above the liquid level. This would produce flames above the foam level, thereby extending the extinguishment time until the foam level reached the flame height or until the hexane liquid was cooled sufficiently and the flame extinguished due to lack of adequate fuel. This problem with the refractory cannot be avoided. Elimination of the refractory lining on the walls would greatly accelerate the pit wall deterioration, necessitating frequent repair (if possible) or pit replacement.

During the testing, a thermocouple was placed in the hexane pool at a known height above the pit floor. Data from this thermocouple indicated that the hexane heated up only in the top 0.5 inch and little of the fire's radiant energy reached below this level. This may be a significant observation to remember when the extinguishing abilities of foams on different liquids are compared. All else being equal, a liquid which is heated in a thin layer would cool to below the boiling point faster than one which is at the boiling point throughout. This might be an important factor for liquids which boil near the prevailing ambient temperature.

The effect of preburn time on the control and/or extingiushment of a hexane fire was also noted during the test sequence. The initial tests were allowed to preburn for 10 minutes before either foam or dry powder agent was applied. Thermocouples were provided to monitor the metal liner temperature both on the upwind and downwind sides of the pool as well as the obstruction temperature. Figure 37 shows a typical time/temperature history of the liner and obstruction. Both the liner and obstruction reached the auto-ignition temperature of hexane ($\sim$ 478°F) in less than one minute and 90 percent of their maximum temperature within 6 minutes. Since only about the upper half inch of the fuel was heated, even during long-term tests, the burning rate reached steady state values within a minute or so. Within the accuracy of the test data, no preburn time effect was noted, so part of the tests were run with shorter preburn times to reduce the quantity of fuel burned.

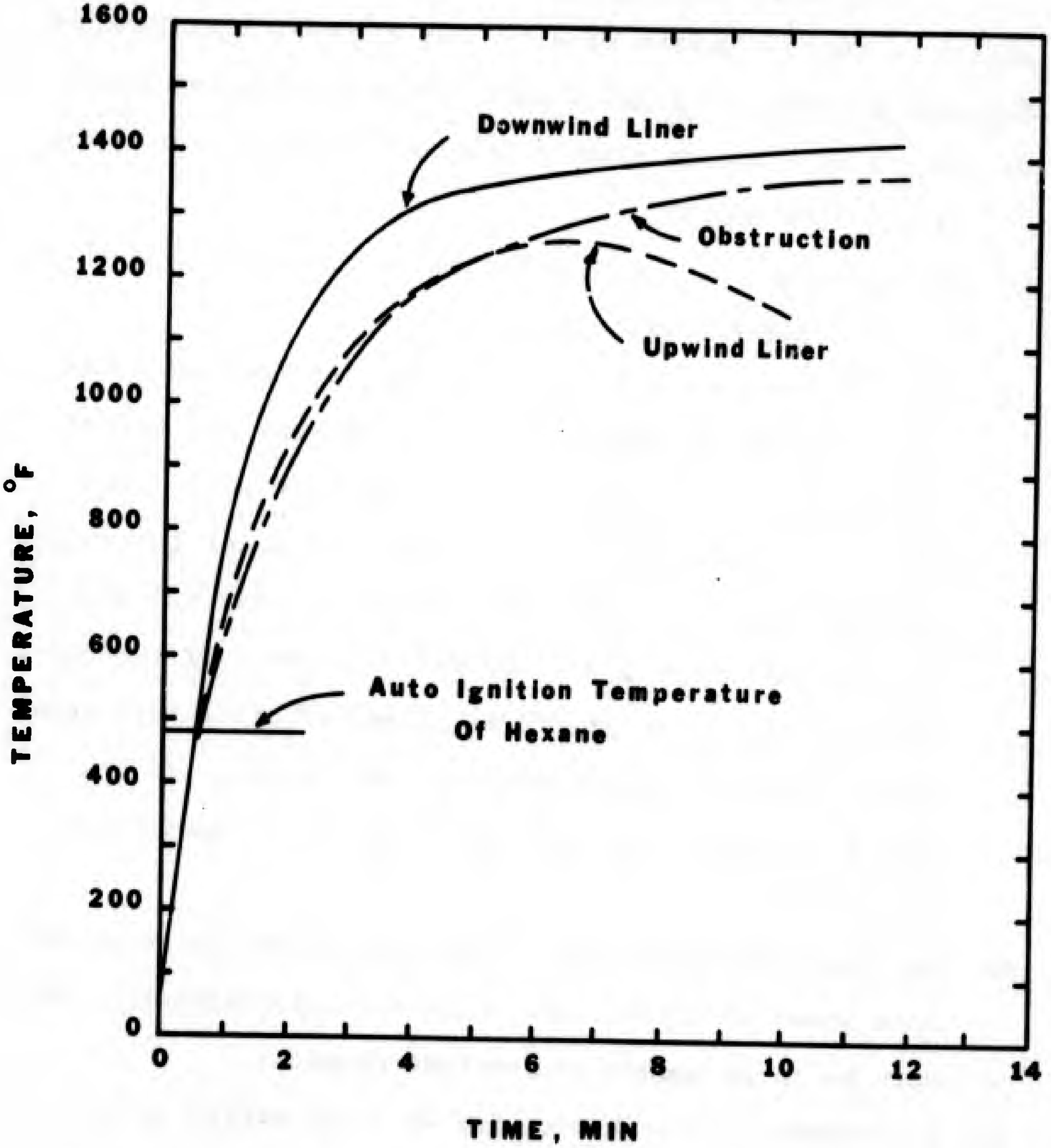


FIGURE 37. TYPICAL PIT LINER AND OBSTRUCTION TEMPERATURES.

KEY ELEMENTS OF THE BASIC TEST METHOD

The basic test method as developed and used in this series of tests consists of a few key elements that must be followed in order to allow direct comparison between tests.

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 circles.

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 ft^2 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 10d. 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 premixed to insure accurate dilution. If premixing is not practical, both the water flow rate 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.

SUGGESTED METHODS FOR COMPARING RELATIVE EFFECTIVENESS OF FIRE CONTROL AGENTS

The primary objective of the work summarized in this report was to set and demonstrate a basic, uniform method for measuring the response of fires to various control agents, thus allowing a comparison of the relative effectiveness of the agents. The test procedures were to be developed without relying on previous test methods and were to cover a size range large enough that scaling effects could be determined.

The standard test methodology has been developed. The results of tests using this standard method show that although there is some data scatter, the data can in general be correlated rather well. If only the unobstructed tests that used fixed nozzle systems are considered and any of the tests in which the agent distribution equipment failed or malfunctioned are rejected, the dry chemical fire extinguishment times and foam fire control times are consistent and repeatable.

The general goal of comparing agent effectiveness can be considered in two ways: (1) different agents can be compared for effectiveness when fighting fires burning the same fuel, and (2) a single agent may be used to attack fires from different fuels to determine differences in effectiveness caused by different fuels. Differences in effectiveness are caused by differences in the interacting chemical and physical properties of the agent-fuel combination.

Differences in effectiveness may also be caused by differences in application technique. In this work the comparison of agent effectiveness was the goal, so a fixed agent delivery system was selected to preclude variability caused by application technique.

It is important to emphasize that the test methodology used here produces data which represent a quantification of a given fire's response to a given agent. Comparison of sets of data allows relative ranking, and therefore, expressions of the relative effectiveness of the fire fighting agents. The methodology does not provide the means for choosing an agent or system or for defining an "acceptable" agent or system. Instead, the methodology measures the purely technical aspect of effectiveness: how well a fire fighting agent fulfills its function in extinguishing or controlling a given fire. As an endpoint or functional goal, extinguishment is a technically self-evident event, control is a technically defined event (although arbitrarily defined). Returning again to the subject of agent or system selection, the process or means of selection (which is usually a comparison of size, cost, maintainability, reliability, availability, a preconceived fire fighting goal, and frequently other factors) is not a purely technical problem which a technical methodology can address. That is why this methodology was designed to quantify relative functional effectiveness, with maximum effectiveness considered to be extinguishment or control of a fire in the shortest time with the lowest agent application rate, expressed in quantitative terms.

In general, foam systems as a class cannot be compared directly with dry chemical agents because of the different extinguishment mechanism. Foams extinguish fires by forming a covering over the fuel surface that restricts or prevents fuel vaporization. Dry chemicals act primarily through a free radical scavenging action that breaks the combustion chain reaction. Foams require longer application times to control or extinguish a fire than dry chemicals, but dry chemicals provide no protection against reignition once agent application stops. Thus, comparing agent effectiveness between the major classes of agents may require an a priori selection of the fire fighting goal.

The results of the fire control and extinguishment tests provide a fairly simple, quantitative method for comparing agent effectiveness. Plots of control time (for foams) and extinguishment times (for dry chemicals) result in hyperbolic curves. In general, each curve can be represented by an equation of the form

$$t - t_m = \frac{K}{(A - A_m)^a}$$

where t = control time or extinguishment time

t_m = minimum time required for extinguishment or control at high application rate

A = application rate

A_m = minimum application rate for extinguishment or control

K, a = constants

Both A and A_m are modified to include burning rate for dry chemical tests.

For any given combination of fuel and agent, the values of t_m, A_m, a, and K may be derived from the fire control or extinguishment data. In the case of the foam tests, A_m was derived from an analysis of the burning rate data. Once the constants are derived from an analysis of the data, comparisons can be made. (Figures 24 and 27 are examples of such curves for hexane fires.)

Figure 38 shows curves of t versus A for two hypothetical agent or fuel combinations. At first glance, it is obvious that Agent X is more effective, functionally, than Agent Y: it controls or extinguishes the fire more quickly and at lower application rates and is effective at application rates at which Agent Y fails or has no demonstrable effect. However, there are additional factors to consider, if one is making a choice of agent or system for fighting fires from a particular fuel. Assume Agent X is much more expensive than Agent Y. Is the improvement in control or extinguishment time worth the additional cost? Or is it acceptable to use a less expensive agent and provide more of it at a higher application rate? A strictly economic judgment may be made based on agent

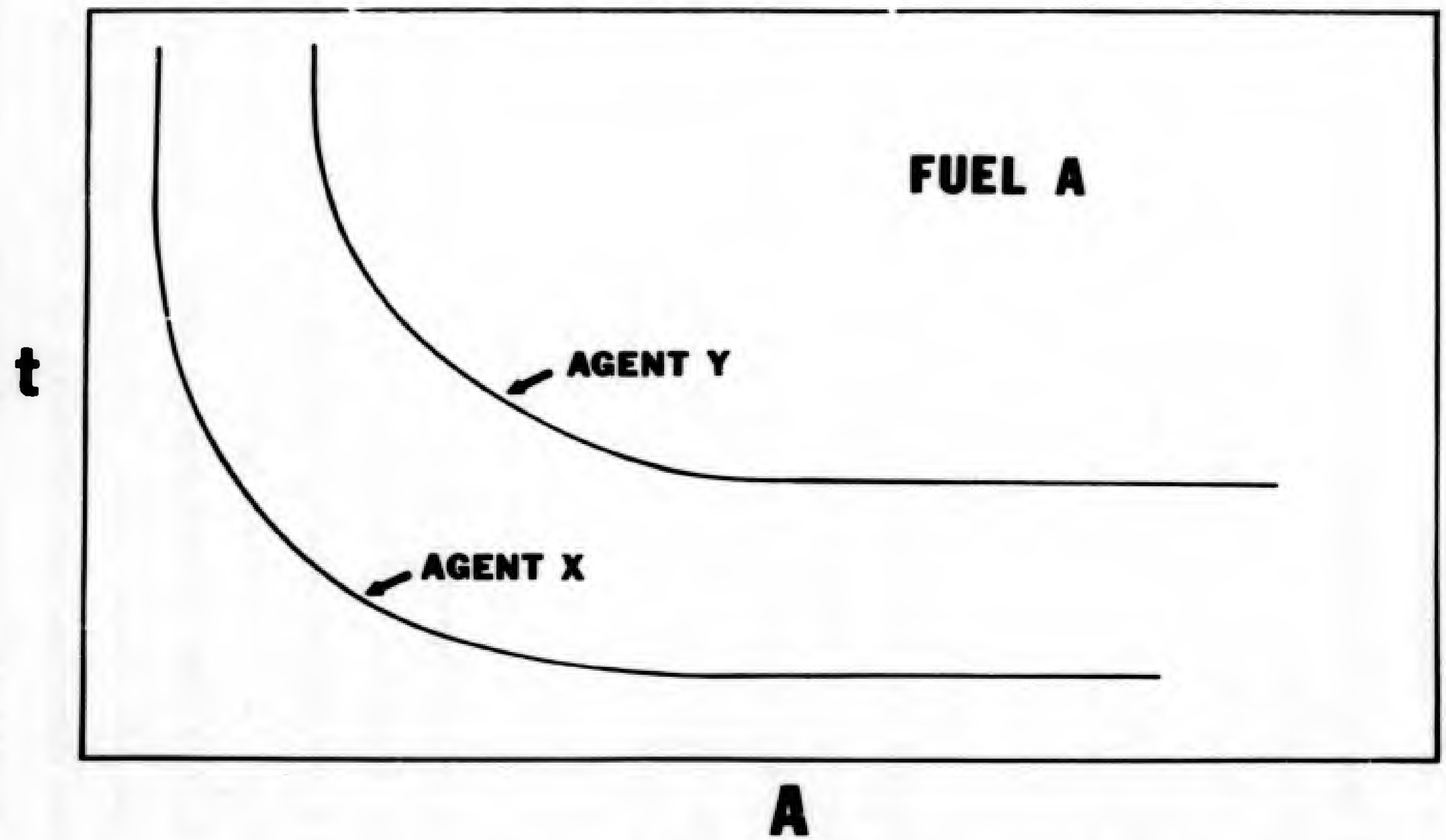


FIGURE 38. CONTROL OR EXTINGUISHMENT CURVES FOR TWO HYPOTHETICAL AGENTS AND A SINGLE FUEL.

cost, storage and delivery system cost, and the number of times use is anticipated. Other factors such as limiting the amount of damage, preventing fire spread, and protecting personnel can also be considered.

Figure 39 shows curves for a different hypothetical situation. A single agent is used for extinguishing or controlling fires in two different fuels. The control or extinguishment time for Fuel B may not be acceptable because the agent cost is too high or the time too long. The curves allow that judgment to be made, and, if curves for additional agents are available, a single agent with acceptable effectiveness for both fuels may be found.

Because of the many variables that are not directly related to a test comparison methodology, it is not possible to specify a set of criteria for agent acceptability. However, it is possible to specify a test methodology and a data comparison technique that can be used to determine agent response. The response data can then be used to specify agent acceptability when considered in conjunction with other relevant factors.

In order to compare data from different test series, several key elements are required in the test program. The previous section lists the key elements which are necessary to account for other factors which affect the fire's response. If they are followed, data from several sources should be comparable. The high purity hexane data in this report can

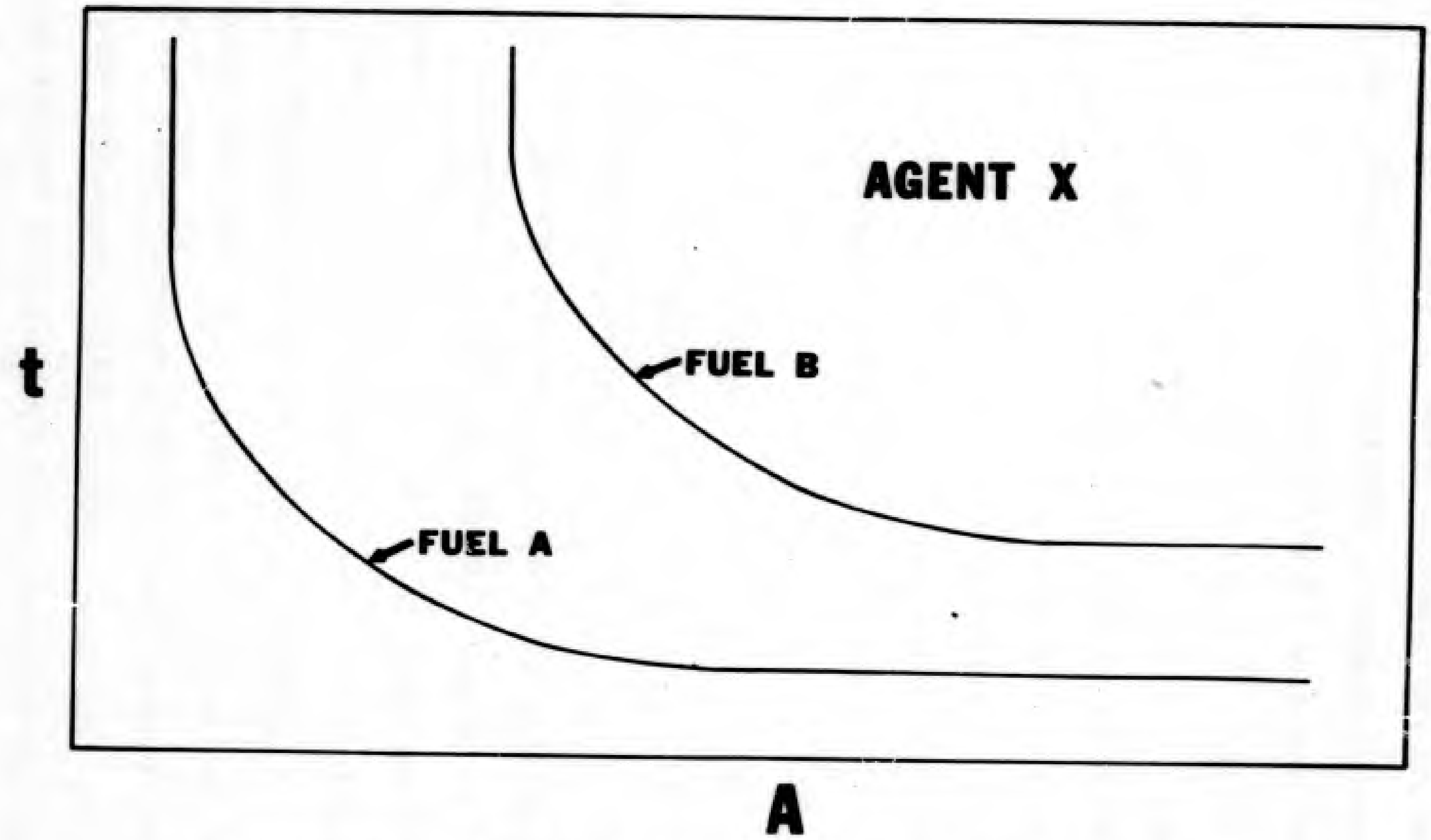


FIGURE 39. CONTROL OR EXTINGUISHMENT CURVES FOR TWO HYPOTHETICAL FUELS AND A SINGLE AGENT.

serve as a baseline for future comparisons. All the agents tested were effective for hexane fires, although there were differences in their ability to control or extinguish the fires.

APPENDIX A

TEST DATA AND COMMENTS

The seven tables presented in this section, Tables A-1 through A-7, 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., datalogger 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 which obstruction, if any, was used (IB = I-beam cross, SC = sheet metal cross, and CC = concentric circles). An "L" in the Liner column denotes that a sheet metal liner was used for that test. An "M" in the Manual column indicates that the extinguishment attempt was by manual application of the agent rather than by a fixed system. Fires which were not controlled by foam application are listed as "NC"; those not extinguished by foam or dry chemical are listed as "NE". An explanation of the dry chemical nozzle types and sizes is given in Appendix C.

TABLE A-1. PROTEIN FOAM DATA

Test ID	Date	Run No.	Pit Size (ft²)	Obstruc.	Liner	Manual	Burning Rate (in/min)	Application Rate (gpm/ft²)	Control Time (sec)	Exting. Time (sec)	Wind Speed (mph)	Preburn Time (sec)	Comments
1	10-30-78	2	25		L		0.15	0.376	43	44	13	540	
2	"	4	25		L		0.14	0.224	60	93	10	600	
3	"	6	25		L		0.14	0.148	87	134	9	560	
4	"	8	25		L		---	0.08	97	207	4	---	
5	11-15-78	2	100		L		---	0.137	51	126	11	---	
6	"	3	100		L		---	0.09	99	162	9	565	
7	11-17-78	2	100		L		---	0.086	117	331	8	---	
8	"	3	100		L		0.24	0.182	76	152	7	530	
9	"	4	100		L		0.27	0.055	186	396	7	220	
10	"	5	100		L		---	0.014	NC	NE	---	300	
11	11-30-78	4	100		L		---	0.40	49	125	7	---	Foam stopped at 80 sec
12	12-11-78	2	100		L		0.31	0.40	52	118	8	---	
13	"	3	100		L		0.36	0.27	52	218	8	510	Foam stopped at 120 sec
14	12-12-78	1	100		L	M	0.31	0.145	60	183	18	750	
15	12-18-78	1	100				0.31	0.40	45	120	15	490	
16	"	2	100				0.24	0.119	52	144	20	425	
17	"	3	100				0.24	0.058	141	448	15	425	
18	"	4	100				0.29	0.016	NC	NE	16	250	
19	12-19-78	1	100	CC			0.26	0.144	160	510	12	410	Foam stopped at 400 sec
20	12-20-78	1	100	IB			0.23	0.140	70	278	16	720	
21	12-21-78	2	100	SC			0.37	0.142	109	435	7	775	
22	12-26-78	1	100	CC	L		0.33	0.140	---	180	11	600	
23	6-14-78	1	400				0.33	0.194	50	96	14	190	
24	"	2	400				0.38	0.092	135	NE	17	185	
25	"	3	400				0.32	0.049	110	177	17	180	
26	6-28-78	1	400	CC			0.36	0.097	NC	NE	---	380	Poor Foam Quality
27	"	2	400	CC			0.36	0.097	330	NE	---	386	
28	7-10-79	1	400			M	0.25	0.097	120	NE	---	120	
29	7-19-79	1	1600				0.33	---	---	---	2	390	Foam Delivery Pipe Ruptured
30	"	2	1600				0.38	0.10	100	341	8	120	Plunging Foam

TABLE A-2. AFFT DATA

Test ID	Date	Run No.	Pit Size (ft^2)	Obstruc.	Liner	Manual	Burning Rate (in/min)	Application Rate (gpm/ft^2)	Control Time (sec)	Exting. Time (sec)	Wind Speed (mph)	Preburn Time (sec)	Comments
1	10-31-78	2	25		L		0.18	0.352	27	36	4	[illegible]35	
2	"	4	25		L		0.16	0.228	48	92	7	720	
3	"	6	25		L		0.18	0.144	37	64	5	525	
4	"	7	25		L		0.17	0.068	63	81	5	575	
5	11-20-78	1	100		L		0.24	0.400	28	73	14	525	
6	"	2	100		L		0.38	0.178	39	NE	10	710	
7	"	3	100		L		0.26	0.120	43	NE	10	840	Foam stopped at 220 sec
8	11-22-78	1	100		L		0.30	0.058	74	701	12	845	
9	"	2	100		L		0.30	0.036	116	NE	12	660	
10	"	3	100		L	M	0.31	0.037	60	263	11	760	
11	11-28-78	1	100		L		0.33	0.277	45	140	15	610	
12	"	2	100		L		0.39	0.155	67	---	16	535	
13	"	3	100		L		0.35	0.178	50	190	14	570	Foam inadvertently stopped
14	11-29-78	1	100		L		0.34	0.088	63	537	11	785	
15	"	2	100		L		0.35	0.088	63	187	14	680	
16	"	3	100		L		0.47	0.134	43	229	14	700	
17	"	4	100		L	M	0.41	0.150	---	103	10	640	
18	12-1-78	1	25				---	0.080	45	100	---	1160	
19	"	2	25				---	0.080	---	---	---	1030	Datalogger malfunctioned
20	12-15-78	1	100				0.25	0.40	34	909	8	500	Datalogger malfunctioned
21	"	2	100				0.29	0.120	32	925	6	490	Foam stopped at 125 sec
22	"	3	100				0.35	0.058	67	993	6	505	Foam stopped at 365 sec
23	"	4	100				0.31	0.016	220	775	6	575	
24	12-19-78	2	100	CC			0.27	0.144	95	364	13	460	Ran out of fuel during test
25	12-20-78	2	100	IB			0.25	0.138	68	306	18	690	
26	12-21-78	3	100	SC			0.31	0.143	69	---	7	550	
27	12-27-78	1	100	CC	L		0.28	0.140	64	109	---	300	
28	6-11-79	1	400				0.25	0.194	30	NE	7	180	
29	"	2	400				0.36	0.097	64	NE	5	180	
30	"	3	400				0.27	0.049	170	NE	4	180	
31	6-28-79	3	400	CC		M	0.32	0.097	---	207	---	120	
32	7-3-79	1	400	CC			0.27	0.097	120	315	5-15	180	
33	7-11-79	1	400			M	0.36	0.097	---	137	10	---	
34	7-16-79	1	1600				0.32	0.100	64	222	5	80	

TABLE A-3. ALCOHOL FOAM DATA

Test ID	Date	Run No.	Pit Size (ft^2)	Obstruc.	Liner	Manual	Burning Rate (in/min)	Application Rate (gpm/ft^2)	Control Time (sec)	Exting. Time (sec)	Wind Speed (mph)	Preburn Time (sec)	Comments
1	11-7-78	2	25		L		0.20	0.336	30	NE	4	560	Foam stopped at 255 sec
2	11-21-78	2	100		L		0.42	0.135	42	82	7	---	
3	"	4	100		L		---	0.057	47	180	6	---	
4	"	6	100		L		---	0.036	90	NE	8	---	
5	11-30-78	2	100		L		---	0.400	43	1200	13	60	Foam stopped at 200 sec
6	12-12-78	2	100		L		0.26	0.290	30	466	12	540	Foam stopped at 265 sec
7	12-13-78	1	100		L		0.34	0.132	39	528	15	615	Foam stopped at 400 sec
8	"	2	100		L		0.30	0.077	47	587	15	675	Burning behind metal pit liner
9	"	3	100		L	M	0.22	0.128	< 60	107	14	480	Inadequate nozzle range
10	12-19-78	3	100	CC			0.26	0.137	72	506	13	540	Foam stopped at 420 sec
11	12-20-78	3	100	IB			0.27	0.133	42	360	21	635	Foam stopped at 315 sec
12	12-21-78	1	100	SC			0.28	0.138	60	282	9	445	
13	6-13-79	1	400				0.25	0.049	85	200	13	180	
14	"	2	400				0.34	0.097	60	150	12	180	
15	"	3	400				0.24	0.194	28	88	12	270	
16	7-3-79	2	400	CC			0.27	0.097	114	228	---	300	
17	7-10-79	2	400			M	0.26	0.097	50	235	---	90	3% Foam concentration
18	7-19-79	3	1600				0.31	0.100	45	533	8	120	

TABLE A-4. HIGH EXPANSION FOAM DATA

Test ID	Date	Run No.	Pit Size (ft^2)	Obstruc.	Liner	Manual	Burning Rate (in/min)	Application Rate (gpm/ft^2)	Control Time (sec)	Exting. Time (sec)	Wind Speed (mph)	Preburn Time (sec)	Comments
1	12-27-78	2	100		L		---	0.18	28	65	18	551	
2	"	3	100		L		0.24	0.18	19	30	17	342	
3	4-12-79	3	100		L		0.34	0.18	21	39	5	416	
4	"	4	100		L		0.34	0.036	NC	NE	7	330	
5	4-17-79	1	100		L		0.32	0.108	47	73	15	335	
6	4-19-79	1	100		L		0.37	0.108	66	65	13	390	
7	"	2	100		L		0.35	0.18	20	26	13	270	
8	"	3	100		L		0.37	0.18	23	21	18	84	
9	"	4	100	CC	L		0.32	0.18	33	45	[illegible]	338	
10	"	5	100	CC	L		0.3[illegible]	0.18	24	25	12	60	
11	4-26-79	1	25		L		---	0.048	45	113	7	519	
12	"	2	25		L		0.26	0.048	40	87	7	446	
13	"	3	25		L		---	---	---	---	3	---	Foam gen. motors damaged by heat
14	4-30-79	7	25		L		0.17	0.096	24	75	9	360	
15	"	8	25		L		0.20	0.048	36	100	9	382	
16	5-16-79	1	400				0.36	0.078	NC	NE	16	66	
17	5-18-79	2	400				---	0.078	132	250	19	20	Non-uniform foam production
18	5-29-79	1	400				0.33	0.066	88	96	11	120	
19	"	2	400				0.33	0.056	58	74	11	120	
20	6-4-79	1	400				0.38	0.066	35	59	10	120	
21	"	2	400				0.28	0.056	42	60	11	120	
22	"	3	400				0.30	0.136	30	30	10	120	
23	"	4	400				0.35	0.129	30	53	10	60	
24	"	5	400				0.40	0.107	23	40	10	210	
25	6-6-79	1	400				0.31	0.092	48	70	14	140	
26	"	2	400				0.32	0.112	36	50	12	120	
27	"	3	400				0.30	0.044	60	118	10	90	
28	7-3-79	3	400	CC			0.31	0.066	62	113	5-15	300	
29	"	4	400	CC			0.33	0.056	83	102	5-15	300	
30	7-23-79	1	1600				0.34	0.088	81	120	6	60	

TABLE A-5. $NaHCO_3$ DRY CHEMICAL DATA

Test ID	Date	Run No.	Pit Size (ft^2)	Obstruc.	Liner	Manual	Burning Rate (in/min)	Application Rate ($lb/sec-ft^2$)	Exting. Time (sec)	Nozzle Type and Number	Wind Speed (mph)	Preburn Time (sec)	Comments
1	10-30-78	1	25		L		0.15	0.220	1.5	2736-1707 (4)	13	485	
2	"	3	25		L		0.12	0.167	5.9	2731-1704 (4)	14	530	
3	"	5	25		L		0.16	0.126	4.8	2730-1704 (4)	9	525	
4	"	7	25		L		0.14	---	NE	2723-1704 (4)	--	490	Nozzles plugged
5	11-7-78	1	25		L		0.15	0.113	6.0	2730-1704 (4)	5	710	
6	"	3	25		L		0.17	0.037	NE	2719-1704 (4)	3	1260	Nozzles plugged
7	11-8-78	5	25		L		0.11	0.043	NE	2723-1704 (4)	16	615	
8	"	6	25		L		0.12	0.058	NE	2723-1704 (4)	14	810	
9	11-15-78	1	100		L		0.42	0.044	NE	2736-1707 (4)	10	500	Inadequate range
10	11-21-78	1	100		L		0.36	0.069	15.6	2741-1710 (4)	6	595	Reignited after extinguishment
11	11-30-78	1	100		L		0.34	0.041	NE	2726-1704 (8)	10	590	Inadequate range
12	12-11-78	1	100		L		0.27	---	NE	2736-1707 (8)	--	480	Inadequate range
13	3-7-79	3	100		L		0.28	0.077	44	259072 (2)	16	525	Liner lifted
14	"	4	100	IB	L		0.29	0.074	55	259072 (2)	18	479	Liner lifted
15	3-13-79	1	100	IB	L		0.26	0.080	7.0	259266 (4)	15	409	
16	"	5	100	IB	L		0.30	0.057	7.6	259266 (4)	20	485	
17	"	6	100	IB	L		0.27	0.049	33.4	259266 (4)	20	372	
18	3-15-79	3	100	CC	L		---	0.080	7.5	259266 (4)	10	---	
19	3-26-79	2	100		L		---	0.040	17.6	ATC-65 (4)	8	180	Nozzles plugged
20	3-27-79	3	100		L		0.27	0.094	5.6	ATC-165 (4)	9	195	
21	3-28-79	1	100		L		0.18	0.061	NE	ATC-165 (2)	15	208	
22	4-2-79	2	100		L	M	0.16	0.058	NE	1 Hoseline	15	53	
23	4-12-79	2	100		L		0.32	---	NE	ATC-50 (4)	10	48	Nozzles plugged
24	5-16-79	1	400				---	---	NE	---	16	70	One nozzle not operational
25	5-18-79	1	400				0.29	0.069	NE	ATC-188 (4)	19	60	Inadequate range
26	6-21-79	1	400				0.26	0.069	11	ATC-188 (4)	11	148	
27	"	2	400				---	0.054	15	ATC-188 (4)	13	139	Datalogger malfunctioned
28	7-30-79	3	400			M	0.21	---	12	2 Hoselines	12	90	Application rate not recorded

TABLE A-6. $KHCO_3$ DRY CHEMICAL DATA

Test ID	Date	Run No.	Pit Size (ft^2)	Obstruc.	Liner	Manual	Burning Rate (in/min)	Application Rate (lb/sec-ft^2)	Exting. Time (sec)	Nozzle Type and Number	Wind Speed (mph)	Preburn Time (sec)	Comments
1	10-31-78	1	25		L		0.18	0.137	5.3	2731-1704 (4)	4	510	
2	"	3	25		L		0.16	0.110	5.6	2728-1704 (4)	4	525	
3	"	5	25		L		0.17	0.070	7.0	2723-1704 (4)	4	800	
4	11-8-78	7	25		L		0.12	---	NE	2723-1704 (4)	14	695	Dry chemical hose plugged
5	11-17-78	1	100		L		0.29	0.033	NE	2732-1704 (4)	9	710	Nozzles plugged
6	11-21-78	3	100		L		0.30	0.062	NE	2741-1710 (4)	6	555	Nozzle heat shield obstructed powder flow
7	"	5	100		L		0.31	0.064	NE	2741-1710 (4)	7	700	
8	11-30-78	3	100		L		0.29	0.042	NE	2736-1707 (8)	9	605	Powder surging
9	3-6-79	1	100		L		0.27	---	NE	---	15	551	
10	3-7-79	1	100		L		0.28	0.058	49	259072 (2)	19	472	Plugging on one nozzle
11	3-8-79	1	100	IB	L		0.31	0.020	NE	259072 (2)	20	438	
12	3-12-79	1	100	IB	L		0.26	0.049	NE	259072 (2)	15	531	
13	3-13-79	2	100	IB	L		0.27	0.089	27	259266 (4)	15	471	
14	"	3	100	IB	L		0.31	---	NE	259266 (4)	15	56	Powder surging
15	"	7	100	IB	L		0.28	0.036	NE	259266 (4)	22	391	Nozzles plugged; inadequate range
16	3-14-79	1	100	IB	L		0.28	0.044	NE	259266 (4)	9	532	Nozzles plugged
17	3-15-79	2	100	IB	L		0.30	0.037	NE	259266 (4)	8	420	Nozzles plugged
18	"	5	100	CC	L		---	0.081	NE	259266 (4)	8	390	Inadequate range
19	3-20-79	1	100		L		0.23	0.076	NE	259266 (4)	23	234	
20	"	2	100		L		0.27	0.067	22	259266 (4)	11	255	
21	3-21-79	1	100		L		0.32	0.053	7.8	259266 (4)	16	300	
22	"	2	100		L		0.3[illegible]	0.041	NE	259266 (4)	18	296	Nozzles plugged
23	"	3	100		L		0.30	0.050	NE	259266 (4)	20	331	Nozzles plugged
24	3-26-79	3	100		L		0.27	0.049	33.2	ATC-65 (4)	10	157	Nozzles plugged
25	3-27-79	1	100		L		0.31	0.075	4.8	ATC-165 (4)	5	161	
26	4-2-79	1	100		L	M	0.41	0.038	NE	1 Hoseline	15	91	Powder surging
27	4-5-79	1	100	CC	L		---	0.047	NE	ATC-165 (4)	10	366	Inadequate range
28	4-11-79	1	100	CC	L		0.17	0.090	NE	ATC-165 (4)	25	60	High wind
29	4-12-79	1	100	CC	L		0.25	0.074	NE	ATC-165 (4)	12	48	Inadequate range
30	4-30-79	5	25		L		0.11	0.190	4.4	ATC-65 (2)	10	386	
31	"	6	25		L		0.17	0.097	5.0	ATC-65 (1)	9	418	
32	6-26-79	1	400				0.29	0.068	14	ATC-188T (4)	5	150	
33	6-26-79	1	400				0.32	0.057	12	ATC-188T (4)	5	124	
34	6-27-79	1	400	CC			0.25	0.094	NE	ATC-188T (4)	15	137	Only inner circle unextinguished
35	7-5-79	1	400	CC			0.24	0.069	NE	ATC-188T (4)	10	122	
36	7-12-79	1	400			M	0.36	0.025	NE	2 Hoselines	5-10	120	
37	"	2	400			M	0.22	---	NE	2 Hoselines	5-10	126	
38	"	3	400			M	0.25	0.03	NE	2 Hoselines	5-10	131	
39	7-30-79	4	400			M	0.26	0.025	NE	2 Hoselines	12	306	
40	"	5	400			M	0.23	0.036	17	2 Hoselines	13	124	

TABLE A-7. UREA - $KHCO_3$ DRY CHEMICAL DATA

Test ID	Date	Run No.	Pit Size (ft^2)	Obstruc.	Liner	Manual	Burning Rate (in/min)	Application Rate ($lb/sec-ft^2$)	Exting. Time (sec)	Nozzle Type and Number	Wind Speed (mph)	Preburn Time (sec)	Comments
1	11-8-78	1	25		L		0.12	0.076	4.5	2728-1704 (4)	19	645	
2	"	2	25		L		0.11	0.058	7.0	2728-1704 (4)	13	615	
3	"	3	25		L		0.11	0.033	NE	2723-1704 (4)	11	840	Nozzles misaligned
4	"	4	25		L		0.10	0.037	7.7	2723-1704 (4)	14	780	
5	3-7-79	2	100		L		0.27	0.052	28	259072 (2)	20	454	
6	3-12-79	2	100	IB	L		0.29	0.055	NE	259072 (2)	15	341	Uneven discharge
7	3-13-79	4	100	IB	L		0.28	0.059	4.5	259266 (4)	25	443	
8	"	3	100	IB	L		---	---	9.5	259266 (4)	22	---	
9	3-14-79	2	100	IB	L		0.33	0.056	31	259266 (4)	11	346	
10	3-15-79	1	100	IB	L		0.30	0.039	18	259266 (4)	6	290	
11	"	4	100	CC	L		---	0.069	13	259266 (4)	6	450	Reignited 30 sec after extinguishment
12	3-26-79	1	100		L		0.36	0.040	7.5	ATC-65 (4)	6	337	
13	3-27-79	2	100		L		0.33	0.067	4.2	ATC-165 (4)	5	278	
14	"	4	100		L		0.35	0.033	NE	ATC-165 (1)	6	182	Uneven flow; inadequate range
15	3-30-79	1	100		L		0.27	0.049	NE	ATC-165 (2)	10	142	Uneven flow; inadequate range
16	"	2	100		L		0.29	0.049	6.9	ATC-50 (4)	11	105	
17	4-2-79	3	100		L	M	0.33	0.037	NE	1 Hoseline	16	64	
18	4-24-79	1	25		L		0.13	0.222	3.5	ATC-165 (2)	13	480	
19	"	2	25		L		---	0.147	3.5	ATC-165 (1)	15	---	
20	4-30-79	1	25		L		0.13	0.136	6.6	ATC-65 (2)	8	439	
21	"	2	25		L		0.11	0.178	3.0	ATC-65 (2)	9	362	
22	"	3	25		L		0.13	0.099	3.9	ATC-65 (1)	10	384	
23	"	4	25		L		0.15	0.049	6.9	ATC-50 (1)	7	362	
24	6-20-79	1	400				0.34	0.058	9	ATC-188T (4)	7	123	
25	"	2	400				0.28	0.033	20	ATC-188T (4)	8	125	
26	7-5-79	2	400	CC			0.25	0.063	NE	ATC-188T (4)	10	120	
27	7-30-79	1a	400			M	0.27	0.049	6.9	2 Hoselines	13	126	
28	"	1b	400			M	---	0.021	12	1 Hoseline	13	30	
29	"	2a	400			M	0.25	0.022	9.2	1 Hoseline	10	120	
30	"	2b	400			M	---	0.021	10.7	1 Hoseline	10	30	

APPENDIX B

OBSTRUCTIONS

Various metal obstructions, illustrated in Figure B-1, were available for use during the tests on the 100-ft^2 and 400-ft^2 fires.

1) I-Beam Cross--This obstruction was constructed of steel I-beams (5 inch by 10 lb/ft) welded into a cross shape. The cross was supported on steel legs adjusted so that the bottom edge of the horizontally oriented cross was at or slightly above the surface of the fuel.
2) Sheet Metal Cross--Two pieces of 10-gage sheet metal were combined to form a 3-ft tall cross. This obstruction was placed directly on the bottom of the pit.
3) Concentric Circles--Two circular segments were fabricated from 10-gage sheet steel. Each segment had a 90° 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.

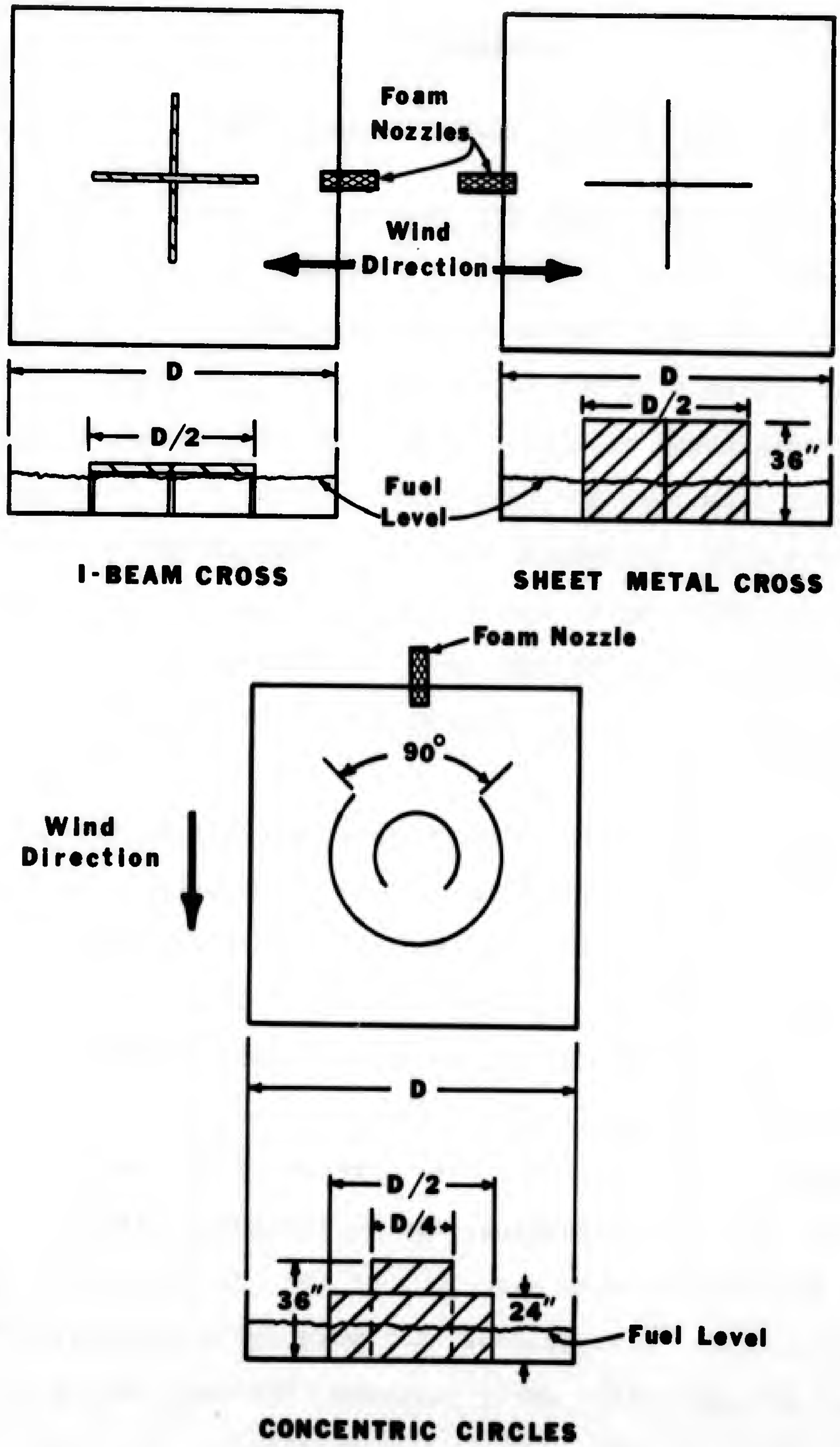


FIGURE B-1. OBSTRUCTIONS FOR USE IN 100-FT^2 AND 400-FT^2 FIRE PITS.

APPENDIX C

DRY CHEMICAL DISTRIBUTION SYSTEMS

Several different dry chemical distribution piping systems were used during the test program. The original plan had been to use four nozzles of the type shown in Figures C-1a, and C-2a, placed 6 inches above grade near each corner of the pit. Because these nozzles produce flat, fan-shaped spray patterns of less than 90°, they were located at a distance back from the pit corners so that the ideal powder distribution pattern would be as shown in Figure C-3. It was quickly determined that these nozzles were very susceptible to plugging and that the wind strongly affected the distribution pattern.

The second system used only two nozzles of the type shown in Figures C-1b and C-2b that were supposed to produce a flat, fan-shaped 180° spray pattern. These two nozzles were located in the two upwind corners of the pit approximately 2 inches below the top of the pit wall so that the wind would not adversely affect their performance. This arrangement, shown in Figure C-4a, proved to be even less effective than its predecessor due to inadequate range.

The third system used four of the nozzles of the type shown in Figures C-1c and C-5a that were designed to produce a flat, fan-shaped 180° spray pattern. The nozzles were located within the pit, approximately 6 inches below the top of the pit wall, one nozzle in each corner as shown in Figure C-4b. The main problem with this system proved to be that the range of the nozzles was insufficient to reach the center of the pit consistently.

The fourth system was a modification of the previous system; the nozzles remained the same and they were still placed about 6 inches below the top of the pit wall, but their location was changed from the corners to the center of each pit wall as shown in Figure C-6. This arrangement proved to be the most satisfactory because the center of the pit could now be reached consistently, all the dry chemical entered the fire zone so the application rate could be computed with confidence, and the effect of the wind was minimized. This same system was also used with only one or two nozzles in order to alter the application rate.

After this fourth system was developed, a number of similar nozzles were fabricated with different slit sizes and in a few cases, with four holes located as shown in Figure C-5b. The slit width was varied in order to provide a means of varying the dry chemical application rate. The extra holes were designed to increase the range of the nozzles toward the center of the pit. Table C-1 lists the pertinent data for the various nozzles.

In all of the above systems, the dry chemical distribution piping networks were designed to be symmetric, balanced

TABLE C-1. DRY CHEMICAL DISCHARGE NOZZLE TYPES AND SIZES

Nozzle Type	Part Number	Equivalent Orifice Diameter (inches)	Slit Width (inches)	Hole Diameter (inches)
A	2719-1704*	5/64		
A	2723-1704*	7/64		
A	2726-1704*	9/64		
A	2728-1704*	5/32		
A	2730-1704*	11/64		
A	2731-1704*	3/16		
A	2732-1704*	13/64		
A	2736-1707*	1/4		
A	2741-1710*	19/64		
B	259072+		0.096	0.156
C	259266+		0.096	0.156
C	ATC-50		0.050	0.125
C	ATC-65		0.065	0.125
C	ATC-165		0.165	0.203
D	ATC-188T		0.188	0.313

* Spray Engineering Co.

+ Walter Kidde and Co., Inc.

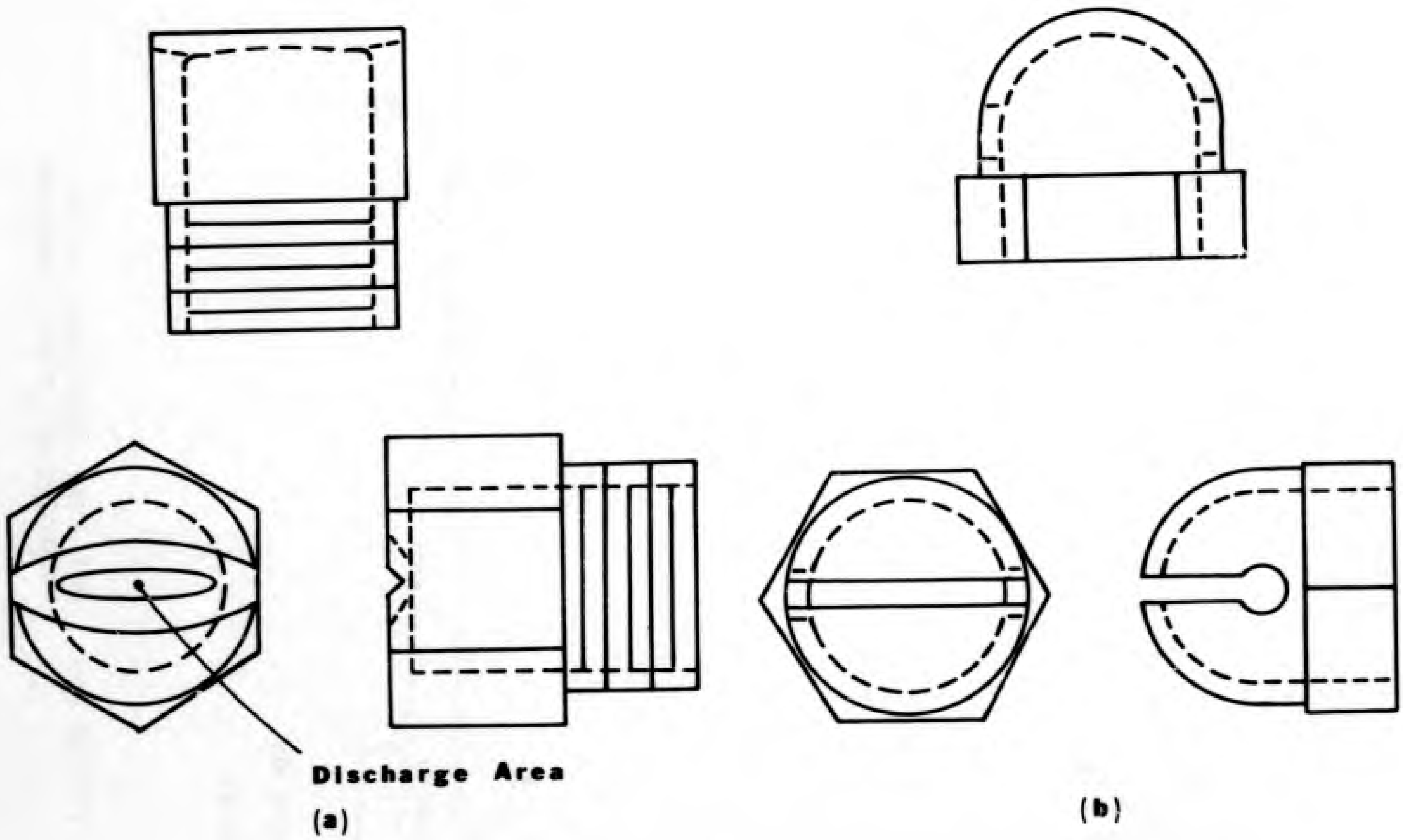


FIGURE C-2. DRY CHEMICAL DISCHARGE NOZZLES.

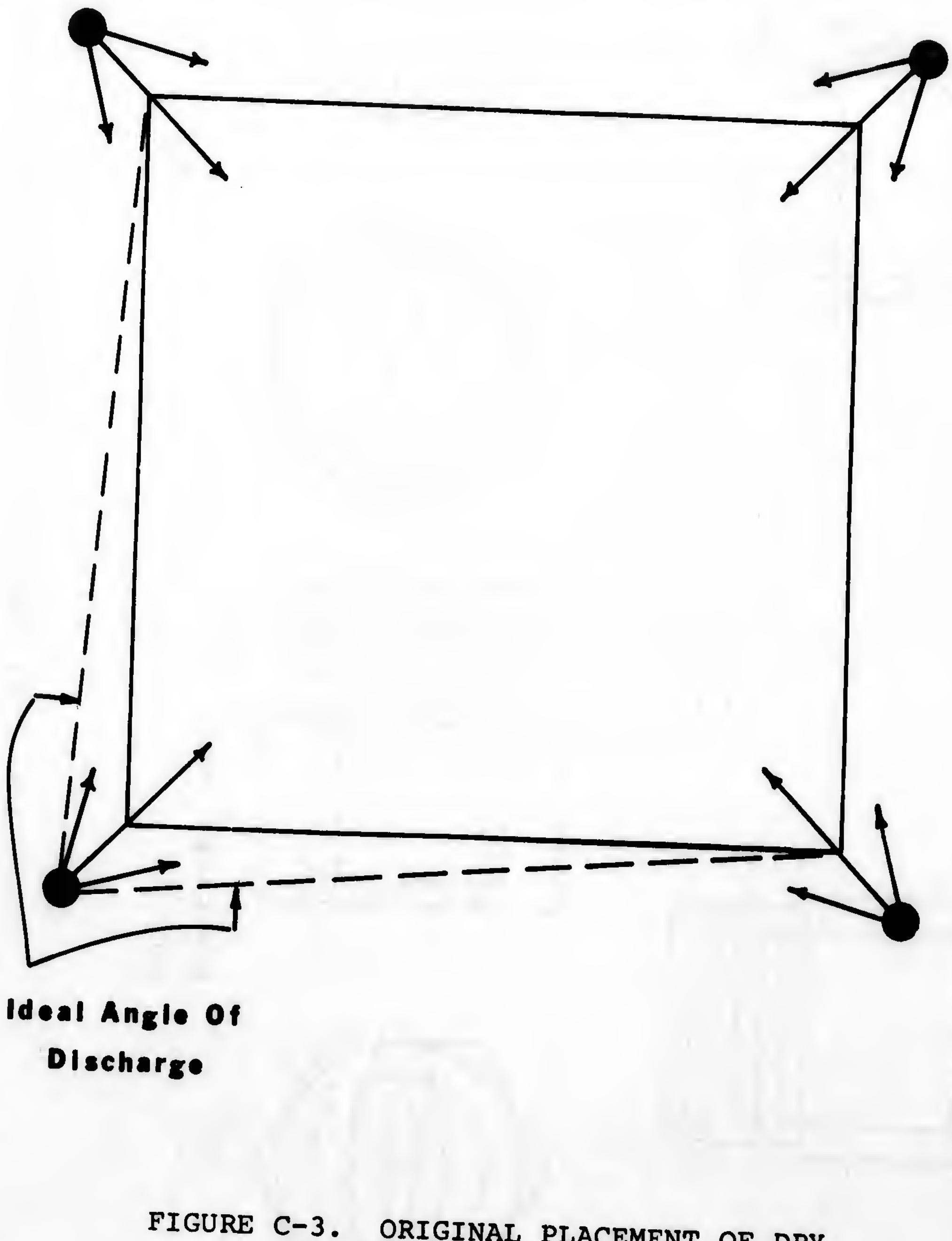


FIGURE C-3. ORIGINAL PLACEMENT OF DRY CHEMICAL DISCHARGE NOZZLES.

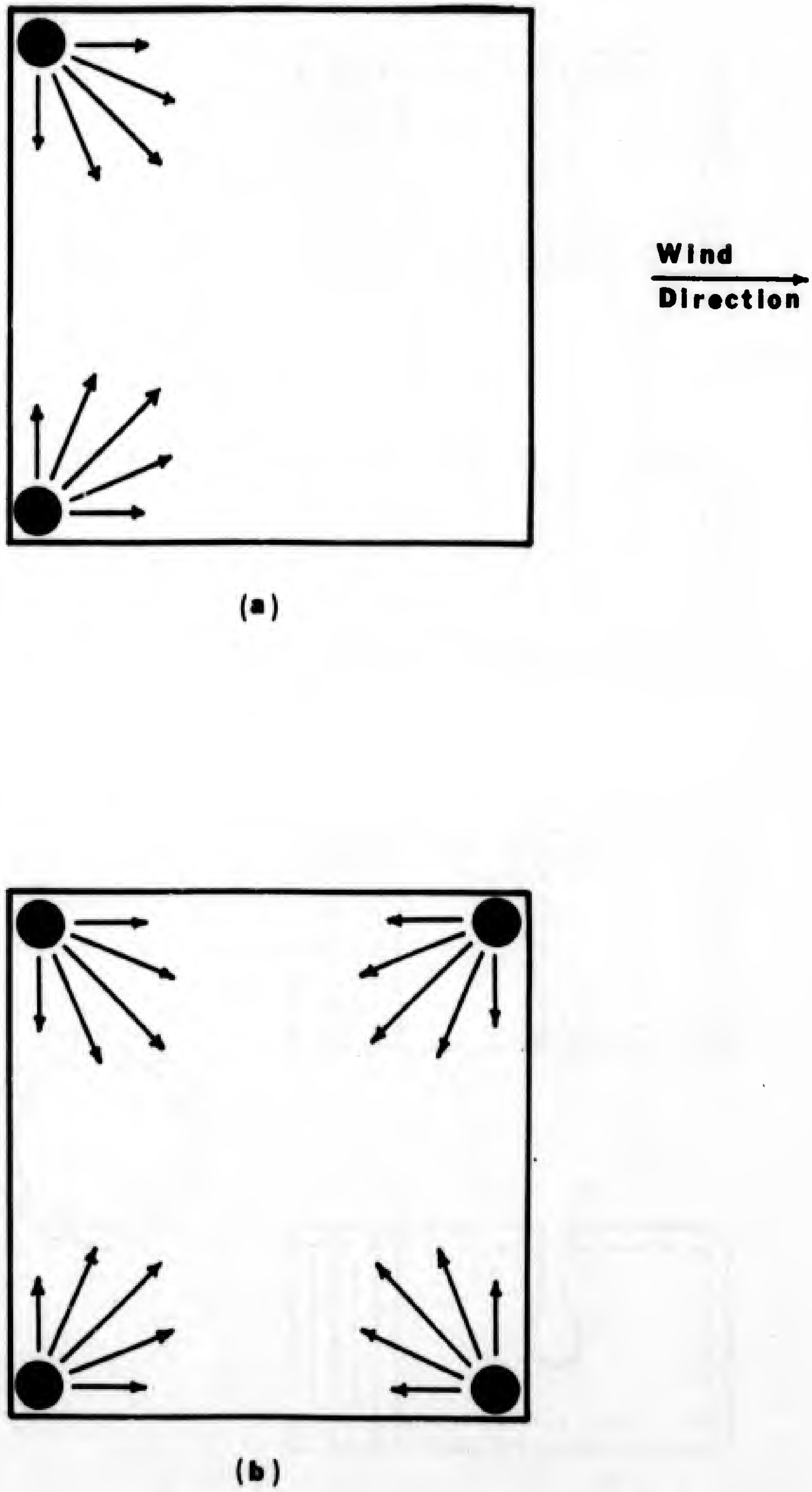
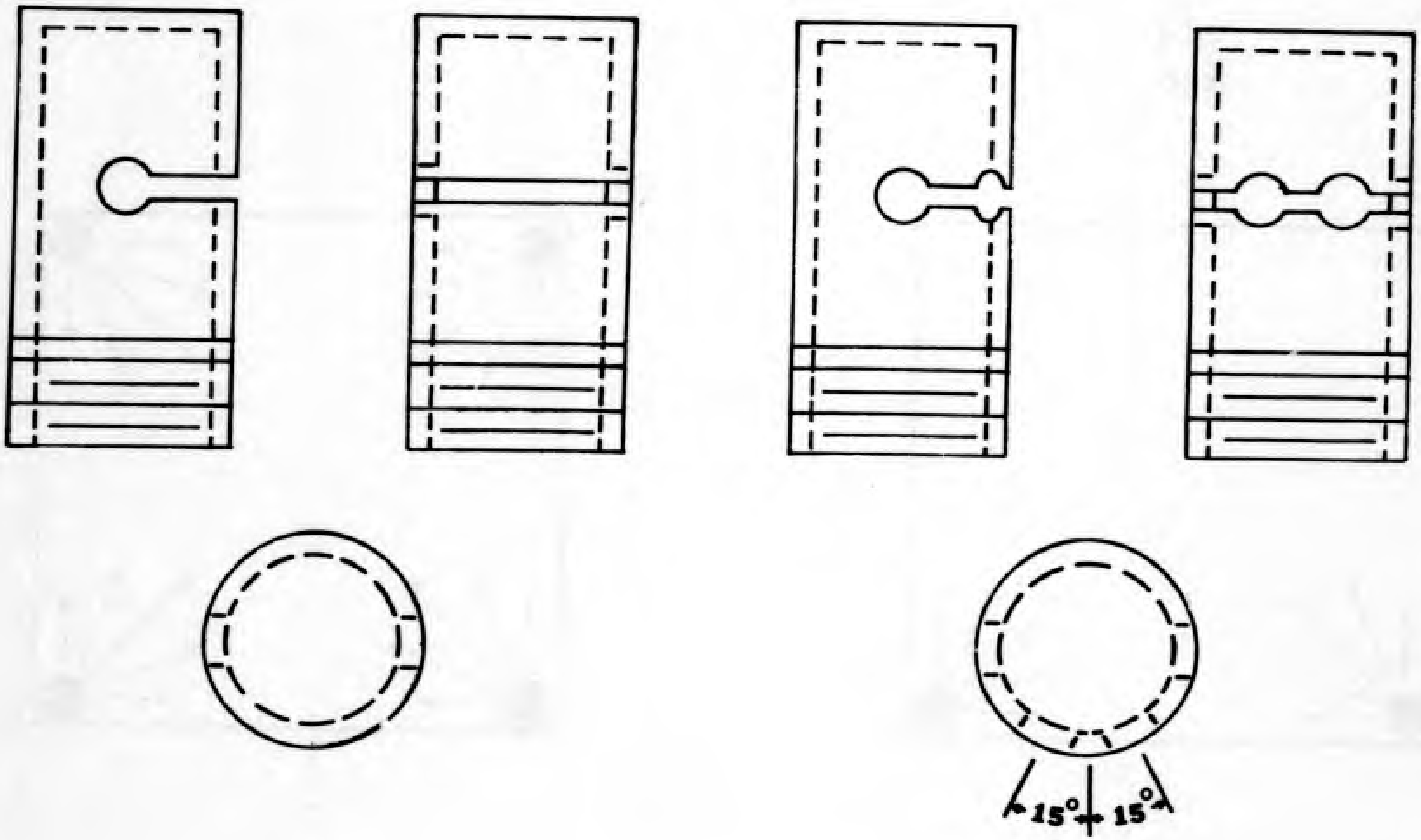


FIGURE C-4. PLACEMENT OF DRY CHEMICAL DISCHARGE NOZZLES;
(a) SECOND SYSTEM; (b) THIRD SYSTEM.



(a) (b)

FIGURE C-5. DRY CHEMICAL DISCHARGE NOZZLES.

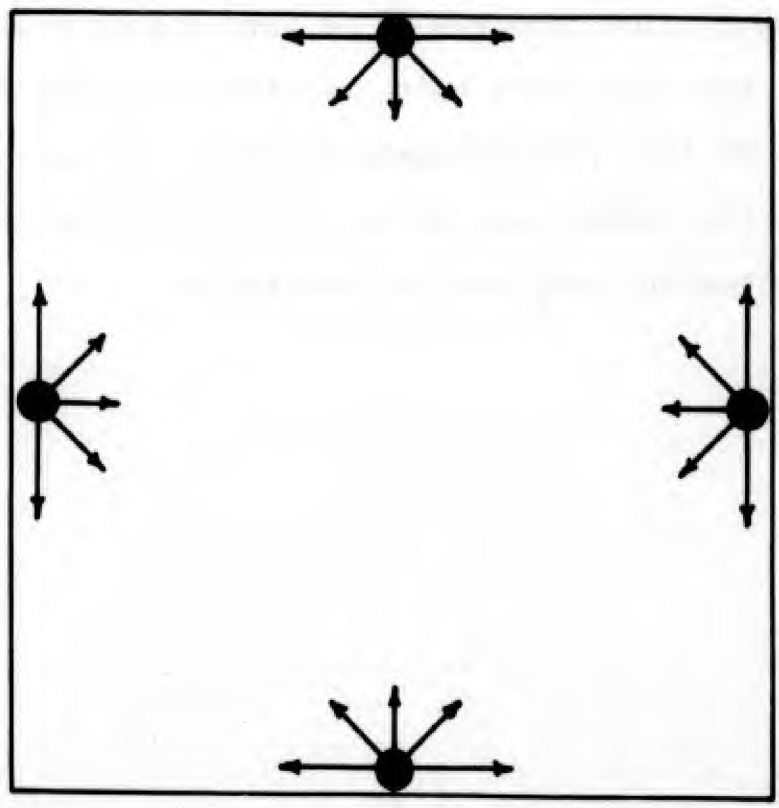


FIGURE C-6. FINAL CHOICE OF LOCATIONS FOR DRY CHEMICAL DISCHARGE NOZZLES.

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 fourth dry chemical distribution system is illustrated in Figure C-7. 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 range; different pipe sizes being 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.

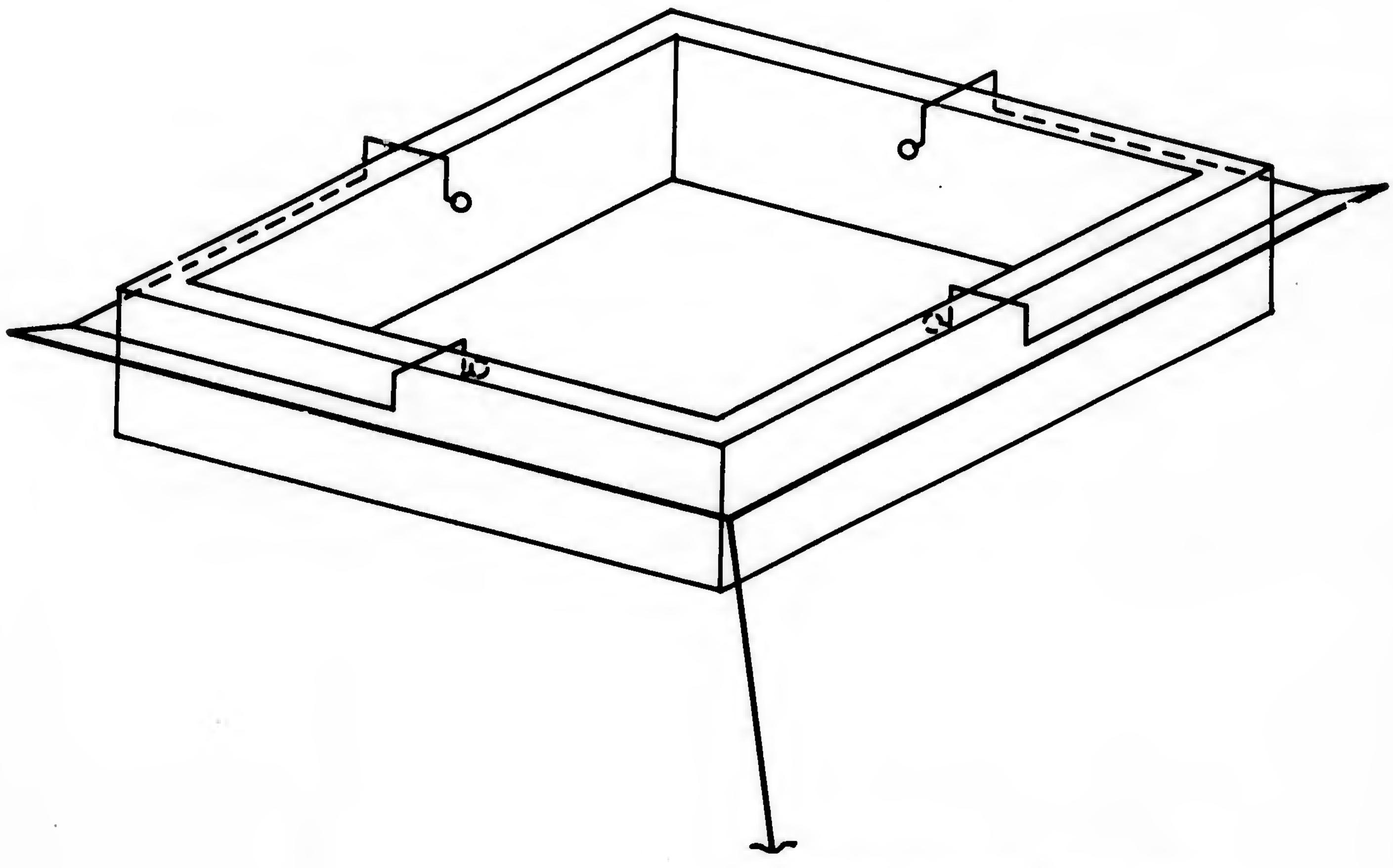


FIGURE C-7. FINAL FORM OF THE DRY CHEMICAL DISTRIBUTION PIPING SYSTEM.

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 System, Inc. Eleven nozzles, ranging in capacity from 2 gpm 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 operating 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

By using two nozzles simultaneously, it was possible to obtain flow rates other than those available with any single nozzles (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 5200 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

Preliminary tests with the 130-cfm units failed to produce high quality foam. Observation of the foam solution revealed that a precipitate was forming shortly after mixing the concentrate with the water. A different foam concentrate (designed for use with brackish water) was then tried. The foam quality was better but the quantity of foam was much too low. Further checking revealed that the spray nozzles supplied with the generators were undersized. After changing to the correct spray nozzles, each of the generators produced approximately 80 cfm of good quality foam. The nominal capacity of 130 cfm was apparently based on the flow rate of air through the fan when tested in free air (i.e., no back pressure). The foam solution on the generator screen causes back pressure on the fan which in turn decreases the air flow rate.

Problems were also encountered with the other sizes of generators. At the design operating pressure, the foam solution tended to spray through the screen rather than form a film over the screen holes. This caused the foam output to be much less than the design rate. Good quality could be made only if the foam solution pressure was set below the design pressure. This changed the foam solution flow rate, expansion ratio, and foam production rate.

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/ft^2). This also made comparisons among the four types of foam much easier.

APPENDIX E

PHYSICAL AND CHEMICAL DATA FOR HEXANE

The high purity normal hexane used as fuel for the fire tests had a guaranteed minimum normal hexane content of 85 percent by volume. The manufacturer* provided the following typical analysis of the fuel supplied.

Component	Volume Percent	Parts per Million
N-Hexane	89.18	---
Methylcyclopentane	7.86	---
3-Methylpentane	2.97	---
Olefins	---	1.4
Carbonyls	---	8.0
Organic Chlorides	---	< 1.0
Phenols	---	< 1.0
Water	---	54.0

Pertinent physical constants for the high purity normal hexane are:

Boiling Range	152-156°F
Flash Point	-10°F
Auto Ignition Temp.	478°F
Density (60°F)	41.8 lb/ft^3
Vapor Pressure (100°F)	5.2 psia typical 6.0 psia maximum

*Phillips Chemical Company

*U.S. GOVERNMENT PRINTING OFFICE : 1980 0-628-390/2612