AD-A014 228

AIRCRAFT GROUND FIRE SUPPRESSION AND RESCUE SYSTEMS. BASIC RELATIONSHIPS IN MILITARY FIRES. PHASES III, V, VI, AND VII

R. S. Alger, et al

DOD Aircraft Gound Fire Suppression and Rescue Office
Wright-Patterson Air Force Base, Ohio

May 1975

253097

DOD-AGFSRS-75-4

ADA014228

AIRCRAFT GROUND FIRE SUPPRESSION AND RESCUE SYSTEMS

BASIC RELATIONSHIPS IN MILITARY FIRES

Phases III, V, VI and VII

NAVAL SURFACE WEAPONS CENTER
WHITE OAK LABORATORY
SILVER SPRING, MARYLAND 20910

and

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA 94025

MAY 1975

FINAL REPORT

Approved for public release; distribution unlimited.

DOD AIRCRAFT GROUND FIRE SUPPRESSION & RESCUE OFFICE
WRIGHT—PATTERSON AIR FORCE BASE, OHIO 45433

157

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report is approved for public release; distribution unlimited.

Reference to trade names is for information only and endorsement by the Department of Defense is not implied.

This technical report has been reviewed and is approved.

Julius Singer

JULIUS SINGER, Program Manager
Aircraft Ground Fire Suppression
and Rescue Office (AGFSRO)

ACCESSION for
NTIS White Section ☐
DDC Buff Section ☐
UNANNOUNCED ☐
JUSTIFICATION ....

BY ....
DISTRIBUTION/AVAILABILITY CODES
Dist. AVAIL. and/or SPECIAL
A

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AIR FORCE/56780/7 July 1975 — 150

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DOD-AGFSRS-75-4	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Basic Relationships in Military Fires, Phase III, V, VI and VII		5. TYPE OF REPORT & PERIOD COVERED Technical Report Oct 71 - Nov 74
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) NSWC: R. S. Alger SRI: Ervin L. Capner		8. CONTRACT OR GRANT NUMBER(s) MIPR FY7615-72-05099 Amendments 1-4
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Surface Weapons Center NSWC/G-107 (Ray S. Alger) Stanford Research Institute Menlo Park CA 94025		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 64714F
11. CONTROLLING OFFICE NAME AND ADDRESS DOD Aircraft Ground Fire Suppression and Rescue System Office (ASD/SMGF) Wright-Patterson AFB Ohio 45433		12. REPORT DATE May 1975
		13. NUMBER OF PAGES 155
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Surface Weapons Center White Oak Laboratory Silver Spring MD 20910		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aircraft Ground Fuel Fires	Radiation Field
Fire Suppression	Substrates
Foam Forming Agents	Crash Vehicle Extinguishment Efficiency
Burning Rates	Fire Suppression Equipment
	Fire Suppression Techniques

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The suppression of two dimensional class B fuel fires with aqueous film forming foam (AFFF) was studied as a function of fuel, environment, and mode of agent application. In idealized laboratory experiments, the contributions to extinguishment from cooling, insulating, and isolating the fuel were examined as functions of conventional foam quality parameters, i.e., expansion ratio, drainage rate, and agent concentration. In field tests on fires ranging in area from 1500 to 48,000 ft^2 suppresion efficiency and burnback protection were

(Continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(Block 20 continued)
measured as a function of foam quality and mode of application from such vehicles as the MB-1, O11B, and Cat-Klein crash trucks. Yardsticks were defined to evaluate the efficiency of equipment and techniques. Two simple extinguishment models were developed to differentiate between the treatment of experimental variables in "total area" agent application as with sprinkler systems and in "incremental" application with a moving turret or nozzle.

Typical findings are (1) the chemical and physical properties of the best foam forming agents are not destroyed by heating to 212°F, (2) a pool of fuel burning under no wind conditions develops the highest burning rate and radiation field; consequently, extinguishment is usually simplified by a prevailing wind and porous substrates such as sand or gravel, and (3) extinguishment efficiency with crash vehicles in the field is considerably lower than in idealized experiments due to difficulties in applying uniform coatings of foam. There is considerable room for improvement in equipment and technique.

PREFACE

Large fire experiments require the cooperation of many people. We are particularly indebted to our NSWC and SRI colleagues, F. I. Laughridge, L. L. Wiltshire, W. H. Johnson, and R. G. McKee for continued assistance and to the Fire Departments at Camp Parks and Lawrence Livermore Laboratory site 300 for support in the suppression phase of the study.

CONTENTS

CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

1.0 INTRODUCTION

It is fortunate that the incidence of fires in aircraft both in the air and on the ground is rather infrequent because our ability to cope with such emergencies leaves much to be desired. Sometime ask a smiling airline stewardess about her fire training. She will know the locations of the fire ax, fire extinguishers, and portable oxygen masks and has been instructed in their use; however, the chances are high that she has never actually used an extinguisher to suppress a fire. She has been cautioned to detect fires while they are small enough to be attacked satisfactorily with the small extingiushers on board. But, when this strategy fails the current procedure calls for a quick landing and evacuation of survivors. On the ground, the men responsible for aircraft fire suppression and rescue also have their problems. The economics of airport operation combined with the restrictions imposed by air pollution control districts, often severely limit the size and frequency of training fires. A typical exercise consists of overwhelming a 50-gallon fire with a thousand-gallon foam truck, hardly a situation designed to challenge the performance or ability of the operator or the equipment. Furthermore, the training truck is frequently loaded with surplus protein foam in order to save the more expensive AFFF for a real accident; consequently, when an emergency develops the AFFF is applied by a technique suitable for protein foam but not optimum for AFFF. The importance of technique has been demonstrated repeatedly in agent evaluation tests. Much of the existing confusion about the relative performance of agents and equipment arises from tests that really measured the performance of people and techniques not the agent.

Even more distressing is the uncertainty regarding yardsticks for evaluating the performance of agents, application techniques, and equipment. This report attempts to remove some of these uncertainties by examining the basic concepts and the important parameters involved in the suppression of class B fires with AFFF. The scope embraces three categories of information: (1) the effect of fuel and environment on fire characteristics, (2) the theory and models for ideal and normal fire suppression, (3) tests and yardstick for evaluating suppression agents, the design and performance of equipment, and the effectiveness of extinguishing techniques.

Table 1.1 outlines the various parts of the overall basic relationships program. Phases I and II were reported in References 1.0 and 1.1. This report covers Phases III, V, VI and VII. Phase IV will be handled in a subsequent report. In format the subdivisions of this report do not follow the phase headings in Table 1.1; however, all the parts are covered.

Table 1.1

RESEARCH PLAN FOR THE BASIC RELATIONSHIPS PROGRAM

Phase I Nomenclature, Units and Presentation of Data

Part 1. Definitions and Units.

Part 2. Format for Presentation of Functional Relationships.

Phase II Test Procedures and Instrumentation

Part 1. Standard Fires, Size, Fuel and Environment.

Part 2. Suppression Test Measurements and Evaluation Procedures.

a. "Ideal" extinguishment: i.e., uniform application of the suppressant.

b. "Normal" extinguishment.

Part 3. Instrumentation.

Phase III Suppression Tests - Two Dimensional Fires

Part 1. Measure suppression characteristics versus types of foam.

Part 2. Measure suppression characteristics versus application rate and patterns.

Part 3. Measure suppression characteristics versus mode of application.

Part 4. Effects of fire geometry on suppression and fire characteristics.

Part 5. Effects of the ground environment on suppression and fire characteristics.

Part 6. Wind effects on suppression and the fire characteristics of standard fires.

Phase IV Suppression Tests on Three Dimensional Fires Involving Moving Fuel

Part 1. Compare the affect of conventional and fast application rates on the application density required to extinguish 100 ft^2 pool fires.

Table 1.1 (Continued)

a. Experimental parameters will include (1) Fuel - JP4, (2) Environment - open pool fire, (3) Agents - Monnex and PkP, the most effective agent will be used for most of the tests; however, some conformation extinguishments will be made with the second agent, (4) application rates - with a conventional 30 pound extinguisher the rates would be from one to two pounds/second while with the rocket disseminator the rates would exceed 100 pounds/second, (5) pattern - the cloud would be ejected horizontally and vertically downward into the flames to determine the most effective point of attack.

Part 2. Large fire tests.

Scaling - If the results from Part I are of interest from an extinguishment standpoint, the critical application densities would be scaled-up to typical AGFSRS type fires, i.e., the maximum fire sizes that can be extinguished with a single disseminator and with two or three disseminators in combination.

Three dimensional fires; dry chemical agents have been successful in extinguishing three dimensional fuel spray and spill fires where low expansion foams are ineffective. If rocket motor dissemination proves effective in Parts 1 and 2, the application would be extended to three dimensional fires involving cascading fuel.

Phase V Effect of Three Dimensional Objects, e.g., Aircraft on Fire Suppression and Fire Characteristics.

Observations will be made during the CASS series of tests where single and multiple aircraft will be employed in the fires. Observations will include effects of aircraft on both the development of the fire and the suppression of the fire.

Phase VI Suppression Tests Under Extreme Conditions of Environment and Fuel. Emphasis is on the Incremental Extinguishment Model.

Part 1. Dependence of the critical application density on the foam quality and the fire environment.

Part 2. Influence of application characteristics on fire suppression and the incremental extinguishment model.

a. Ratio of stream impact area, i.e., the incremental area to the total fire size.

b. Effect of sweep velocity, i.e., the specific application rate is controlled by the velocity with which the incremental area moves over the fire bed.

Table 1.1 (Continued)

c. Effect of sweep pattern.

d. Effect of multiple nozzles moving in consort.

Part 3. Measure suppression characteristics for extremes in ground material.

Part 4. Measure suppressions characteristics with particular emphasis on the critical application density and burn-back resistance as a function of the rock substrate temperature.

<u>Phase VII Develop Modeling and Prediction Capabilities</u>

2.0 BACKGROUND

Table 2.1 of Reference 1 listed the various parameters involved in describing a fire, the associated hazard, and the suppression requirements and the matrices in Figure 3.1 and 3.2 indicated the relative strength of interactions between the independent experimental parameters and the dependent fire characteristics and suppression requirements. Subsequent experience has generally confirmed these assignments except in the area of suppression where additional nomenclature has been added to clarify the difference between the parameters pertinent to the pumping or discharge of the agent and the agent that actually arrives at the scene of the fire. This augmented nomenclature is included along with the parameters from Reference 1 in a revised Table 2.1. Table 2.2 is the corresponding matrix which shows the expected strength or degree of interaction between variables. From Table 1.1 it is apparent that the overall objective of the program is to define and experimentally observe the most important of these interactions.

In Table 2.1 the nomenclature covering the fuel, environment, and fire characteristics is quite standard; however, in an effort to be more explicit in describing suppression, new terms have been introduced in two areas: First, a distinction is drawn between the agent sent or discharged and the agent that arrives at the surface of the fire. Second, the rates of agent application are divided into instantaneous and average catagories. The first distinction is concerned with the method of measuring solution application densities. Since it is difficult to determine or control the amount of agent lost between the nozzle and the fire bed, the application density usually is determined from the solution collected in sample pans outside the combustion zone or computed from the total agent discharged and the foamed area. Such procedures either neglect the losses entirely or reduce them to a minimum. The substantial dispersion observed in reported application densities required to extinguish test fires often reflects operator skill in minimizing the losses defined in Table 2.1, e.g. L_a, L_m, L_u, L_e. Throughout this report the gross discharge and application parameters are reserved for the agents sent, while the deposition parameters apply to agent reaching the surface of the fuel. In the limit, with the most efficient application techniques, the critical application density will approach the critical deposition density.

The second distinction involves the convention sometime encountered in the literature for computing application rates. Since practical considerations such as the extinguishment time and the total agent required are commonly plotted as functions

Table 2.1

PARAMETERS INVOLVED IN DESCRIBING A FIRE, THE ASSOCIATED HAZARD AND THE SUPPRESSION REQUIREMENTS

Parameter	Unit
Fuel	
Flash point	°F
Heat of combustion	BTU/lb
Heat of vaporization	BTU/lb
Amount	gal
Area	ft^2
Depth of fuel (AVG)	in
Uniformity	
Temperature	°F
Environment	
Air temperature	°F
Pressure	psi
Humidity	% relative humidity
Wind direction	with respect to fuel bed
Wind velocity	KTS
Wind velocity (forced)	KTS
Cloud cover	%
Substrate temperature	°F
Fire Characteristics	
Flame spread	
Area rate	ft^2/sec
Linear rate	ft/sec
Time to full involvement	sec
Preburn time	sec

Parameter	Unit
Burning Characteristics	
a. Fire size	Ratio $\frac{height}{diameter}$
b. Specific burning rate	in min^{-1}
Fire Effects	
a. Radiation envelope	BTU ft^{-2} sec^{-1}
b. Flame temperatures	°F
Suppression	
a. Discharge parameters	
1. Pump rate = R_p	GPM
2. Nozzle discharge rate = R_N	GPM
3. Specific discharge rate = R_N foam print area = r_s	GPM ft^{-2}
b. Deposition parameters	
1. Specific deposition rate = D_S (rate agent arrives at fuel surface)	GPM ft-2
2. Specific deposition density = D_D (total agent deposited per unit area)	GPM ft^{-2}

Table 2.1 (Continued)

Parameter	Unit	Parameter	Unit
3. Critical deposition density = D_{DC} (minimum D_D to extinguish fire)	GAL ft^{-2}	e. Application pattern	
c. Loss parameters		1. Total coverage = instantaneous coverage over entire Fire Area A	ft^2
1. Overkill - agent lands in extinguished area = L_A	%	2. Incremental coverage = instantaneous coverage over small fraction of A, i.e., a	ft^2
2. Misdirected foam, lands outside fire bed = L_M	%	3. Foam print = nozzle pattern area = a	ft^2
3. Evaporation loss in transit through flames = L_E	%	4. Sweep path, path followed by foam print in covering the total Fire Area (A)	
4. Updraft loss - foam carried away by updraft = L_U	%		
5. Drainage rate - foam converted to solution L_D	% min^{-1}		
6. Total Loss =E = $L_A + L_M + L_E + L_V + L_D t$	%		
d. Application Parameters			
1. Specific application rate = $S_S = \frac{D_s}{1-L}$	GPM ft^{-2}		
2. Specific application density = $S_D = \frac{D_D}{1-L}$	GPM ft^{-2}		
3. Critical application density = $S_{DC} = \frac{D_{DC}}{1-L}$	GPM ft^{-2}		
4. Critical application rate = S_{SC} (minimum S_S to extinguish fire)	GPM ft-2		

Table 2.2

IMPORTANCE OF THE VARIOUS FIRE VARIABLES ON FIRE CHARACTERISTICS AND EVALUATION PARAMETERS

	Flame Spread	Burning Rate	Fire Size	Radiation Field †
Fuel				
1. Type	L	M	M	S
2. Characteristics				
a. Flash point	L			
b. Heat of combustion		S	S	
c. Vapor pressure	L			
d. Heat of vaporization		M	M	S*
3. Distribution				
a. Pattern	S	S	S*	S*
b. Area	M	S	L	S*
c. Depth	S	S	S	S
d. Uniformity	S	S	S*	S*
4. Temperature	L	S	S	S
Environment				
1. Air				
a. Temperature	S	N	N	N
b. Humidity	N	N	N	N
c. Wind velocity	L	S	M	M
2. Substrate				
a. Composition	L	L*	L	L
b. Thermal properties	M*	M*	M*	M*
c. Wettability	M*	M	M	M
d. Porosity	L*	L	L	L
e. Fuel to substrate ratio	L	L	L	L
3. Objects in Fire	M	S	S	M

Table 2.2 (Continued)

Fire Characteristic	Hazard From Radiation	Suppression Effectiveness
Burning Rate	L	M*
Fire Size	L	M
Suppression Rate	L	L

L = large effect > 50 percent change in the fire characteristics or evaluation parameter.

M = medium effect 25 to 50 percent change.

S = small effect five to 25 percent.

N = negligible effect < five percent change.
†At distances measured in fire diameters.
*Next to the blanks i.e. where ratings were not attempted, the values marked with an * are least reliable.

of the application rate, the presentation should differentiate between instantaneous rates and obscure averages. In total area instantaneous suppression, there is no problem with defining the application rate as the pumping rate or discharge rate of the nozzle divided by the fire area. However, in incremental extinguishment where an agent is applied to only a fraction of the fire area at any one time, such a definition departs from physical reality by predicting a change of rate with fire size; even though, the discharge rate, foam print, and pattern of application remain constant. The instantaneous application rate will be used for all incremental extinguishments to avoid this complication. In Section 4.3 where application models are considered in detail, the significance of this concern will be clarified. It is the instantaneous application rate that determines pump capacities, nozzle sizes, and foam prints.

Most of the losses in Table 2.1 are self explanatory; however, the foam that evaporates in the combustion zone or drains into the liquid fuel may make some contribution to extinguishment and therefore is not a total loss. These possibilities will be examined in detail in Section 4.0. Most of the time the evaporation in the flame will be treated as a loss, but drainage at the surface usually performs useful work.

3.0 FIRE CHARACTERISTICS

A number of variables which are important to the fireman in fighting aircraft fuel fires are discussed in this section. In addition to the fuel and environmental parameters that control the fire characteristics listed in Table 2.1, the fireman must also cope with a variety of logistic problems that determine the overall response time, i.e. the time from ignition to the onset of suppression. If the fire is attacked before it can spread and involve all of the available fuel, suppression is simplified. There is less likelihood of fuel tanks exploding if the suppression efforts are successful in limiting fire spread and buildup. Once the crash occurs the fire size depends primarily on the amount and type of fuel spilled, the terrain and the wind speed and direction. Then the time required for suppression is dependent upon a variety of factors, some of which are within the sphere of influence of the crash and rescue crew, some not. For example the response time depends on the crew readiness and the distance to the crash. In addition to the crash site, other factors outside the control of the firemen include type of aircraft, amount of fuel, type of fuel spilled, the terrain and the wind speed and direction. The importance of many of these uncontrolled variables with respect to fire characteristics will be developed as the data are presented. The influence of the variables on suppression time will be explored in Sections 4.0, 5.0 and 6.0.

3.1 Fuel Effects

3.1.1 Types: AVGAS, JP4 and JP5

Experimentally the burning rates of AVGAS, JP4 and JP5 were determined using a variety of methods (Reference 1.1) and fires ranging in size from 3 feet in diameter to 200 x 240 feet. The burning rates in 3 and 10 feet diameter pans were measured by recording the weight loss during combustion with the pans supported on load cells. For larger fires burning rate was calculated from the change in liquid level. Initially the average burning rates were estimated using before and after measurements of the fuel thickness. Corrections were made for the reduced burning rates during ignition and suppression based on the corresponding areas under the radiation curves and the assumption that the radiation level was always proportional to the burning rate. Later in the program, continuous records of the fuel level were obtained by photographing manometers with a time lapse camera. Also, flame heights were recorded photographically.

Blinov and Khudiakov (Reference 3.1) have shown that in most liquid fuel fires with pool diameters above 100 cm the burning rate becomes reasonably constant as the pool dimensions increase. In our field tests the burning rates varied by a factor of two or three, dependent upon the environment and pool size. These observations hold true also for the ratio of flame height to pool diameter. The Russian data for tractor kerosene is reproduced in Figure 3.1 along with burning rates and flame heights for AVGAS, JP4 and JP5 measured during this program. The reasons for the variability in the field test data will be considered in Section 3.2. In order of descending burning rates, typical average values were found to be 6 mm/min for AVGAS, 5 mm/min for JP4 and 4.4 mm/min for JP5. This information is of twofold importance to firemen extinguishing such fuels. For spills of equivalent thicknesses, the higher burning rate fuels will burn out quicker and dissipate their energy in a shorter period of time. Consequently, such fires will tend to be larger and will radiate more thermal radiation. Greater standoff distances may be required in fighting such fires thereby placing more stringent requirements on suppression equipment. Secondly, if these hotter fires are to be suppressed within the first several minutes of ignition, a higher rate of foam application would be required. This latter requirement is subject to various environmental factors that can alter the fire characteristics. For instance an airplane structure in the fire or the wind direction and speed, could outweigh differences in fuel burning rate in determining the suppressant application rate required to combat the fire successfully.

Since higher burning rate fuels put larger amounts of combustion products into the fire plume per unit time, the larger plumes tend to radiate more thermal energy. Again, field testing conditions cause considerable spread in the data because of the influence of wind speed and direction upon the view factor which the radiometers perceive. In Figure 3.2 the heat flux from pool fires of AVGAS, and JP5 with dimensions of 30 feet x 30 feet are given as a function of the distance from the fire divided by the characteristic fire dimension viewed by the line of radiometers. The data support the logic that the radiation increases with the burning rate. Fu (Reference 3.2) reports that the radiation from AVGAS fires is about 60% higher than for JP5 fires at $x/D = 3$. Other measuring stations gave proportionately higher heat fluxes from AVGAS fires than either JP4 or JP5 although some JP4 fires appeared to have fluxes close to those radiated by AVGAS. His experiments were carried out in the laboratory where more control could be exercised over the experimental parameters than in field tests. As previously stated the practical significance of this fact is to increase the stand-off distance for fighting AVGAS fires as compared to JP5 fires and to place more stringent requirements on the equipment.

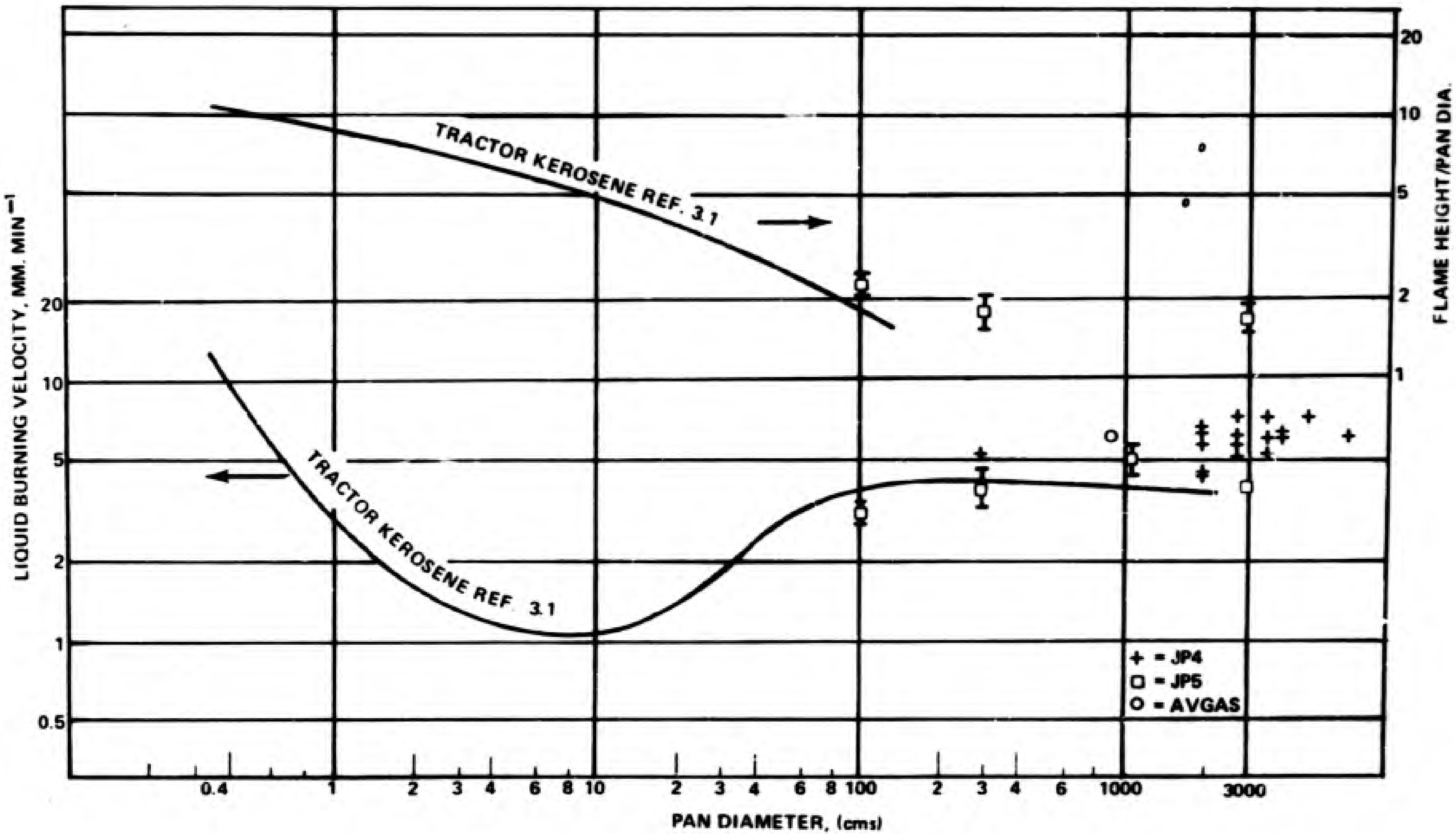


FIG 3.1 PEAK FLAME HEIGHTS AND BURNING RATE FOR JET FUELS

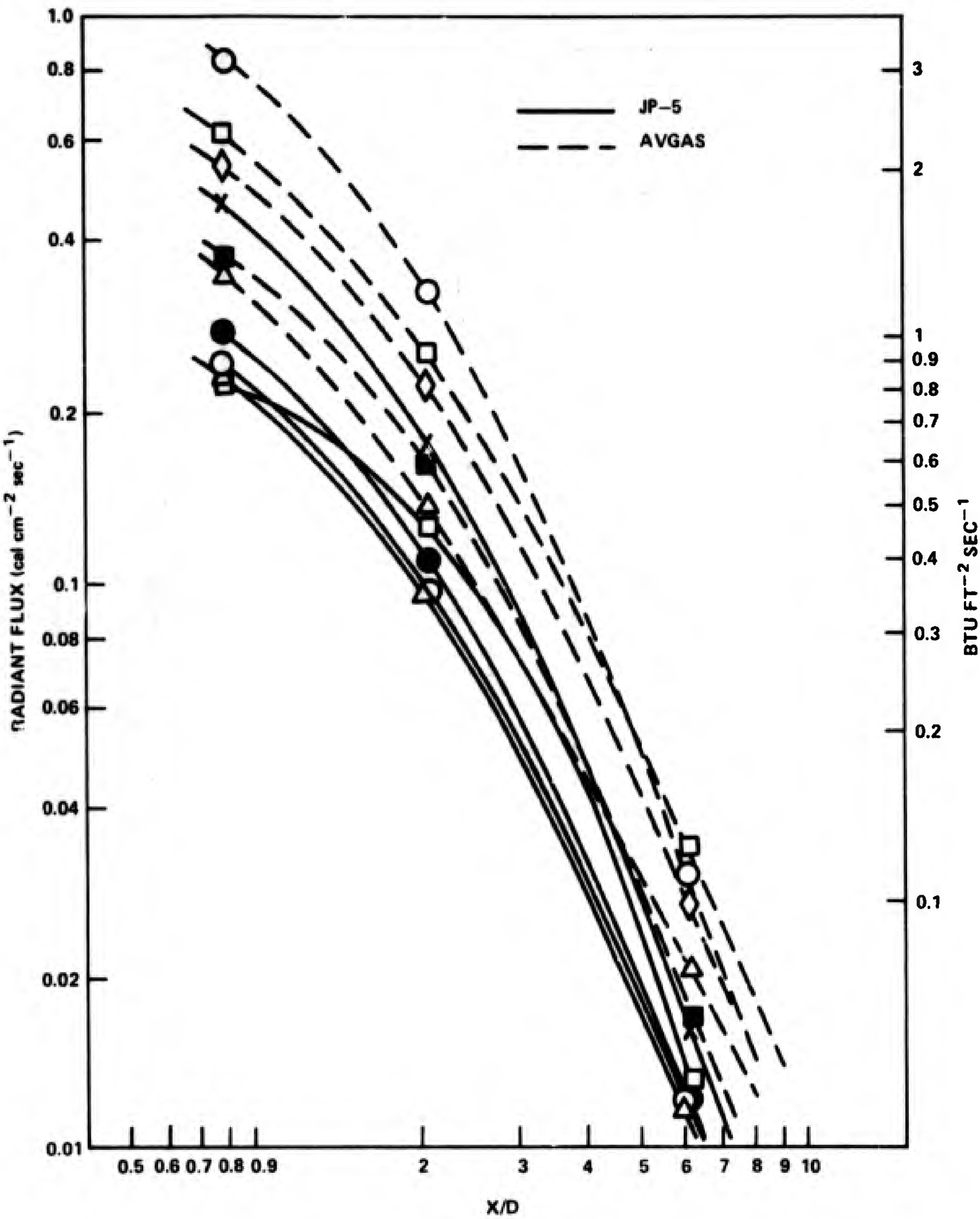


FIG 3.2 A COMPARISON OF THE HEAT FLUX FROM JP–5 AND AVGAS FIRES

3.1.2 Fuel Area

The test data indicate that both burning rates and plume heights are reasonably predictable within a factor of two or three. In our previous report (Reference 1.0) it was shown that wind velocity has a small effect on burning rates for fires with dimensions 10 feet in diameter or smaller. However, the flame heights of all fires are notably dependent upon wind velocity. With small fires a wind of about 10 mph causes the flames to be blown along the ground so as to make flame height a meaningless measurement. With the larger fires studied in this program wind speeds in the range of 12 mph and up complicated the identification of a flame height. Some idea of the variation in flame heights for the CASS 83 foot x 90 foot fires of JP5 is given in Figure 3.3. Note particularly the curve for Test 14 where the 20 KT wind reduced the height 40%. The heights reported herein are those shown by visible fire balls recorded photographically.

The major fire characteristic influenced by the area of fuel is the heat radiation from the fire plume. This heat flux is dependent primarily upon the size of the fire plume which in turn is related to the size of the burning pool. In the AGFSRS test series at China Lake, pool fires of JP4 were varied from 40 foot x 100 foot to 200 foot x 240 foot in a sufficiently controlled manner so as to minimize the contribution of environmental factors and instrumentation variation to the measured fire characteristics. In Figure 3.4 the average heat flux is plotted as a function of the normalized distance from the radiometers to the fire, i.e. the distance (X) divided by the length (D) of the pool side observed. The measured heat flux in this test series at a distance of one characteristic length (D) from the fire ranges from 0.08 to 0.4 BTU/ft^{-2} sec^{-1}.

A comparison of the results of our thermal radiation measurements from large fires with known theories shows a serious discrepancy, i.e., the plots of Q versus X/D are segregated significantly by fire sizes. If the flame is considered a surface emitter and atmospheric attenuation is neglected, then the heat flux detected by the target radiometer is,

$$Q = F_{\tau \to f} \, q_f \qquad (3.1)$$

where Q = radiant heat flux incident on radiometer, BTU/ft^{-2} sec^{-1}.

$F_{\tau \to f}$ = view factor from target to flame, unitless

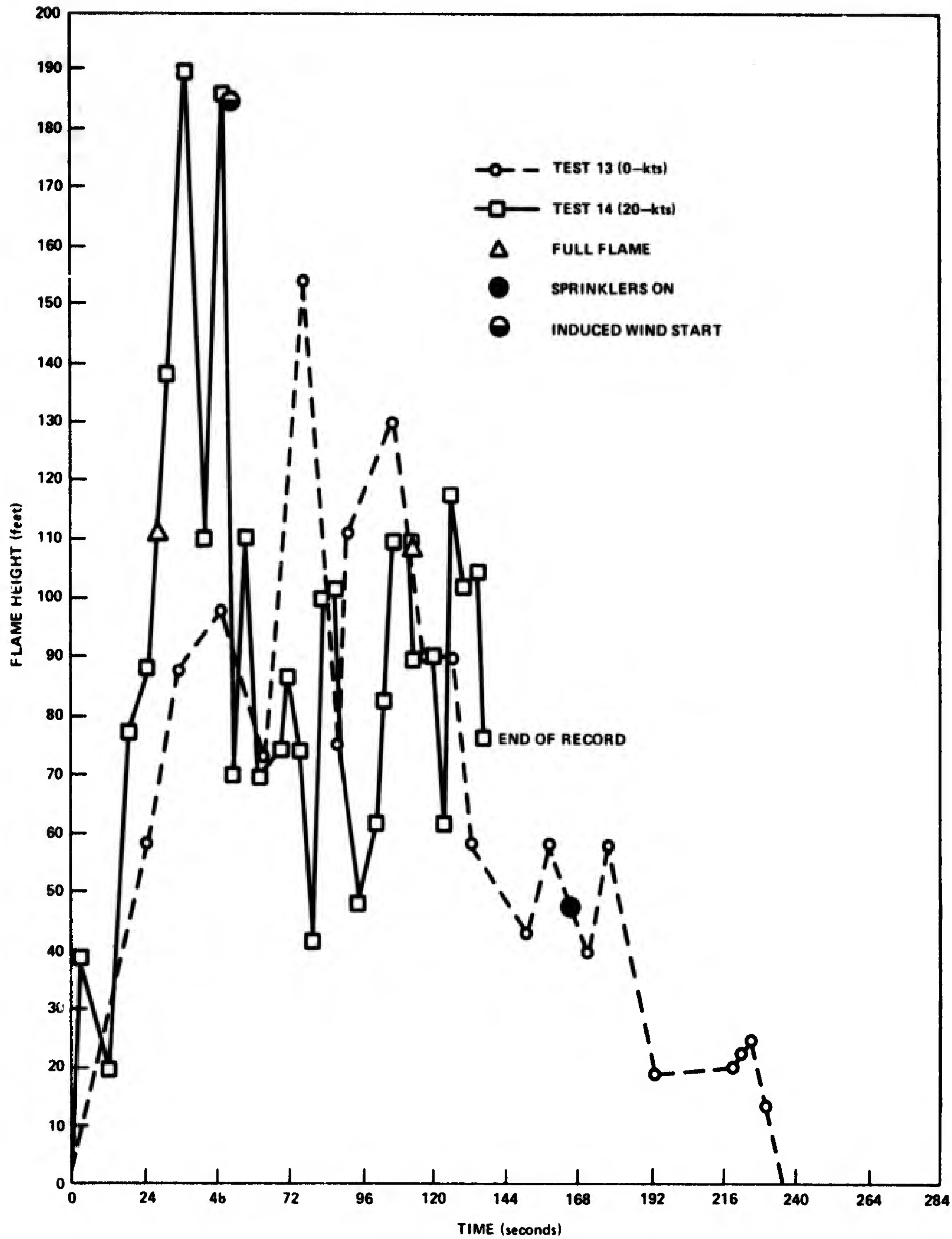


FIG 3.3 MAX. FLAME HT. VS TIME CASS TESTS 13 & 14

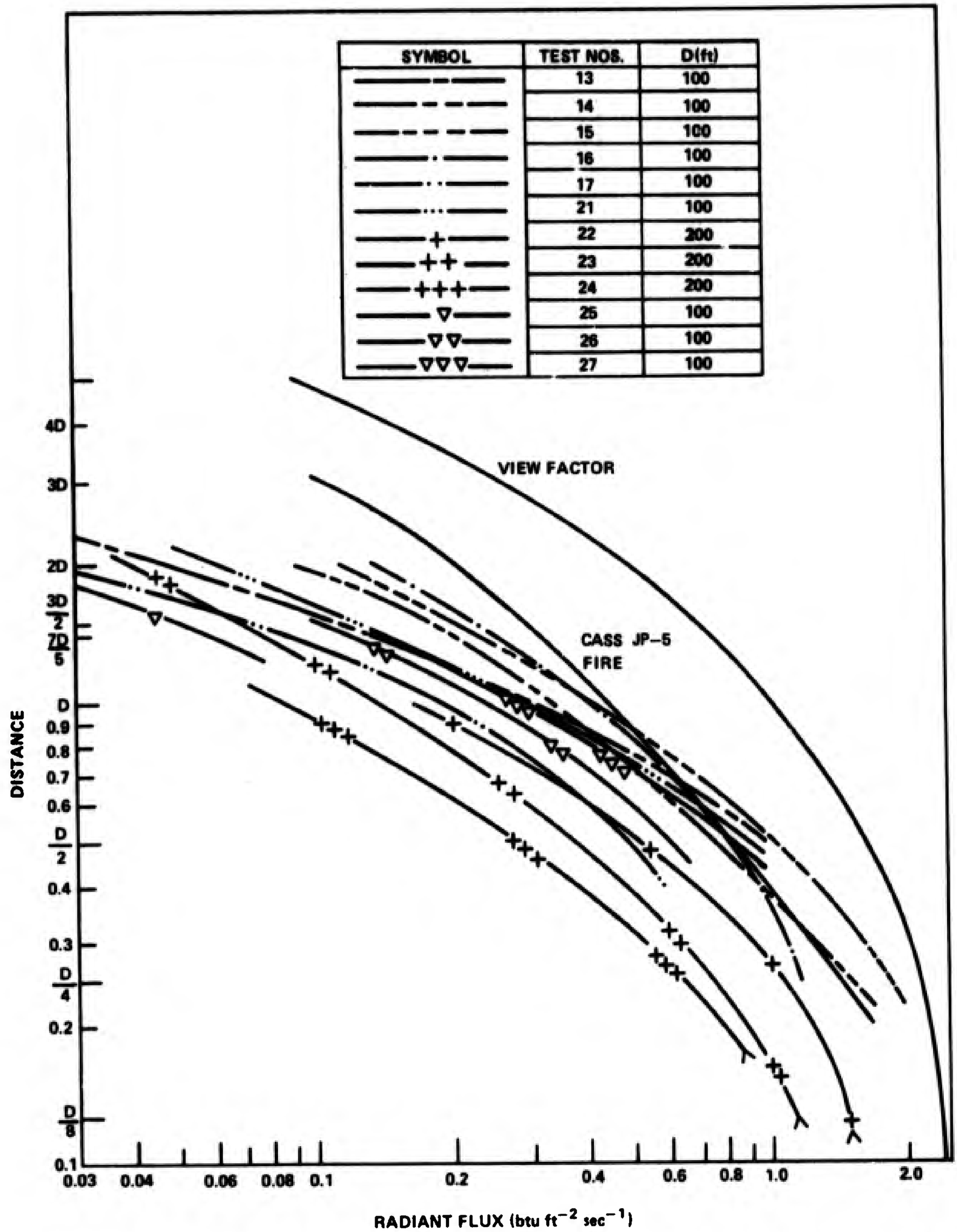


FIG 3.4 COMPARISON OF HEAT FLUXES FROM VARIOUS SIZED JP–4 FIRES AT AGFSRS CHINA LAKE TESTS

q_f = surface heat flux of flame, $BTU/ft^{-2}\ sec^{-1}$

The view factor is given by:

$$F_{\tau \to f} = \int \frac{\cos \beta_1 \cos \beta_2 \, dA_f}{\pi r^2} \tag{3.2}$$

where the geometry used is shown in Figure 3.5. Sleipcevich (Reference 3.3) has calculated radiation view factors for tilted cylinders (simulating fire plumes). If there is a constant relationship between the height of the fire plume and the diameter of large pool fires as indicated in Figure 3.1, then calculations from the data presented by Sleipcevich yield a single view factor for each $\frac{X}{D}$ value irrespective of the fire diameter. The variables in the combined Equations (3.1) and (3.2),

$$Q = q_f \int \frac{\cos \beta_1 \cos \beta_2 \, dA_f}{\pi r^2} \tag{3.3}$$

were examined for terms which might explain the experimental fact that different sized fires give different thermal fluxes per unit area of target radiometer when viewed from the same X/D distance. First it has been shown by Graves (Reference 3.4) that the fire plume from hydrocarbon fires emits thermal radiation from a finite depth within the plume, so q_τ is apparently not constant as fire size varies. There is also other experimental and theoretical evidence that the view factor and therefore flux density also changes with fire size. Steward (Reference 3.5 and 3.6) has shown that the radiant flux density from a flame is a function of both the flame absorption coefficient and flame height. He also predicted that the flame height would be proportional to the mass burning rate (F_m) to the two-fifths power.

To determine whether the mass burning rate is a variable of significance, which would explain in part the discrepancy between field measurements and theory, the AGFSRS data on large JP-4 fires was tested by regression analysis using as variables F_m in pounds per second and X/D. In the AGFSRS test series the heat flux from JP4 fires with characteristic dimensions of 100 feet and 200 feet was measured at distances of D/4, D/2, and D from the fires. The regression equation

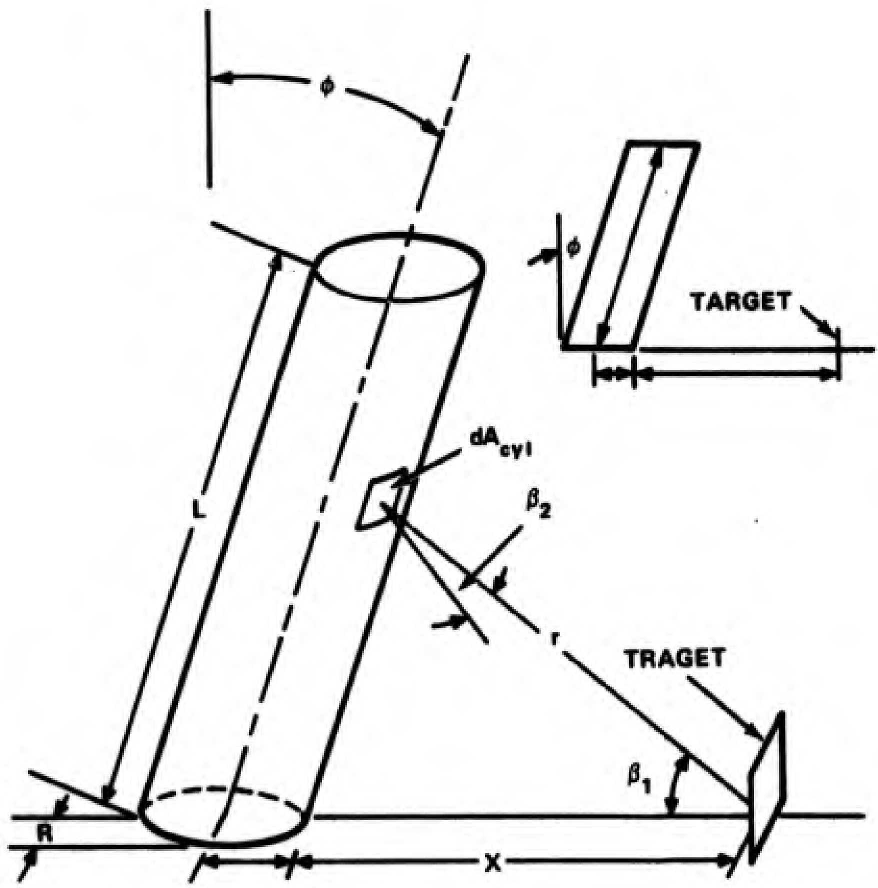


FIG 3.5 GEOMETRY USED FOR CALCULATION OF VIEW FACTORS. FROM REF. 3.3

$$Q = 3.641\, F_m^{-.519} \left[\left(\frac{X}{D}\right)\right]^{-1.17} \qquad (3.4)$$

correlating the variables was found to be significant at the 0.01 probability level, i.e., there is only a 1% probability of being wrong if we say that the thermal flux is correlated by the variables indicated. The regression equation accounts for 94% of the total squared log deviations of Log Q. Further the variable F_m accounts for 28% and the variable X/D accounts for 66% of the total squared log deviations. A comparison of calculated and measured heat fluxes is shown in Figure 3.6 for distances D, D/2, and D/4 from the fires.

In Table 3.1 the heat fluxes calculated from the regression equation are compared to measured values. An examination of the residual differences between calculated and measured values reveals that the greatest deviation occurs at an X/D of one where the average deviation of calculated Q is about twice that for Q calculated at an X/D of 0.5 and 0.25, i.e., the lower the heat flux the greater the deviation (measured as a percent of Q) from the regression line. This deviation may indicate the influence of other random variables on the thermal radiation measurements at longer distances from the fire, e.g., atmospheric absorption and/or a changing view factor caused by the wind. In Figure 3.4 the radiometers located at position D are either 100 or 200 feet from the fire. From atmospheric absorption measurements made on JP5 fires at similar distances, 100 feet of air reduced the flux level approximately 10%, i.e., a negligible amount compared to the differences in Figure 3.4. The wind effect may be more pronounced. For example, the motion pictures show the flame tilt away from the radiometers increases progressively from Tests 22 and 24. The importance of a changing view factor as a variable which should be included in any predictive model for thermal heat flux may be illustrated further by examination of a residual plot against Q, the measured quantity. Figure 3.7 shows that the deviations in calculated values tend to grow larger the higher the Q measured, i.e., the closer the fire is to the measuring radiometers. This nearness of course makes the target radiometers more subject to variations in view factor caused by wind-directed fluctuations of the fire plume.

In addition to the statistical inferences which were derived from our rather involved analysis of the radiation data, there is a practical advantage to be gained. The correlation developed allows us to predict the heat flux as a function

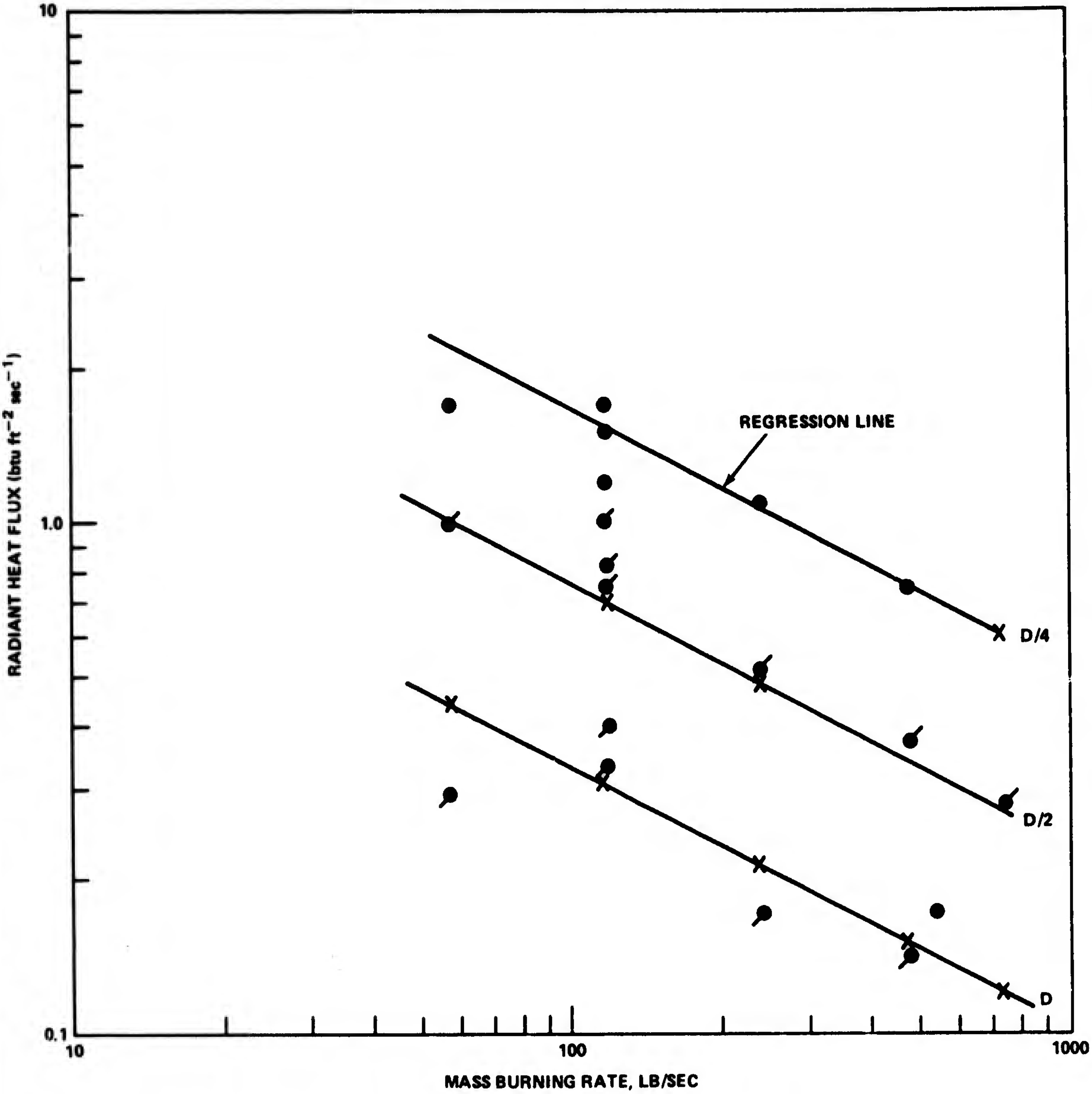


FIG 3.6 THERMAL FLUX FROM 200' AND 100' FIRES OF JP–4

Table 3.1

REGRESSION ANALYSIS RESULTS

Measured Heat Flux, Q BTU FT^{-2} SEC^{-1}	Calculated Heat Flux, Q' BTU FT^{-2} SEC^{-1}	Residual Q - Q'	Percent Deviation	Mass Burning Rate, LB/SEC	X/D
0.086	0.120	-0.034	-39.5	727.6	1
0.28	0.268	+0.012	+ 4.3	727.6	0.5
0.62	0.603	+0.017	+ 2.7	727.6	0.25
0.14	0.15	-0.01	- 7.1	473.7	1
0.37	0.33	+0.04	+10.8	473.7	0.5
0.75	0.75	0	0	473.7	0.25
0.17	0.21	-0.04	-23.5	241	1
0.51	0.48	+0.03	+ 5.9	241	0.5
1.1	1.07	+0.03	+ 2.7	241	0.25
0.4	0.31	+0.09	+22.5	117	1
1.05	0.69	+0.36	+34.2	117	0.5
1.7	1.56	+0.14	+ 8.2	117	0.25
0.4	0.31	+0.09	+22.5	117	1
0.82	0.69	+0.13	+15.8	117	0.5
1.2	1.56	-0.36	-30	117	0.25
0.32	0.31	+0.01	+ 3.1	117	1
0.75	0.69	-0.06	- 8	117	0.5
1.5	1.56	-0.06	- 4	117	0.25
0.30	0.44	-0.14	-46.7	57.4	1
0.98	1.00	+0.02	+ 2	57.4	0.5
1.7	2.25	-0.55	-32.3	57.4	0.25

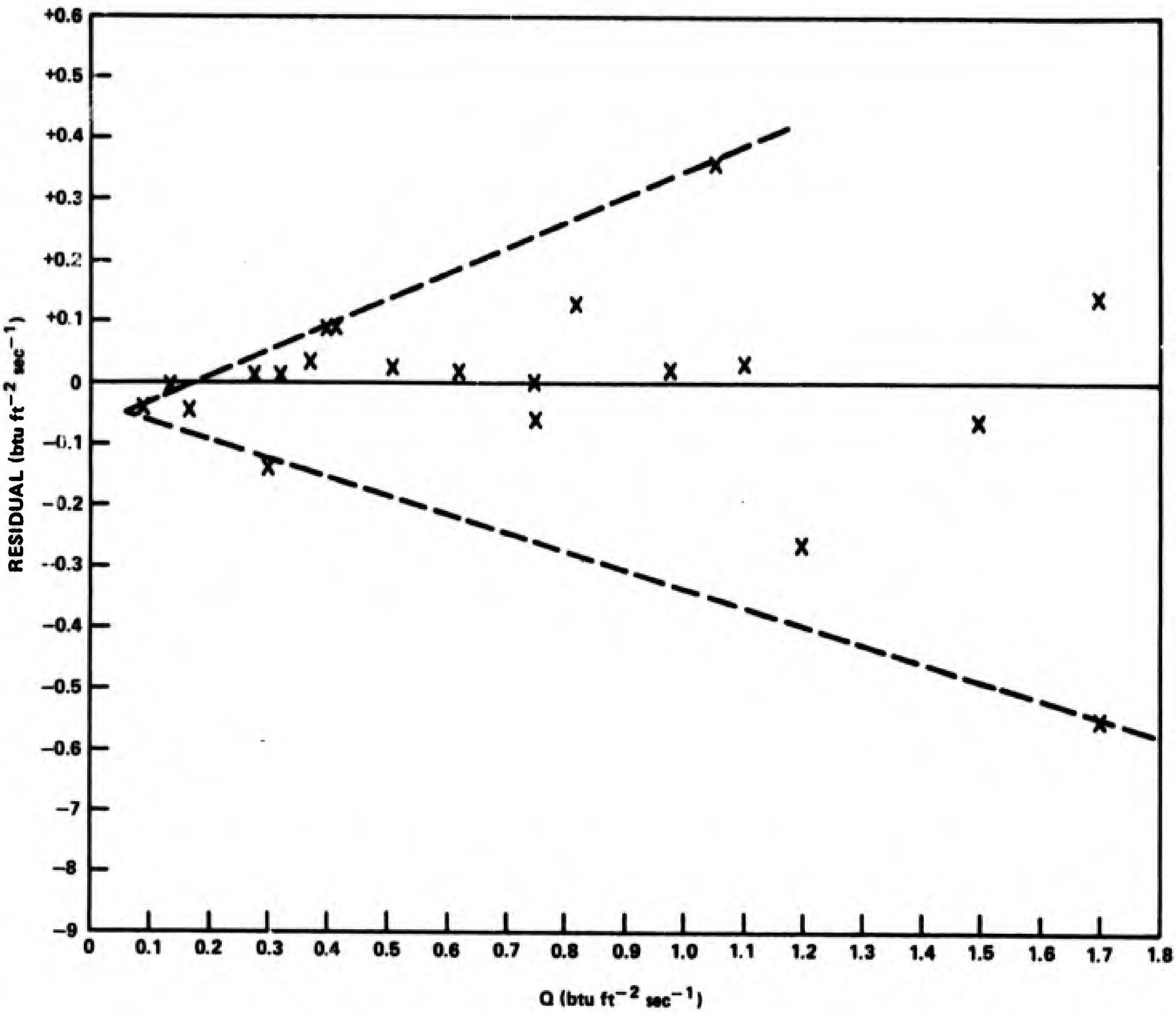


FIG 3.7 PLOT OF RESIDUALS VS Q, MEASURED FLUX

of distance from very large fires with a maximum error of 47%. With only X/D as a variable the maximum variation in measured values is 365%. So the introduction of F_m as a variable in heat flux measurements improved the prediction capabilities by a factor of almost eight for the specifically selected test series considered. Whether this variable is strong enough to pull together the radiation measurements from the range of fires which were studied in this program will be considered next.

JP5 has been used extensively in fires ranging in size from 3 feet diameter to the 83 foot x 90 foot fires in the CASS program at China Lake. The heat flux from the smaller fires was significantly higher than from larger fires when measured at the same characteristic length (D) which for circular fires refers to the diameter of the pool and for rectangular pools corresponds to the longer dimension. Typical radiation data are shown in Figure 3.8 plotted as a function of X/D. As a correlator for heat flux from hydrocarbon fuel fires of varying sizes, the term X/D does not remove the deviations as well as the power function of F_m and X/D applied to the large AGFSRS China Lake fire data. If all of the flux measurements from 3 feet to 90 feet fires are compared the variability ranges from 223% at the D/2 measuring station to 600% at the 3D station. All of these measurements involved the same investigators, instrumentation, and data analysis techniques. The variability is even more serious when the results of different investigators are considered as in Figure 3.9. For X/D = 1 the radiant flux varies from 0.08 to 2.2 BTU FT^2 SEC^{-1}, a ratio of approximately 27 for fires with characteristic dimensions from 10 feet to 200 feet. Obviously a differentiation by major variables in addition to X/D is called for.

A regression analysis was performed on the NOL/SRI radiation data collected on JP5 fires from 3 feet diameter to the CASS 83 foot x 90 foot fires. The regression lines for distance X/D = 0.5, 1 and 2 are plotted in Figure 3.10 and compared with experimental measurements. The equation correlating these data is:

$$Q = 0.4616(F_m^{-.09102})\ (X/D)^{-1.164} \tag{3.5}$$

For fire areas that ranged from 7 to 7470 ft^2 the dependence of flux upon mass burning rate and the distance X/D proved to be highly significant at the probability level of .01, i.e., 1% chance of being wrong when we say the variables correlate

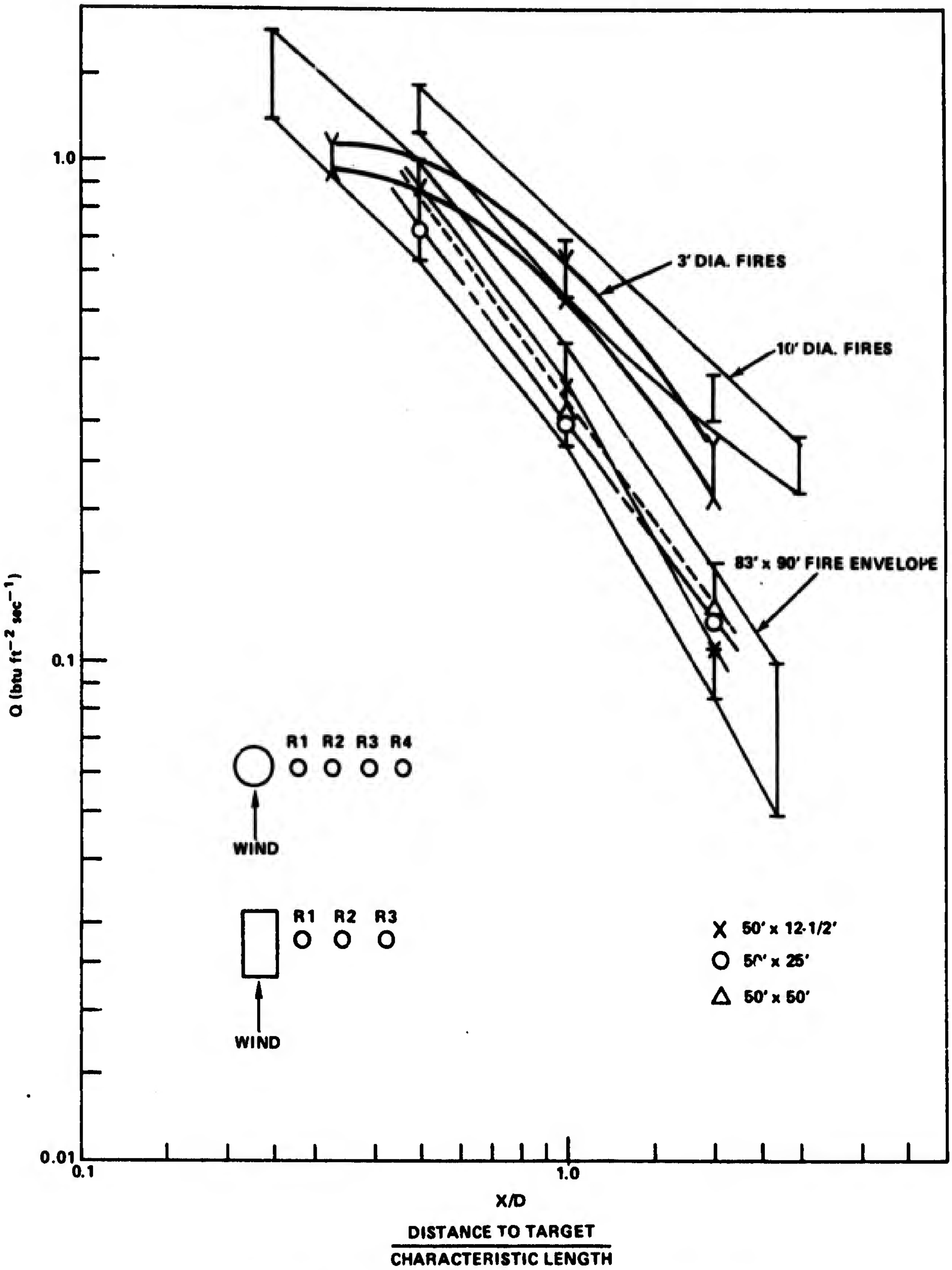


FIG 3.8 THERMAL RADIATION FROM 3', 10', 50' & 90' FIRES OF JP–5

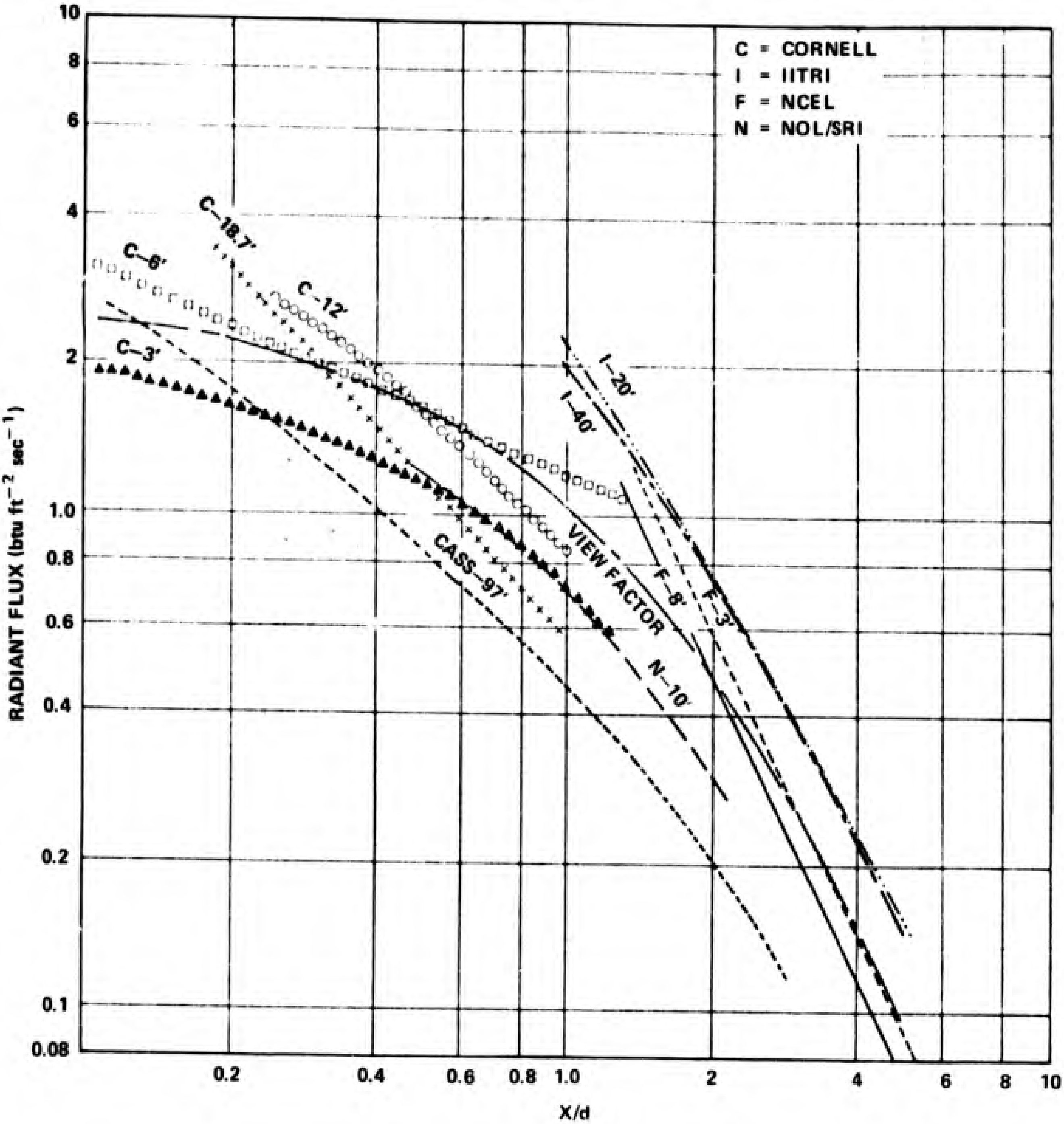


FIG 3.9 RADIANT FLUX AS A FUNCTION OF DISTANCE FROM FIRE

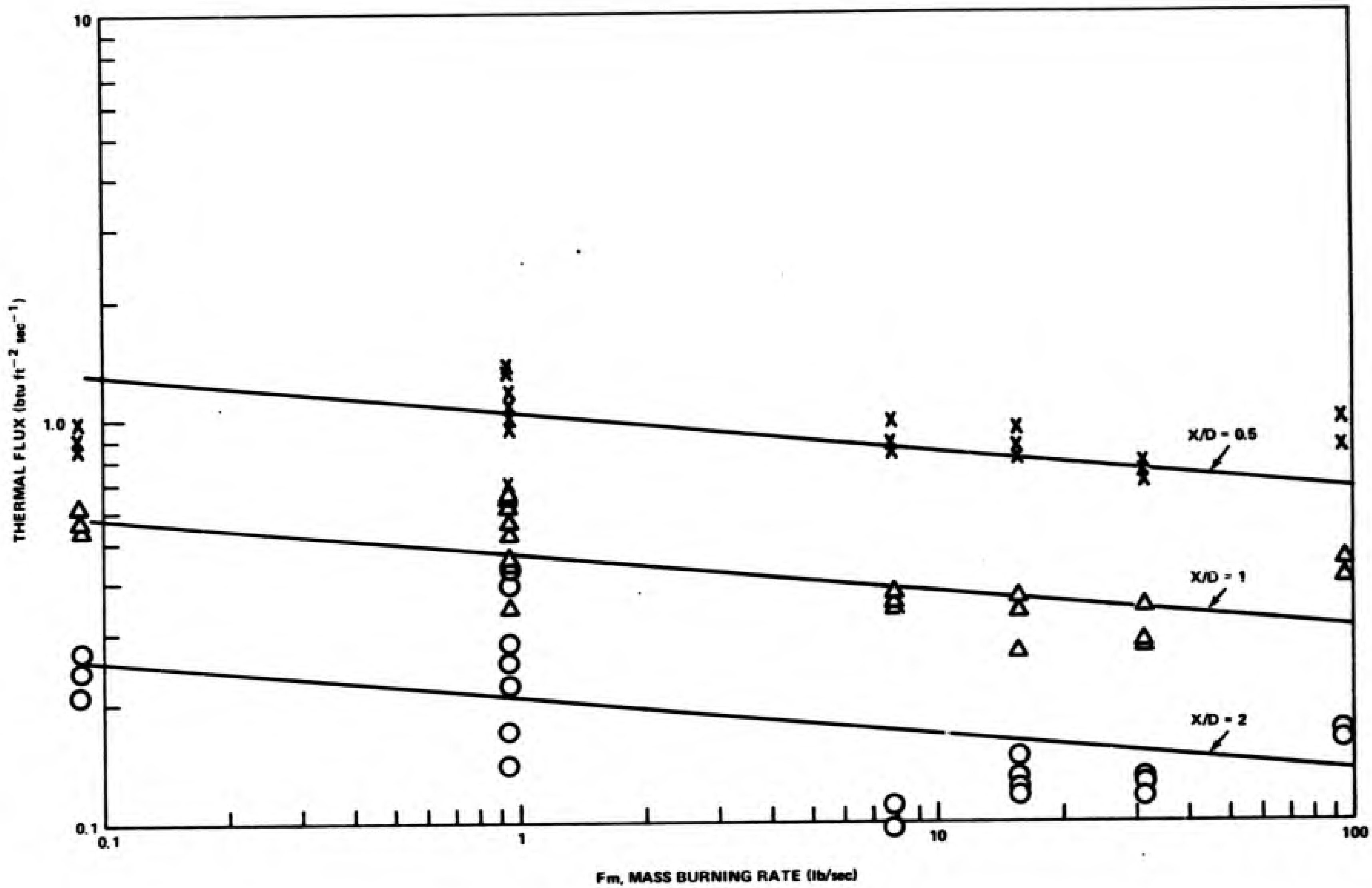


FIG 3.10 THERMAL HEAT FLUX VS THE MASS BURNING RATE AT VARIOUS DISTANCES FROM JP–5 POOL FIRES

with thermal flux. In this case, however, the dependency of flux upon the mass burning rate was not as pronounced as in the case of the AGFSRS 100 foot and 200 foot JP4 fires. The correlation equation accounted for 87% of the total squared log deviations of Log Q. In this case the variable F_m accounted for 6.4% of the squared log deviations whereas the variable X/D accounted for 80.6% of the deviations. In both correlations the thermal flux (Q) was proportional to $(X/D)^{-n}$ where n = 1.17 for the larger fires and n = 1.16 for smaller fires, a value somewhat less than the inverse square predictions, but remarkably close considering these were field test fires ranging from 3 feet diameter to 200 feet x 240 feet.

3.2 Environmental Effects

3.2.1 Wind

Sleipcevich (Reference 3.3) has shown with small circular pool fires varying in diameter from 4 inches to 2 feet that the burning rate of hydrocarbon fuels decreases as wind velocity increases. It was proposed that the mechanism of heat feedback as expressed by Hottel readily explained this decrease. For a circular pool of diameter "d" the rate of heat feedback by conduction, convection, and radiation respectively is:

$$q = \frac{4\,k(T_F - T_B)}{d} + U(T_F - T_B) + \sigma F(T_F^4 - T_B^4)\,(1 - e^{-Kd}) \quad (3.6)$$

If the temperature difference between flames and fuel $(T_F - T_B)$, the heat transfer coefficients k, U, and σ, and the Beer's law extinction coefficient K for the fuel are all held constant the only remaining variable is the geometrical view factor, F, in the radiation term. This view factor is dependent upon the position of the flames with respect to the pan and the position can be obtained from the Walker and Sleicevich (Reference 3.7) expression for the bending angle θ of the wind-blown flame;

$$\frac{\tan\theta}{\cos\theta} = 3.3\,Re^{0.07}Fr^{0.8}\left(\frac{\rho_g}{\rho_a}\right)^{-0.6} \quad (3.7)$$

where Re = Reynolds number $\left(\frac{d\rho_a V}{\mu}\right)$

Fr = Froude number $\left(\frac{V^2}{dg}\right)$

ρ_g = Density of combustion gases

ρ_a = Air density

d = Length

V = Velocity

μ = Viscosity

g = Gravity

For the model flame shown in Figure 3.11 an increase in the wind velocity bends the flame away from the pan reducing the volume of gases effectively radiating to the fuel surface. The Froude number represents the major variable in the expression. The field test burning rate data from this program for circular, rectangular, and square fires of JP5 are plotted against the Froude numbers in Figure 3.12. The plot shows that the influence of wind velocity becomes almost negligible for fires with a dimension greater than 10 feet. An examination of the photographs for these fires shows that the wind influences the larger fires to a far lesser degree than smaller fires.

Figure 3.13 shows the bend angle θ computed by means of the Sleipcevich correlation for a number of different diameter fires. As an example of the effect of wind on fire size a 10 knot wind bends the 10 foot fire at an angle of 47°, the 35 foot fire 24° and the 100 foot fire only 9°. Hence the influence of wind upon the feedback mechanism and therefore burning rate should be far less with larger fires. Our data appear to confirm these deductions.

Since the wind does influence the stretching of the fire plume, it appeared reasonable to assume that the radiation data would show the influence of wind upon the view factor at different fire sizes. A regression analysis was made in an attempt to correlate the heat flux with the fuel mass burning rate and the Froude number. The thermal flux measurements from pool fires of JP5 ranging from 3 feet in diameter to a 83 foot to 90 foot rectangle were used in the analysis. The data are given in Table 3.2. Values of the radiation flux were measured by side-looking radiometers aligned perpendicular to the characteristic dimension; i.e., the general wind direction was

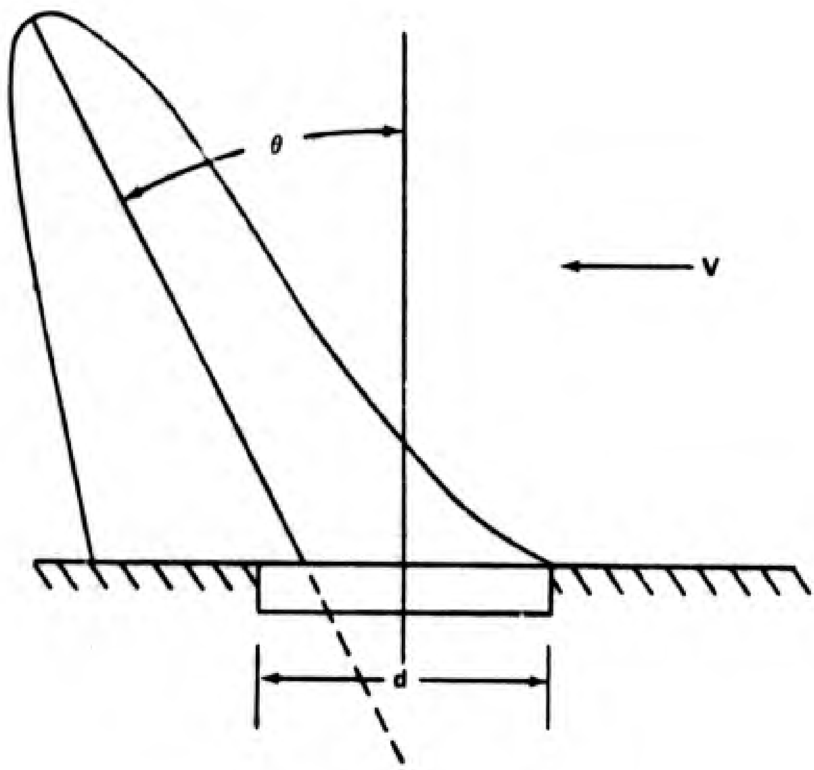


FIG 3.11 FIRE MODEL OF WIND–BLOWN FIRE FROM A CIRCULAR BURNER

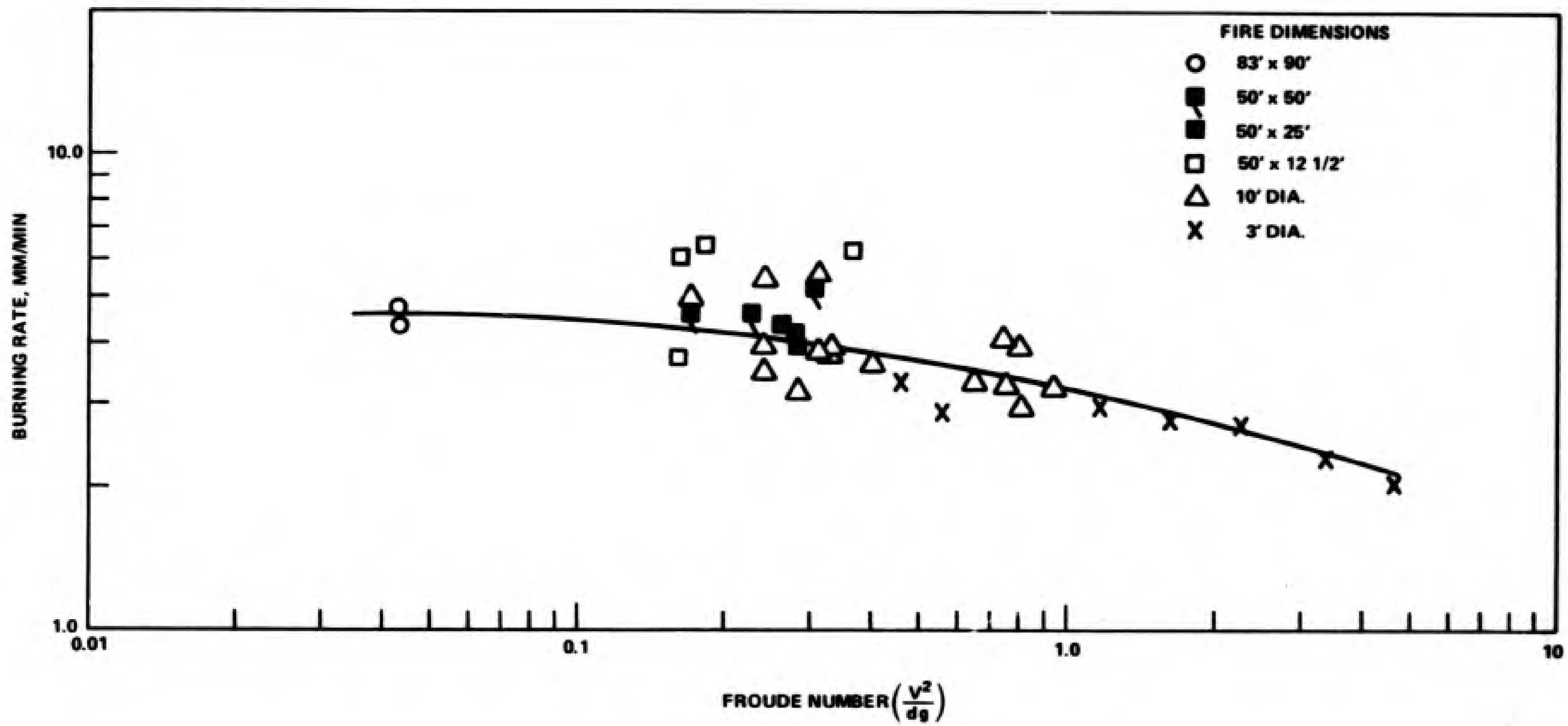


FIG 3.12 BURNING RATES OF JP–5 FIRES VS FROUDE NUMBER

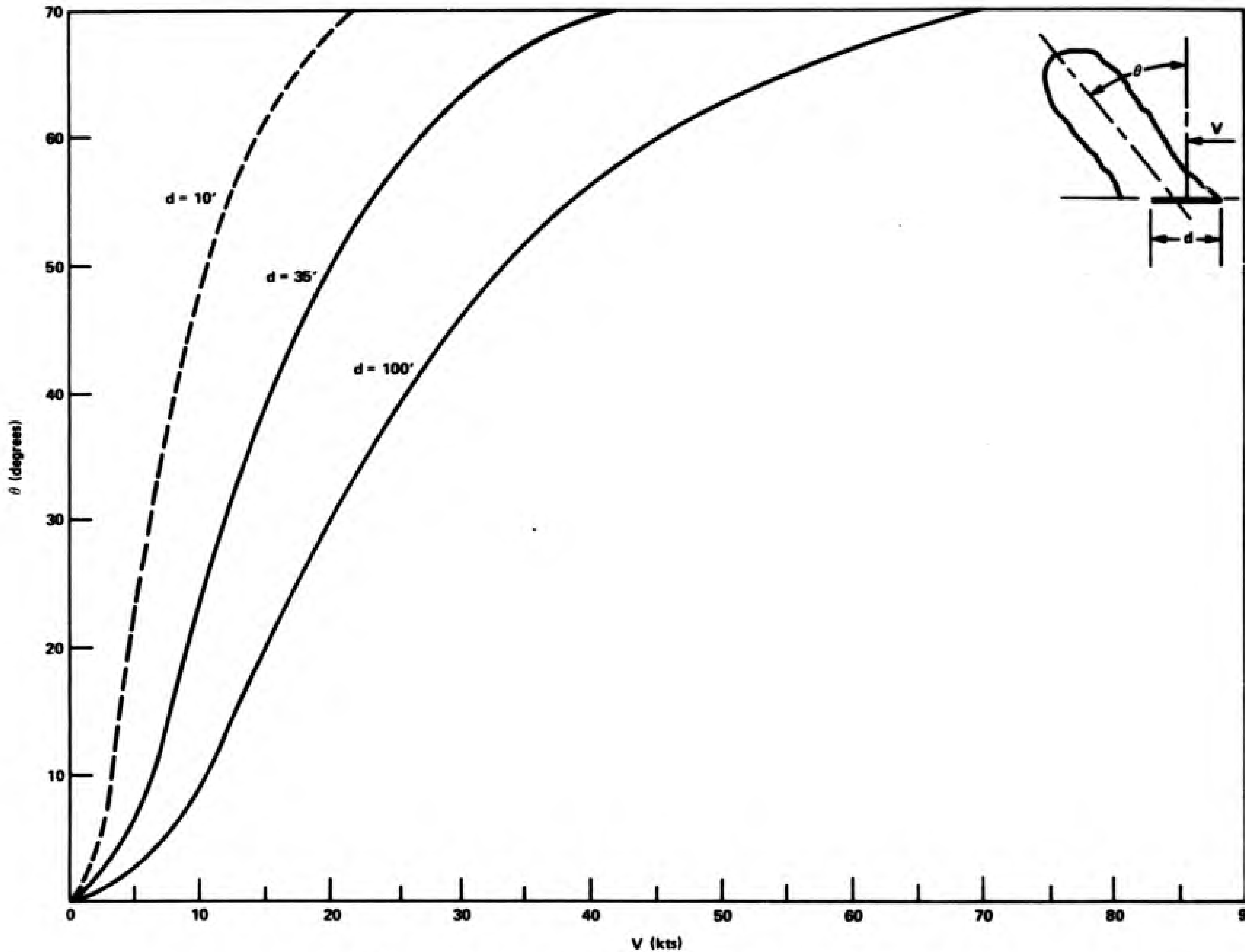


FIG 3.13 COMPUTED PLUME TILT ANGLE "θ" AS A FUNCTION OF WIND VELOCITY

Table 3.2

PREDICTED THERMAL FLUX AT DISTANCE D/2 FROM JP5 FIRES

Measured Q BTU FT^{-2} SEC^{-1}	Predicted Q* BTU FT^{-2} SEC^{-}	Fuel Mass Burning Rate (F_m) LB/SEC	Froude Number (Fr)	Fire Size
0.89	0.96	0.0846	0.55	3' dia
1.00	1.06	0.0846	1.16	3' dia
0.87	1.09	0.0846	1.62	3' dia
1.07	0.97	0.94	0.74	10' dia
1.00	0.99	0.94	0.93	10' dia
0.68	0.82	0.94	0.17	10' dia
0.66	1.00	0.94	0.64	10' dia
1.30	0.97	0.94	0.74	10' dia
0.95	0.90	0.94	0.40	10' dia
1.35	0.88	0.94	0.31	10' dia
1.15	0.97	0.94	0.80	10' dia
0.98	0.79	7.825	0.16	12-1/2' x 50'
0.83	0.80	7.825	0.18	12-1/2' x 50'
0.87	0.80	7.825	0.18	12-1/2' x 50'
0.81	0.82	15.65	0.26	25' x 50'
0.86	0.83	15.65	0.28	25' x 50'
0.95	0.83	15.65	0.28	25' x 50'
0.84	0.85	15.65	0.36	25' x 50'
0.77	0.77	31.3	0.17	50' x 50'

*Regression Equation: $Q = 0.996\, F_m^{-0.0179}\, F_r^{0.107}$

Table 3.2 (Cont.)

PREDICTED THERMAL FLUX AT DISTANCE D/2 FROM JP5 FIRES

Measured Q BTU FT^{-2} SEC^{-1}	Predicted Q* BTU FT^{-2} SEC^{-1}	Fuel Mass Burning Rate (F_m) LB/SEC	Froude Number (Fr)	Fire Size
0.71	0.82	31.3	0.29	50' x 50'
0.70	0.80	31.3	0.23	50' x 50'
0.90	0.65	93.6	0.043	83' x 90'
0.42	0.65	93.6	0.043	83' x 90'

*Regression Equation: $Q = 0.996\ F_m^{-0.0179}\ F_r^{0.107}$

perpendicular to the radiometers. The regression equation was not significant. The photographs of the fires reveal that one of the most significant variables not appearing in the regression analysis was one that would correlate the change in view factor produced by wind directions which were not at right angles to the line of radiometers. This variable is an unavoidable fact-of-life in field test and particularly influences smaller fires. It was not included because of the difficulty in intrepreting the rapidly changing wide angle and therefore flame response with respect to the radiometers. The plot of heat flux versus Froude number for X/D = 0.5 is shown in Figure 3.14. As a result of the negative statistical significance test for the mass burning rate and Froude numbers as variables, the best predictor of the heat flux rate at D/2 is the mean of all the measurements, i.e., 0.92 BTU FT^{-2} SEC^{-1}. However, when the data are correlated against F_m and X/D the correlation becomes very significant as we have indicated in the previous paragraphs.

3.2.2 Substrate: Water, Sand, Rock

The influence of substrate on burning rates and radiation fields from pool fires of JP5 in the 10-foot diameter pan was found to be considerable. In Table 3.3 the burning rates of JP5 on water, sand, and rock substrates are compared. As soon as burning is no longer dependent upon the radiant feedback mechanism and becomes conduction limited, the fuel burning rate in sand and rock diminishes continuously until the heat conducted beneath the surface no longer is sufficient to vaporize fuel and maintain the surface fuel/air ratio above the flammability limit. In both sand and rock, extinguishment occurred when the liquid level was about one inch below the surfaces. The rate data in Table 3.3 are for the first few minutes during which time an equilibrium burning rate is established. Both sand and rock substrate reduced the burning rate, the rock substrate initially by a factor of one-tenth and the sand substrate by only two-thirds. When wet the apparent weight loss on a sand substrate is about equal to that measured for fuel or water substrates.

As with burning rates it was found that the thermal flux from fires on sand and rock substrates was significantly reduced after burning lowered the fuel level below the surface of the substrate. In Figure 3.15 the heat flux from JP5 fires on substrates of water, sand (dry), and sand with 4.8% water is reduced by about one-third when the sand is not initially wet with water. If the sand contains 4.8% water before it is saturated with fuel, the radiation level appears to be the same as that from a fire on a water substrate. The

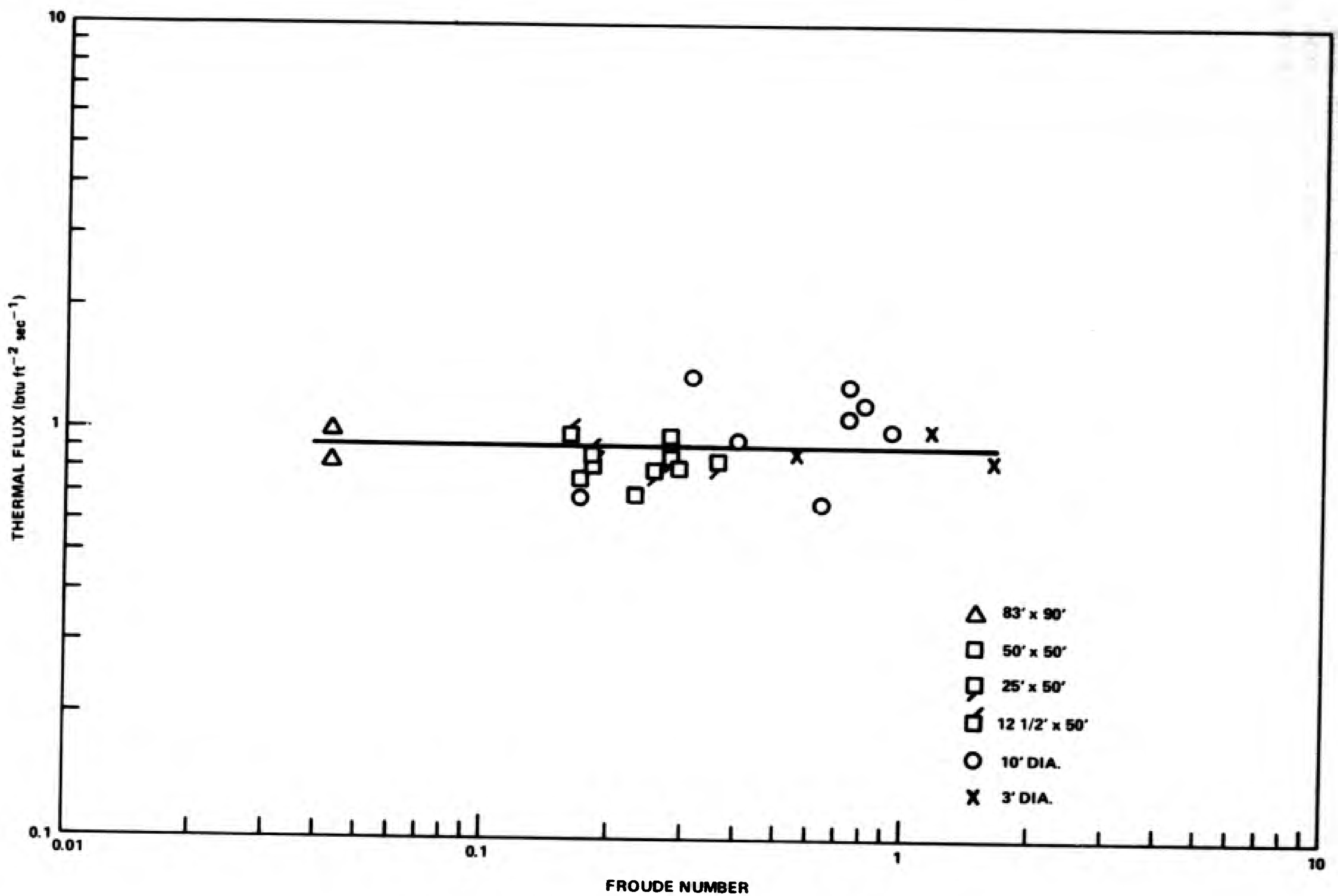


FIG 3.14 THERMAL HEAT FLUX AT DISTANCE D/2 FROM JP–5 POOL FIRES

Table 3.3

INFLUENCE OF SUBSTRATES ON JP5 BURNING RATES

Substrate	Specific Mass Burning Rate, LB SEC^{-1} FT^{-2}
H_2O	0.012
Sand (dry)	0.008
Sand (4.8% water)	0.013
Rock	0.001

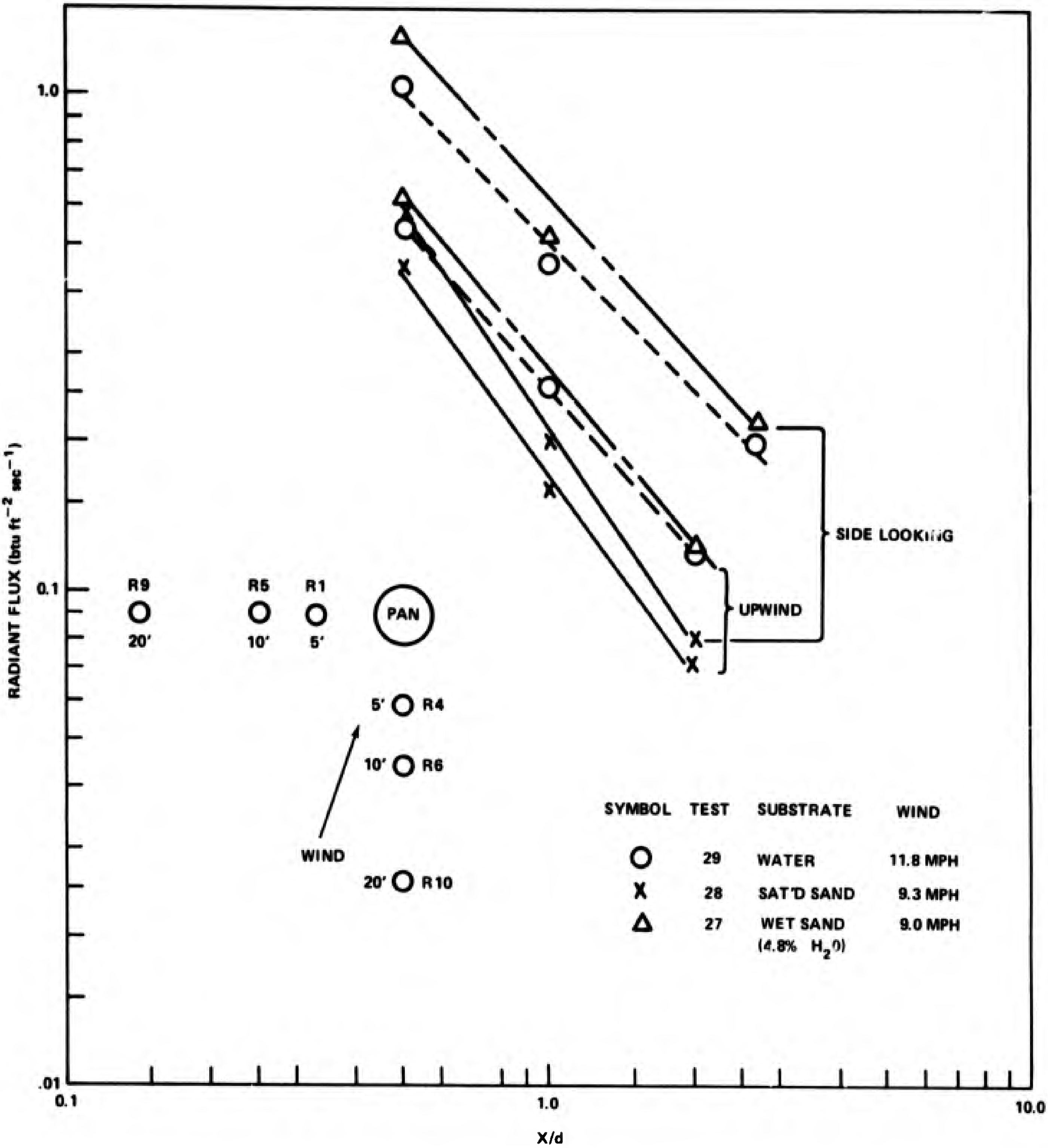


FIG 3.15 RADIATION FROM 10' DIAMETER JP–5 FIRES WATER VS SAND SUBSTRATES

radiation from fires on rock and water substrates are compared in Figure 3.16. Fires on rock and dry sand substrates follow the same trend once the fuel level is below the substrate surface.

3.2.3 Objects: Passive Versus Active

The influence of passive objects, i.e., non-burning structure, on the radiation field was demonstrated in the simulated C5A burns at China Lake. Figure 3.17 shows two test configurations with the same fuel area but with the C5A mock-up centered in the fuel bed in one case and completely outside the fire in the other. The radiation fields for the five tests included in Figure 3.17 exhibit sharply reduced thermal flux readings at X/D values greater than 0.5 when the structure is in the fire. Although the wind varied from 3.1 to 10 mph during these tests, the regression analysis of radiation flux versus Froude number supports the assumption that the effect of these winds on the radiation field from such large fires could be considered negligible.

The influence of active objects such as burning aircraft within the burning pool fires was shown on the 83 foot x 90 foot minideck at China Lake. Five closely packed deactivated F-11A aircraft were placed on the deck as indicated in Figure 3.18. Ambient winds during the test series never exceeded 3 knots. Forced winds up to 35 knots over the front surface of the pond were generated by the prop wash from a C-97 aircraft. These winds produced relatively minor perturbations of the smoke column. The major effect of the aircraft was to create a high degree of turbulence between and around the planes. This modified the air flow and affected the radiation field in several ways. First, the amplitude fluctuations in the thermal flux rate are larger when the plane created turbulence is present. Second, the turbulence caused higher radiation readings on the closer radiometers when the local turbulence caused the flames to envelope the measuring station. Besides modifying the air-currents and obstructing spray patterns from the monitor and hand lines, the planes presented at least two direct threats. First there exists the possibility of explosions on the aircraft in as short a time as two minutes, e.g., in one test a gas tank exploded. Operational aircraft would contain more explosion hazards than these cannibalized, deactivated aircraft. Second, the aircraft contain Class A fuels of various kinds that ignited and gave the fire a three dimensional fuel array as well as sources of reignition for the jet fuel. The reinforced plastics in the wings, tail section, and radar domes ignited and frequently were still burning when JP5 had been extinguished. However, these sources did not reignite the jet fuel. The tires were of particular interest because they were in direct contact with the JP5. When examined after several

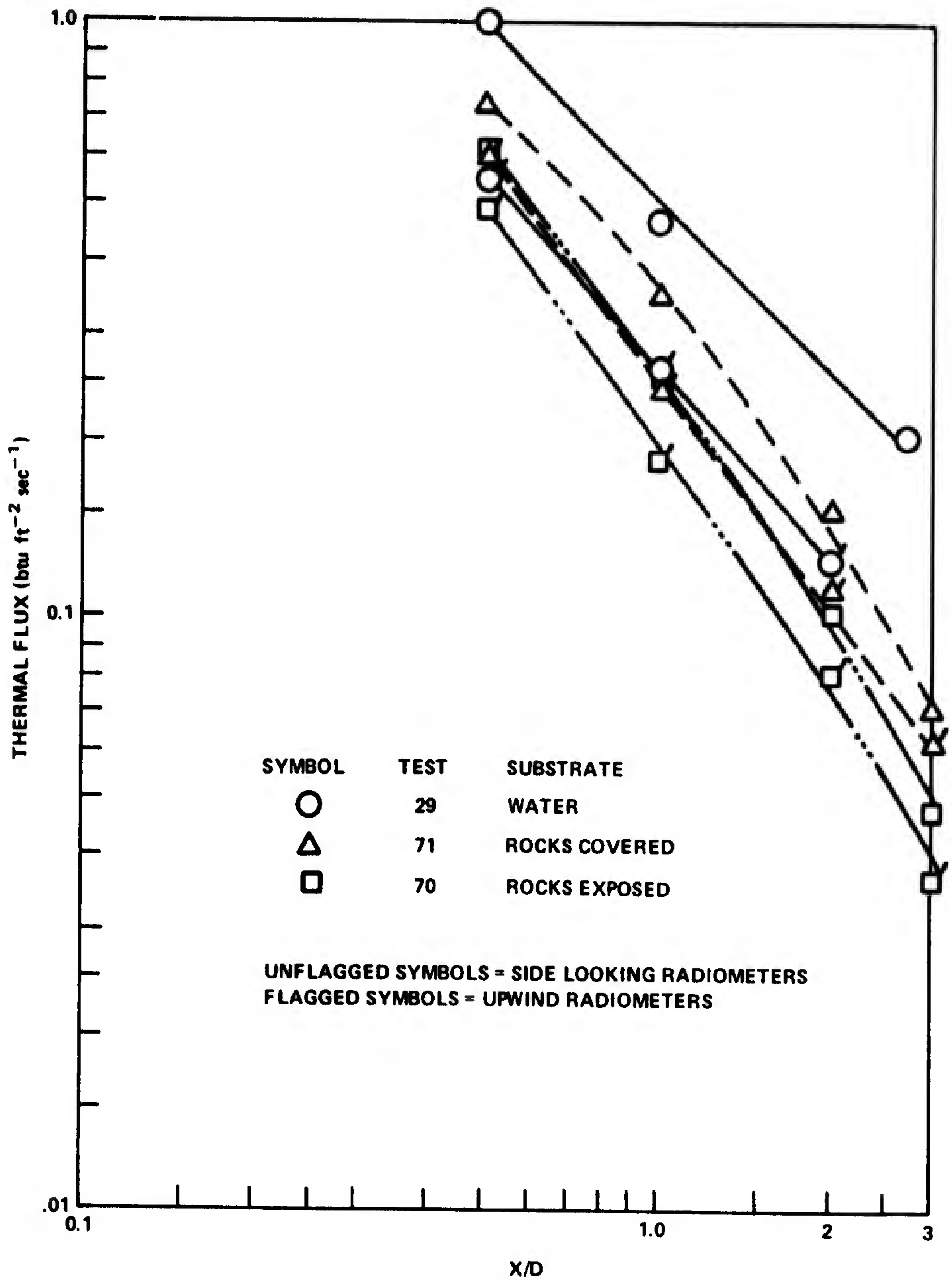


FIG 3.16 RADIATION FROM 10' DIAMETER JP–5 FIRES ON WATER AND ROCK SUBSTRATES

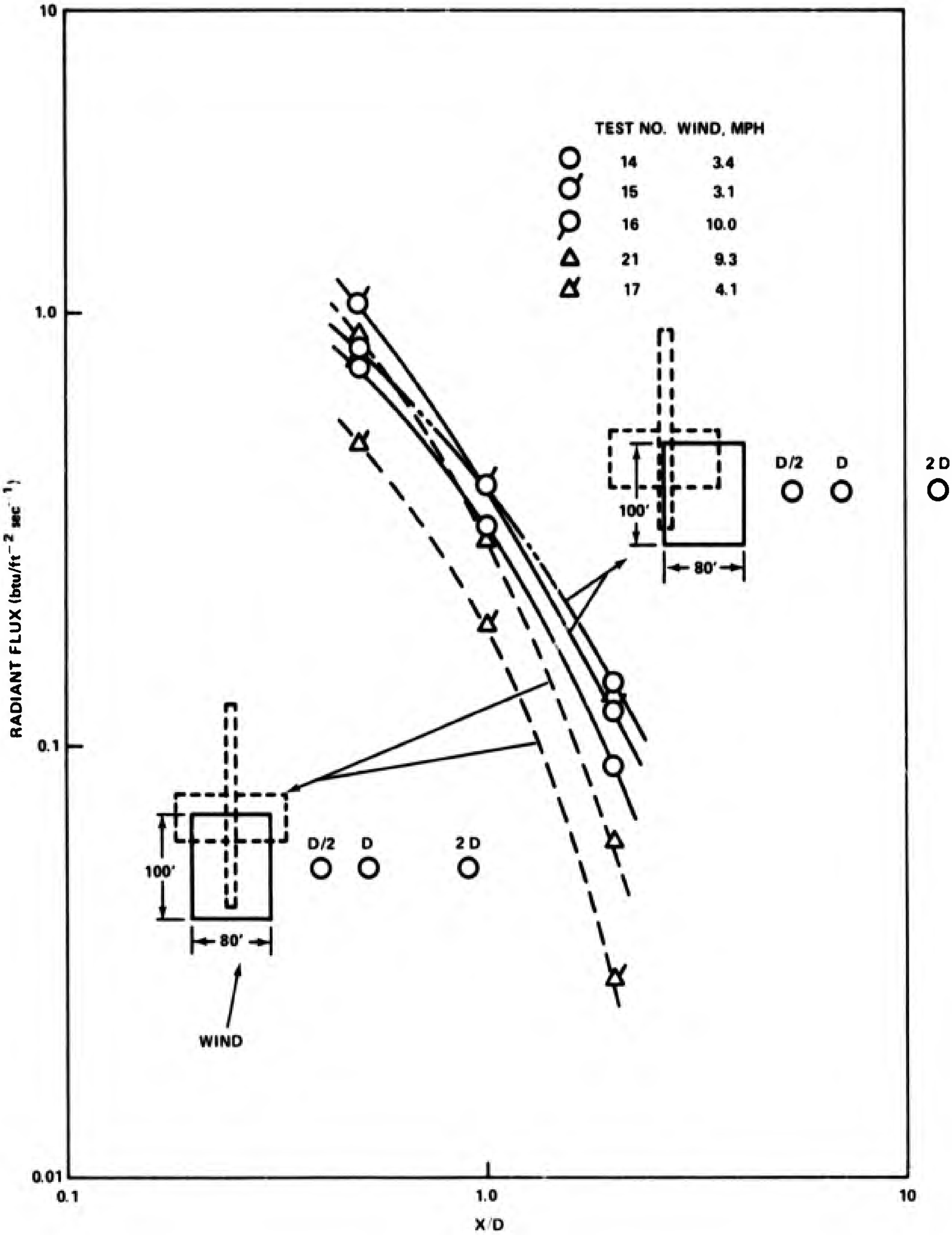


FIG 3.17 THERMAL FLUX FROM LARGE FIRES WITH PASSIVE OBJECTS

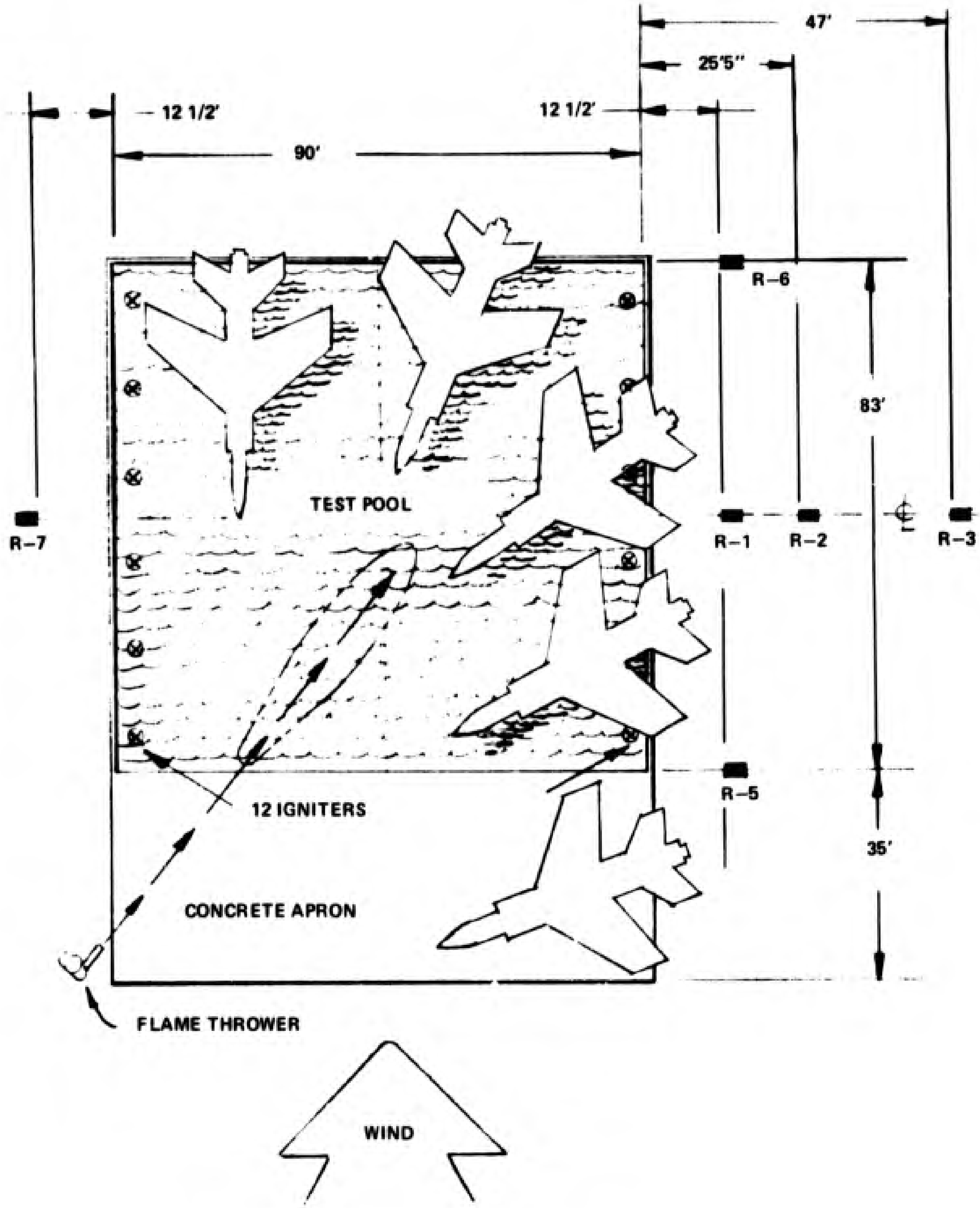


FIG 3.18 ARRANGEMENT OF F-11A AIRCRAFT PARKED IN TEST AREA

test fires the tires were charred clear through the tread to the cord, but they did not burn after the surrounding fuel was extinguished nor reignite the fuel. Finally, molten aluminum dripped into the JP5 pool as the aluminum skin melted. This hot metal did not alter the fire or the suppression in a detectable way.

4.0 IDEAL SUPPRESSION

The objectives of this section are (1) to describe the process of suppression with AFFF in sufficient detail to permit predictions of the effects of varying the principal experimental parameters, (2) to provide a physical basis for the amount of agent required for extinguishment, (3) to indicate how to optimize the use of foam agent, and (4) to provide yardsticks for evaluating the performance of men and equipment. For convenience the discussion is divided into two parts where the first step deals with the events at the surface of the fuel, i.e., Sections 4.1 and 4.2 and the second part is concerned with the problems involved in applying the foam, i.e., Sections 4.3 and 4.4. Some of the important parameters involved at the surface are inaccessible to direct measurement, therefore the conservation of energy and the conservation of agent are employed to relate these surface parameters to the application or operating variables.

4.1 Mechanism of Extinguishment with Foam

The model for extinguishment commences with the assumption that the burning rate (R_b) is equal to the rate of fuel evaporation (R_e) both for the total fuel consumed and on a unit area basis. The energy responsible for this evaporation must be fed back into the fuel from the combustion zone. At any instant, the conservation of energy implies that the energy fed back into the fuel (E_f) equals the energy expended in evaporating the liquid plus the energy lost from the liquid to other heat sinks (E_l). Rearranging the terms, the rate of evaporation becomes

$$R_e = \frac{E_f - E_l}{H_e} \qquad (4.1)$$

where (H_e) equals the heat of evaporation. Following ignition there is a transient period while the flame size increases causing the heat feedback E_f to increase faster than the losses E_l. H_e is reduced somewhat as the temperature of the fuel approaches the boiling point, and the burning rate increases to an equilibrium value characteristic of the fuel and environment. In the large fires of interest here, the flame volume ultimately reaches dimensions greater than the path length for total infrared radiation absorption, then the combustion zone appears like a thermally infinite source, no further increase in the energy feedback occurs and the specific burning rate, i.e., the rate per unit surface area, becomes essentially constant and independent of the fuel bed size.

According to Equation (4.1), the burning rate can be influenced by tampering with E_f, H_e, E_l either singularly or in combination. AFFF operates on all three factors. First a layer of AFFF on the surface has the same affect as increasing the heat of evaporation H_e because the agent interferes with the escape of fuel molecules. This vapor barrier action is the characteristic usually emphasized in discussions of AFFF. Second, a layer of foam makes an excellent thermal shield to absorb and reflect the radiant and convective energy E_f fed back from the combustion zone. Third, the water in contact with the hot fuel surface absorbs heat and increases the loss term E_l. According to this picture, any AFFF arriving at the fuel surface will reduce the burning rate; however, extinguishment will occur only when the agent arrives faster than it departs through evaporation and run off. The critical deposition density will just complete extinguishment as the last of the foam is destroyed. Since heat of evaporation, feedback energy spectrum, and temperature will vary from fuel to fuel, the critical deposition density can be expected to vary from one fire environment to another.

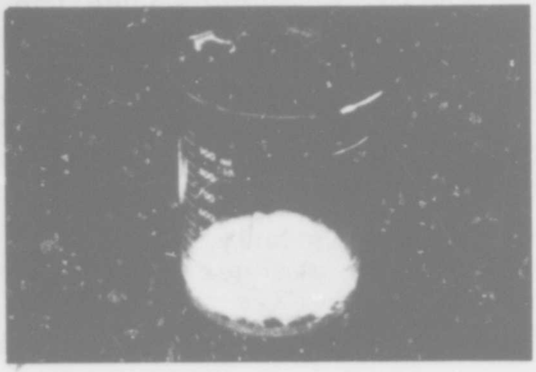
A series of laboratory experiments was performed to determine the relative importance of cooling the thermal shield and the vapor barrier action of AFFF in extinguishing jet fuel fires. Before describing these individual measurements it is instructive to look at the general activity occurring at the fuel surface during extinguishment. In a JP5 fire shortly after ignition, the fuel at the surface reaches a temperature of about 420° F, i.e., intermediate in the boiling range which extends from 370 to 530° F. Since typical foams contain 94% water, steam will be generated when the water contacts the hot fuel. Obviously the water will not remain in the condensed phase until the fuel temperature cools below 212°F. If the water arrives at the surface in drops large enough to penetrate slightly, the expanding steam will blow fuel into the air and the fire will flare up. When the water is applied as a fog or stable foam so that the water does not penetrate the fuel, steam is generated without explosively dispersing the fuel. Since foam is a good thermal insulator, only the part in contact with the fuel converts to steam. Furthermore, the steam inflates the foam to several times the original volume and prevents good thermal contact with the fuel. The inflating vapor is assumed to be steam because deflation occurs when the foam temperature cools to 212°F. Comparable inflation also occurred when foam was deposited on JP5, aluminum and rocks all at the same initial temperature. A slower inflation, i.e., the production of secondary foam by evaporating fuel is sometimes observed with JP4 and AVGAS but this was not the dominant process in these laboratory experiments. This inflation with steam describes the behavior of AFFF which is chemically stable in boiling water and changes physically only when the foam breaks down. In contrast, protein foam changes chemically and coagulates at about 165°F with a rapid release of water which causes more penetration into the fuel resulting in turbulent bubbling.

The sequence of photographs in Figure 4.1 compares the behavior of AFFF and protein foam when applied to boiling JP5. Immediately after application (top frames) the more pronounced steam cloud is characteristic of the protein foam. In the second frame, the protein foam is mixing into the fuel and there is much bubbling and turbulence. By contrast, the AFFF remains on the fuel surface where it has become inflated and still provides complete coverage. When the fuel has cooled to 212°F (bottom frame) the protein foam is completely destroyed while the AFFF not evaporated to cool the fuel still remains on the surface. Since the barrier for energy going from the combustion zone to the fuel bed and for fuel molecules going in the reverse direction depends on intact layers of agent, the high temperature stability of the AFFF makes it more effective than the protein foam.

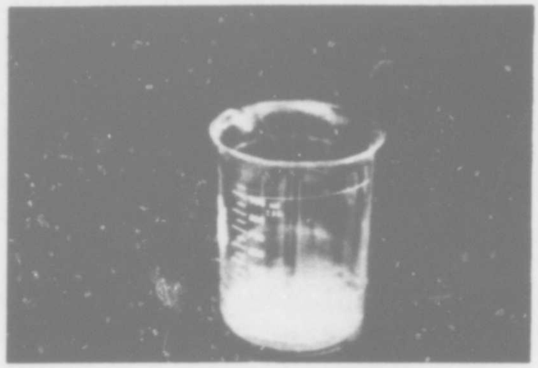
4.1.1 Cooling the Fuel by Evaporating Water

Figure 4.2 shows the simple laboratory arrangement for demonstrating the cooling effect along with a typical cooling curve obtained when the fire was extinguished with an application density of two gallons per hundred ft^2. The thermocouple was used to probe the temperature gradient in the fuel during the preburn period but during extinguishment the position was just below the surface as indicated in the enlarged view. Just before extinguishment the temperature ranged from 420°F at the surface to about 200°F at the water interface one centimeter below. In the cooling curve of Figure 4.2 the surface temperature drops from the original value to the boiling point of water in just under five seconds. Under the equilibrium burning rate conditions JP5 is consumed at a rate of about 0.36 g cm-2min^{-1}. Just below the boiling point of water, i.e., 200°F, the evaporation rate is about 2.5×10^{-3} g cm^{-2} min^{-1}. Consequently, the cooling effect reduces the fuel

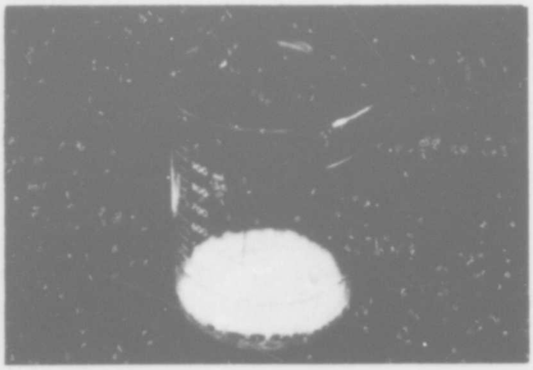
AFFF



PROTEIN



AFFF



PROTEIN

AFFF

PROTEIN

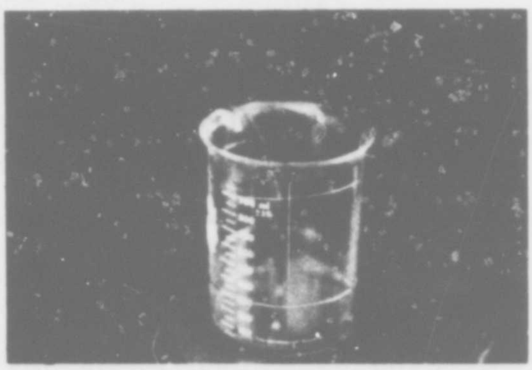


FIG 4.1 PHOTOGRAPHS OF PROTEIN AND AFFF FOAMS COOLING HOT JP–5

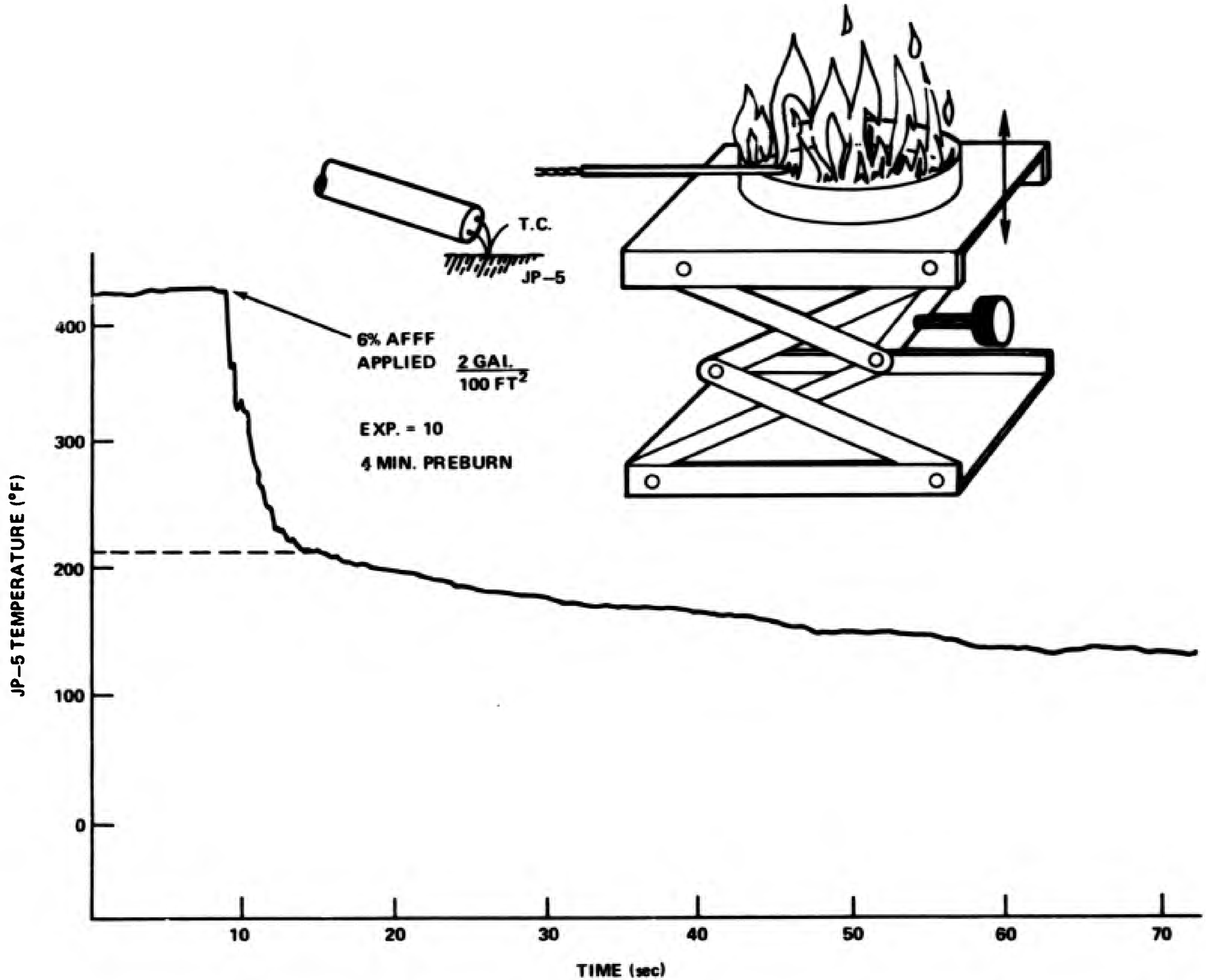


FIG 4.2 JP–5 COOLING CURVE AFTER APPLICATION OF FOAM

evaporation rate by a factor of about 140. Figures 4.3 and 4.4 show the effect of temperature and material respectively on the cooling produced by a 2 gal/100 ft^2 deposit of AFFF. Three temperature regions are of interest as illustrated with the aluminum substrate in Figure 4.3. Well above the boiling point of water, the foam in contact with the substrate quickly turns to steam and inflates the foam to several times the initial expansion ratio. As described in Section 4.1 this inflation interferes with foam to substrate contact; consequently, the cooling rate is modest, the foam remains highly expanded, and all the weight loss is due to evaporation. Near the boiling point, contact improves and rapid cooling ensues until the foam and substrate are below 212°F, then the steam inflated foam collapses and water emerges from the drainage hole. Below the boiling point no inflation occurs and the foam decays slowly in comparison to the two high temperature regions. Similar inflation and collapse of the foam occur on other surfaces, i.e., rock, and JP5. The curves in Figure 4.4 demonstrate the influence of substrate heat capacity and thermal conductivity on the cooling rate and survivability of the foam. These substrates were heated to the boiling point of the JP5 which is the limiting temperature as long as fuel covers the surface; however, when areas protrude through the fuel, much higher temperatures become possible. Also, longer heating periods will store more energy in the fuel and substrate. From a practical fire fighting standpoint, prompt suppression is required to minimize the agent evaporated in cooling the fuel and substrate.

4.1.2 Heat Barrier

Figure 4.5 illustrates the apparatus and procedure used to measure the decrease in evaporation rate (R_e) due to a layer of foam or foam solution on the surface of the fuel. Radiation levels from 5.4 to 1.8 BTU ft^{-2} sec^{-1} were obtained by varying the distance between the lamp bank and the sample dish. The lamp spectrum at the top of the figure has a tail that extends into the visible region where water solutions are transparent; therefore, the absorption factor will not be as large as for infrared flame spectra. Nevertheless, the family of points show that one gallon per 100 ft^2 of liquid can reduce the transmitted energy by 40% and a similar amount of liquid converted to foam produces an order of magnitude reduction, i.e., scattering in the foam is more effective than absorption in the liquid for reducing energy transmitted to the fuel surface. If the loss term (E_l) in Equation (4.1) is small or linearly proportional to the energy fed back (E_f), the burning rate (R_b) would also drop by an order of magnitude. Apparently the percentage agent

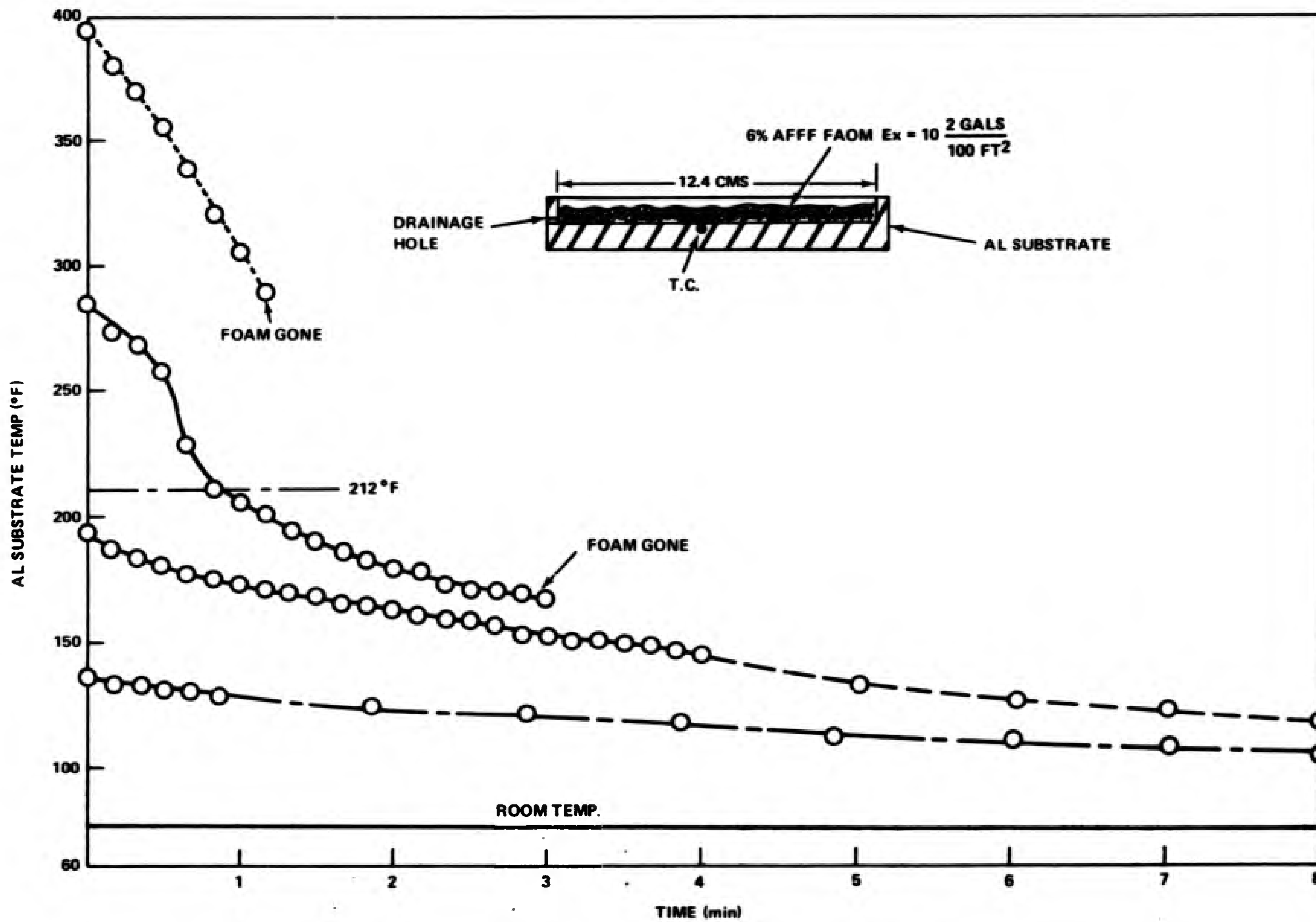


FIG 4.3 EFFECT OF SUBSTRATE TEMPERATURE ON COOLING

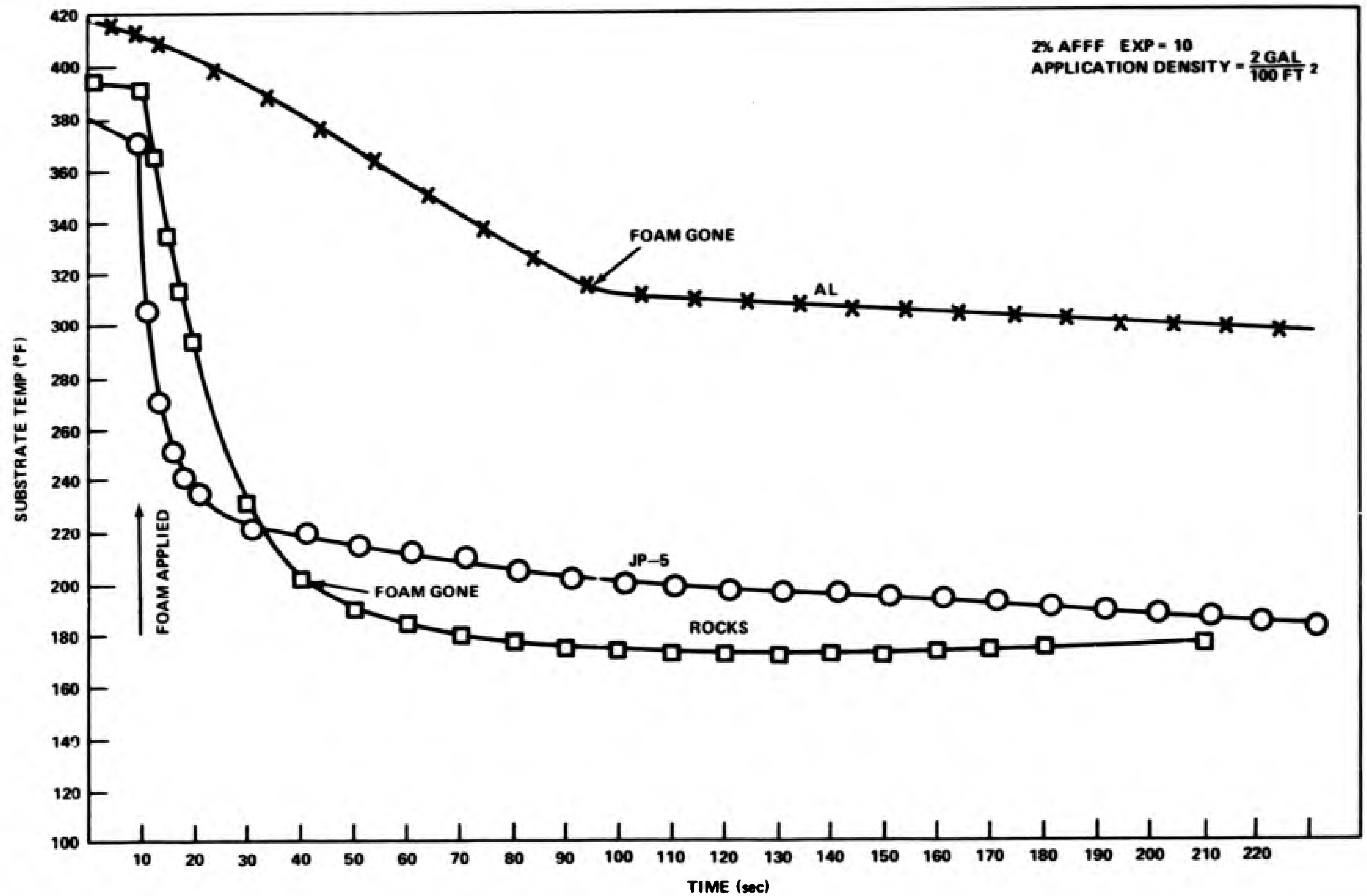


FIG 4.4 EFFECT OF SUBSTRATE MATERIAL ON COOLING

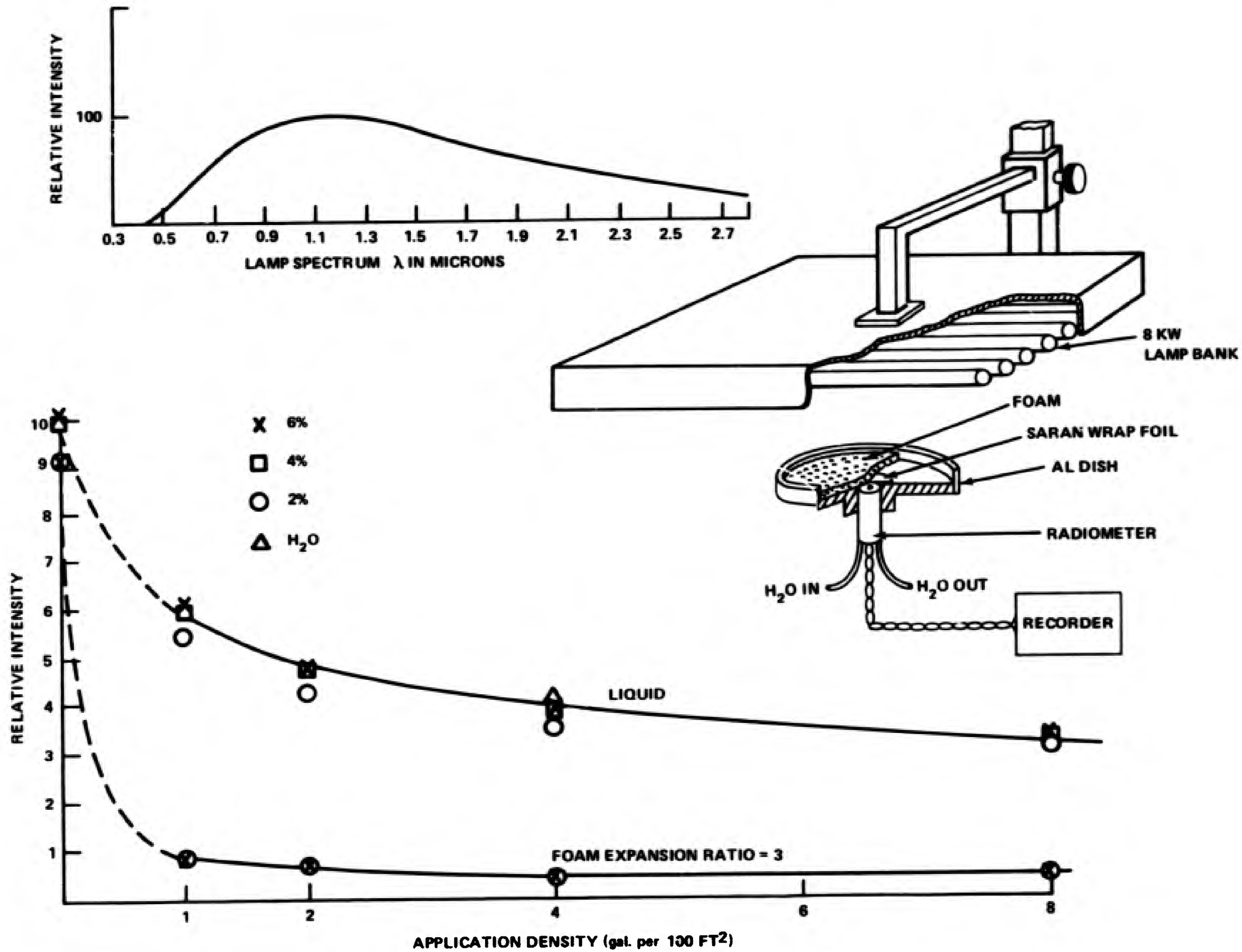


FIG 4.5 FOAM AS A THERMAL BARRIER

concentration and the expansion ratio have little influence on absorption and scattering.

Measurements of foam stability were made in the apparatus shown in Figure 4.6 which combines the insult from above by thermal radiation from the lamp bank with heat from below by the preheated aluminum substrate. Weight losses were measured with a Mettler balance equipped with a photocell to count the number of dial markings passing a viewing slide. The term weight-loss is preferred to drainage rate because at high temperatures the water evaporates and very little moisture collects in the catch beaker. Figures 4.7, 4.8, and 4.9 show weight loss curves for three modes of thermal insult. In Figure 4.7, 2% and 6% AFFF samples were exposed to four radiation levels typically encountered at various distances from the flame front. Figure 4.8 shows the influence of starting substrate temperatures when heat is applied only from below, i.e., foam was applied when the thermocouple in Figure 4.6 registered the temperatures indicated on the respective curves. Figure 4.9 covers a condition where the losses are about equally divided between the two insults. Figure 4.9 contains data for a variety of concentrations and expansion ratios, while Figure 4.10 compares weight-losses for several application densities. In Figure 4.10 the one-gallon per 100 ft^2 curve is a little misleading because the foam could not cover the entire bottom of the heated pan; consequently, heat was not absorbed as fast as in the larger application densities. The significance of the results in Figures 4.6 to 4.9 for fire suppression depends on the course of events at the flame--ront-foam interface. According to Figure 4.7 about half the incident radiant energy is consumed in evaporating water and half is scattered away. From Figure 4.9 it appears that at a position just outside the flame front, the rates of energy transfer to the foam from the flames and hot substrate are about equal; therefore, their relative importance will depend on time. If the flames are extinguished quickly, i.e., in times short compared to the time required to cool the fuel, the foam destroyed by radiation will be negligible. However, the cooling energy is a relatively fixed quantity while the radiant energy will continue as long as the flame front presists, e.g. as in a burnback protection situation.

4.1.3 Vapor Barrier

This characteristic is difficult to evaluate quantitatively at high temperatures because of the difficulty in separating the barrier and cooling effects. Above the boiling point of water, the rapid temperature changes illustrated in Figure 4.2 coupled with the very transient existence of the foam complicate observations in the critical temperature range.

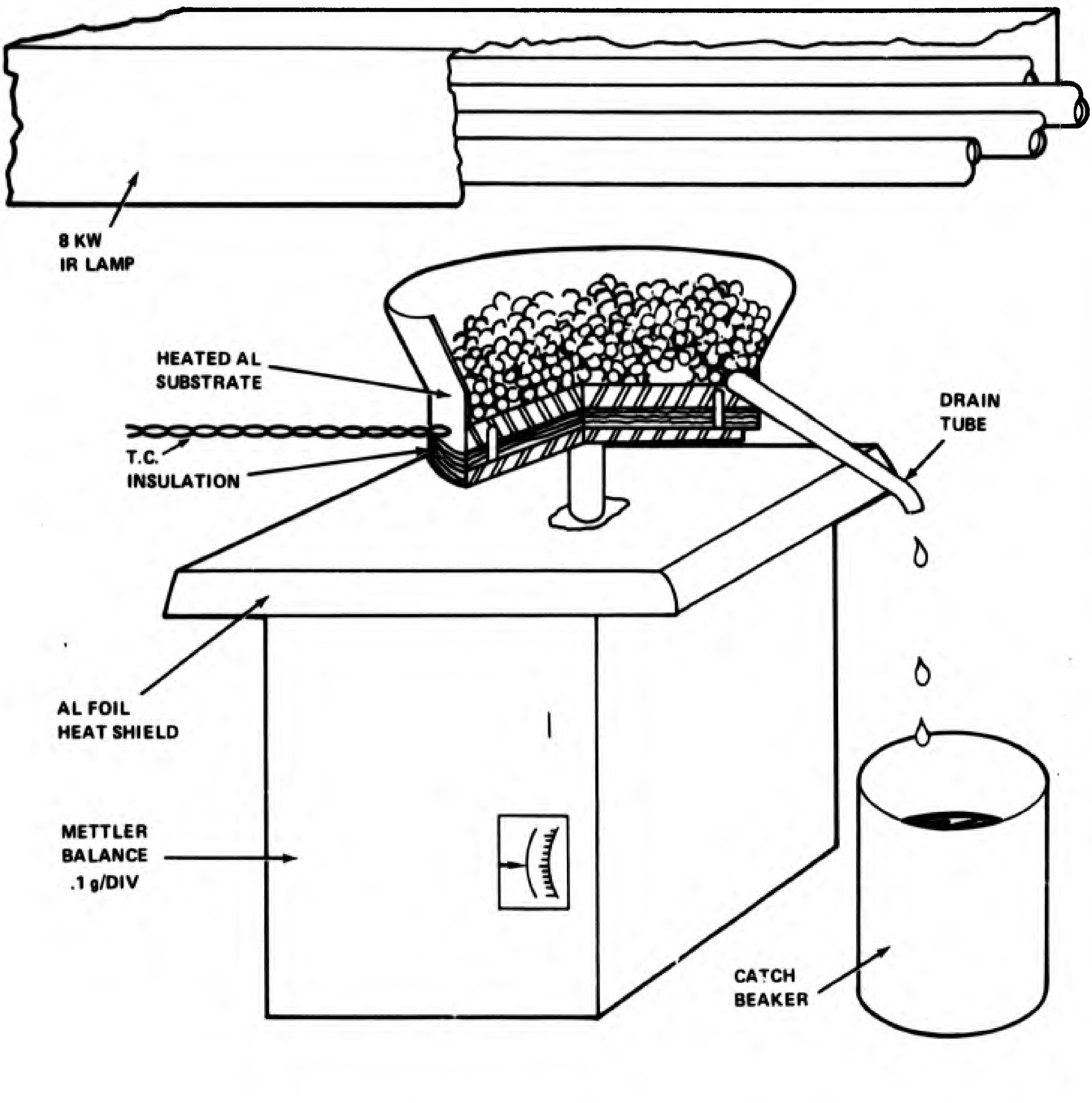


FIG 4.6 THERMAL STABILITY APPARATUS

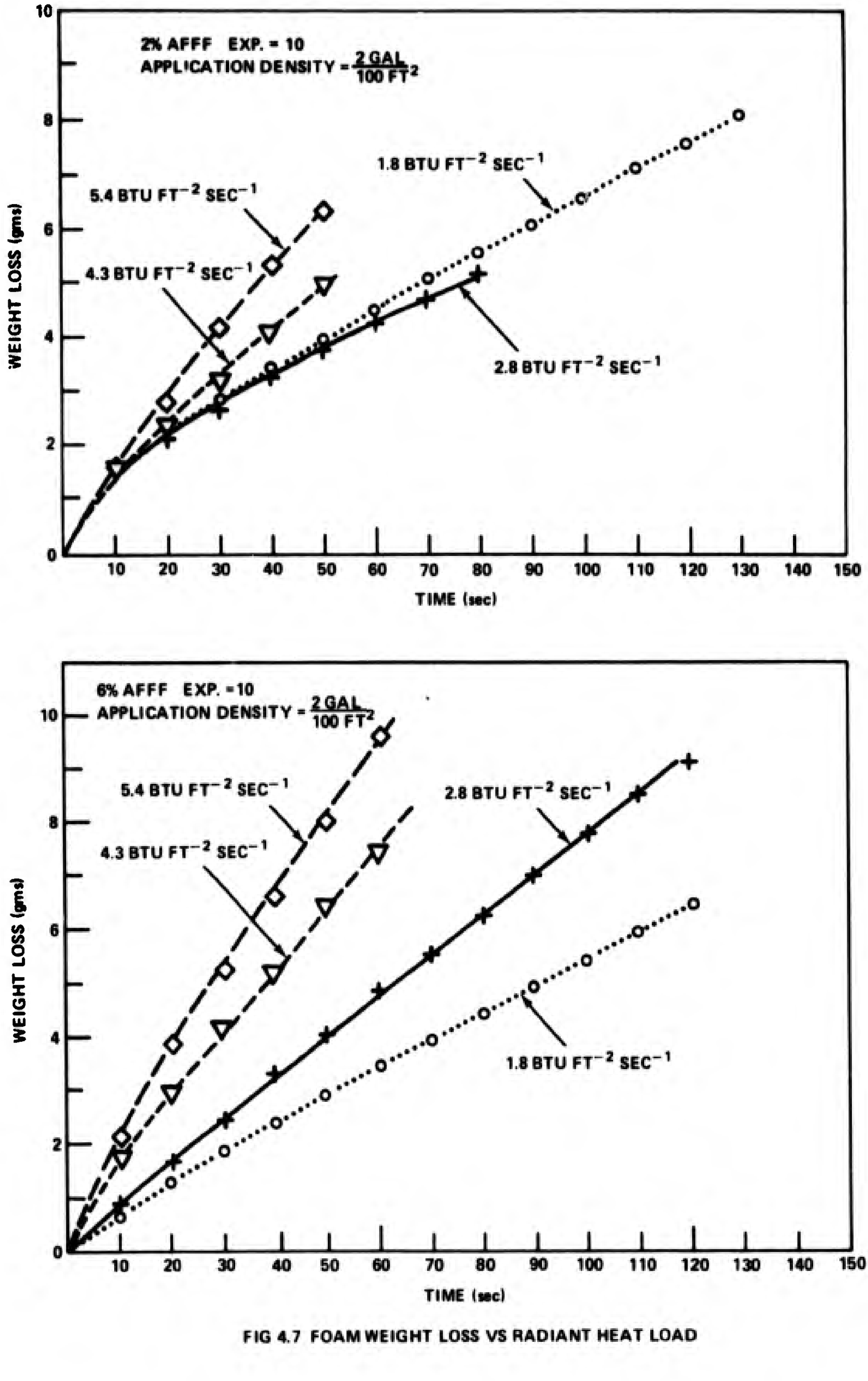


FIG 4.7 FOAM WEIGHT LOSS VS RADIANT HEAT LOAD

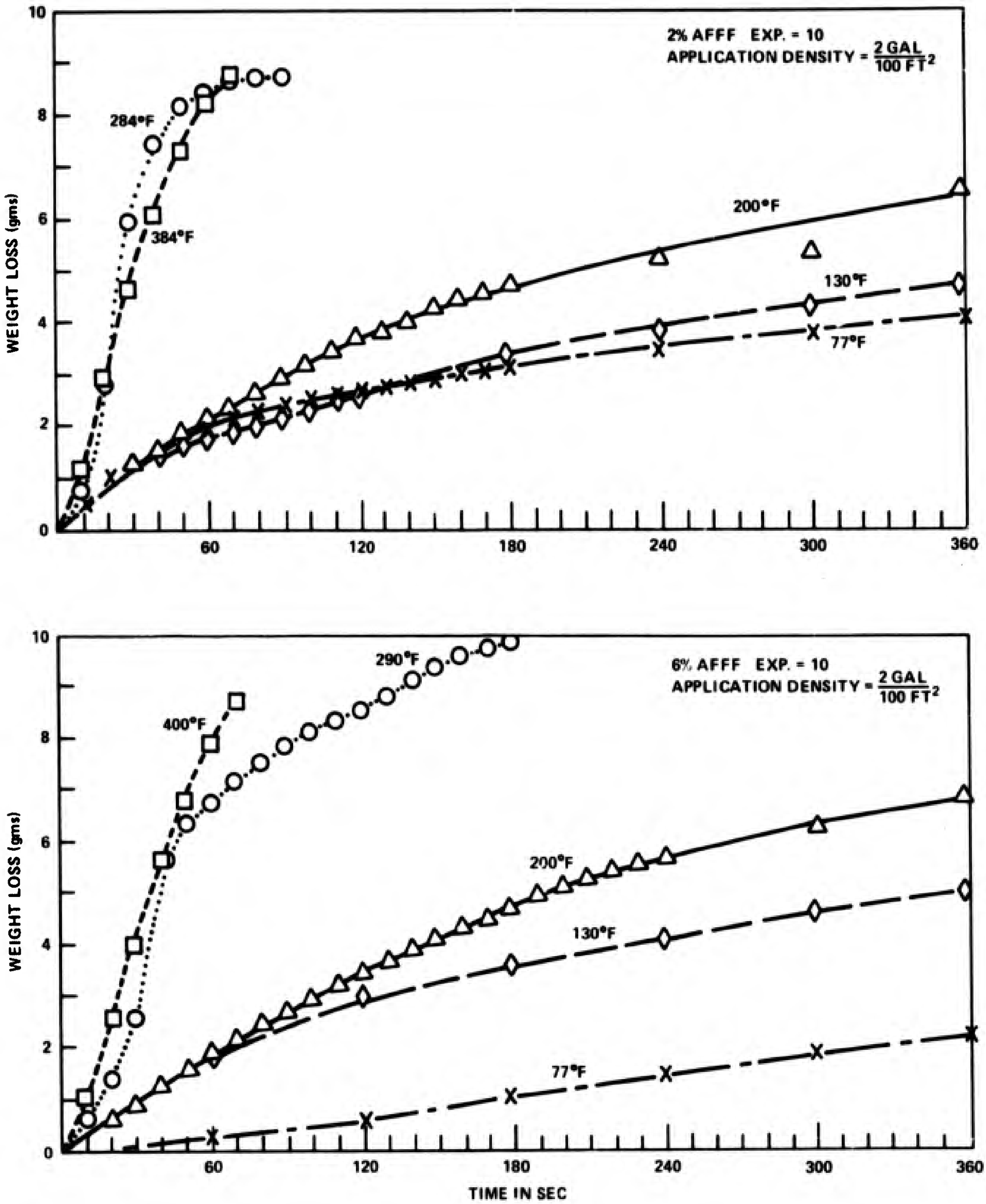


FIG 4.8 FOAM WEIGHT LOSS AS A FUNCTION OF TIME FOR VARIOUS INITIAL SUBSTRATE TEMPERATURES

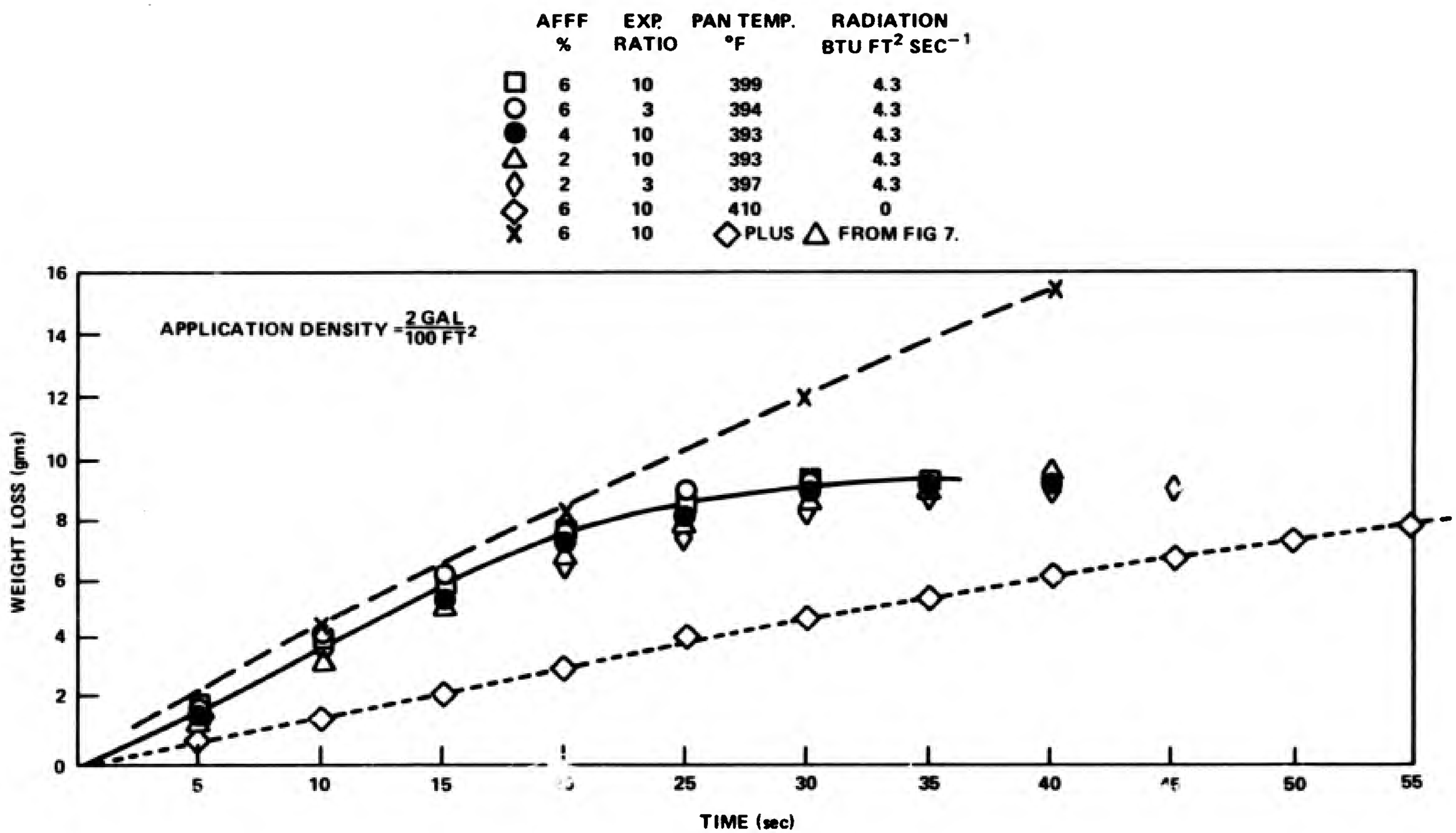


FIG 4.9 FOAM WEIGHT LOSS VS % AFFF AND EXPANSION RATIO EFFECT OF AGENT CONCENTRATION AND EXPANSION RATIO ON WEIGHT LOSS

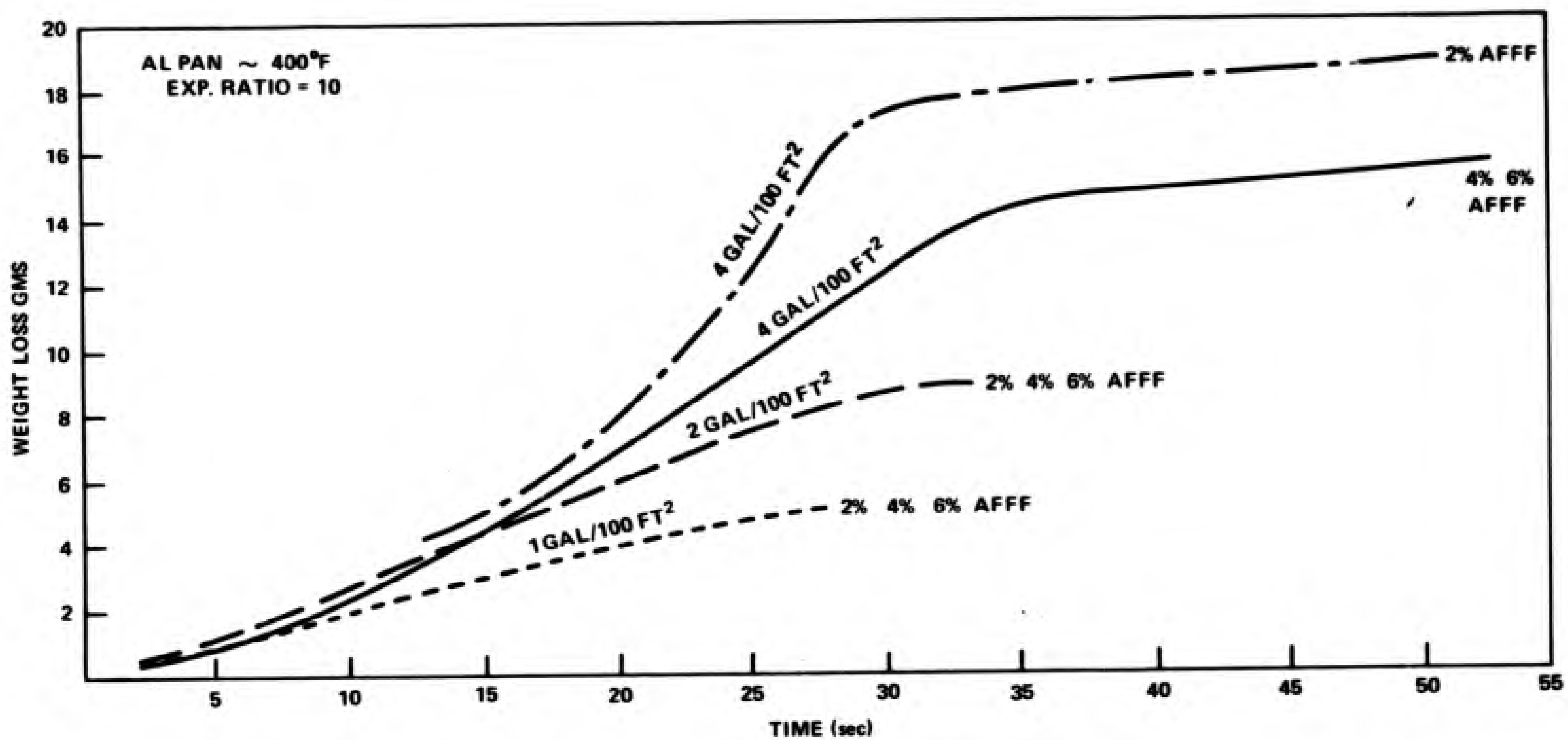


FIG 4.10 FOAM WEIGHT LOSS VS APPLICATION DENSITY

Consequently the present evaluation of barrier efficiency is based on circumstantial evidence in addition to measurements at lower temperatures. Moran, Burnett, and Leonard (Reference 4.1) demonstrated that at room temperature, thin layers of 6% FC-195 solutions reduced the vapor concentration over hydrocarbons such as cyclohexane and JP5 by a factor of 10 or more. The critical film thickness was about 10 microns or about 0.025 gallons per 100 ft^2. Thicker layers up the limit for stability on the surface reduced the concentration by only another factor of about 2. These fundamental experiments provide important insights into the action of AFFF but a quantitative extrapolation to elevated temperatures and multiple cells for a foam structure is not immediately forthcoming.

A few observations have been made just below the boiling point of water where the reduced cooling rate and increased foam life-time permit observations for several minutes in contrast to seconds at the higher temperatures. Figure 4.11 shows the simple experimental arrangement along with several evaporation curves for JP5. At 200°F the evaporation rate is about 0.0025 g cm^{-2} min^{-1}, i.e., down by the previously mentioned factor of about 140 from the 0.359 g cm^{-2} min^{-1} observed during combustion. When the foam is applied the increased weight produces a sudden downward displacement in the weight-loss curve followed by a gradual return to the initial evaporation rate. This transient period depends on the fuel temperature and the amount of foam applied, e.g., the foam lasted about 5 to 10 minutes at 200°F and 20 minutes at 144°F. As long as foam remained visible on the surface, the weight loss rate exceeded the value for fuel alone. With the 6 g foam sample there was no visible evidence of agent sinking below the surface either during application or throughout the life of the foam. With the 9 to 10 g samples a few drops of liquid in the foam sank to the bottom of the crystallizing dish during foam application but no lens formation or drops developed subsequently. Evidently the agent departed by evaporation. In the 6 g case the total rate just before foam application equalled the rate when the foam had just vanished; consequently it is tempting to assume that the displacement (d) corresponds to the fuel that did not evaporate because of the foam barrier. With the heavier application densities some of the displacement stems from the agent that sank during application. This temptation to assume a cessation of fuel evaporation is encouraged by the observation that new bubbles did not appear and existing bubbles did not increase in size during the foam lifetime, i.e., the secondary foam that forms with more volatile fuels such as AVGAS was not observed with JP5. The combination of visual observations and weight loss measurements strongly suggests that the foam effectively

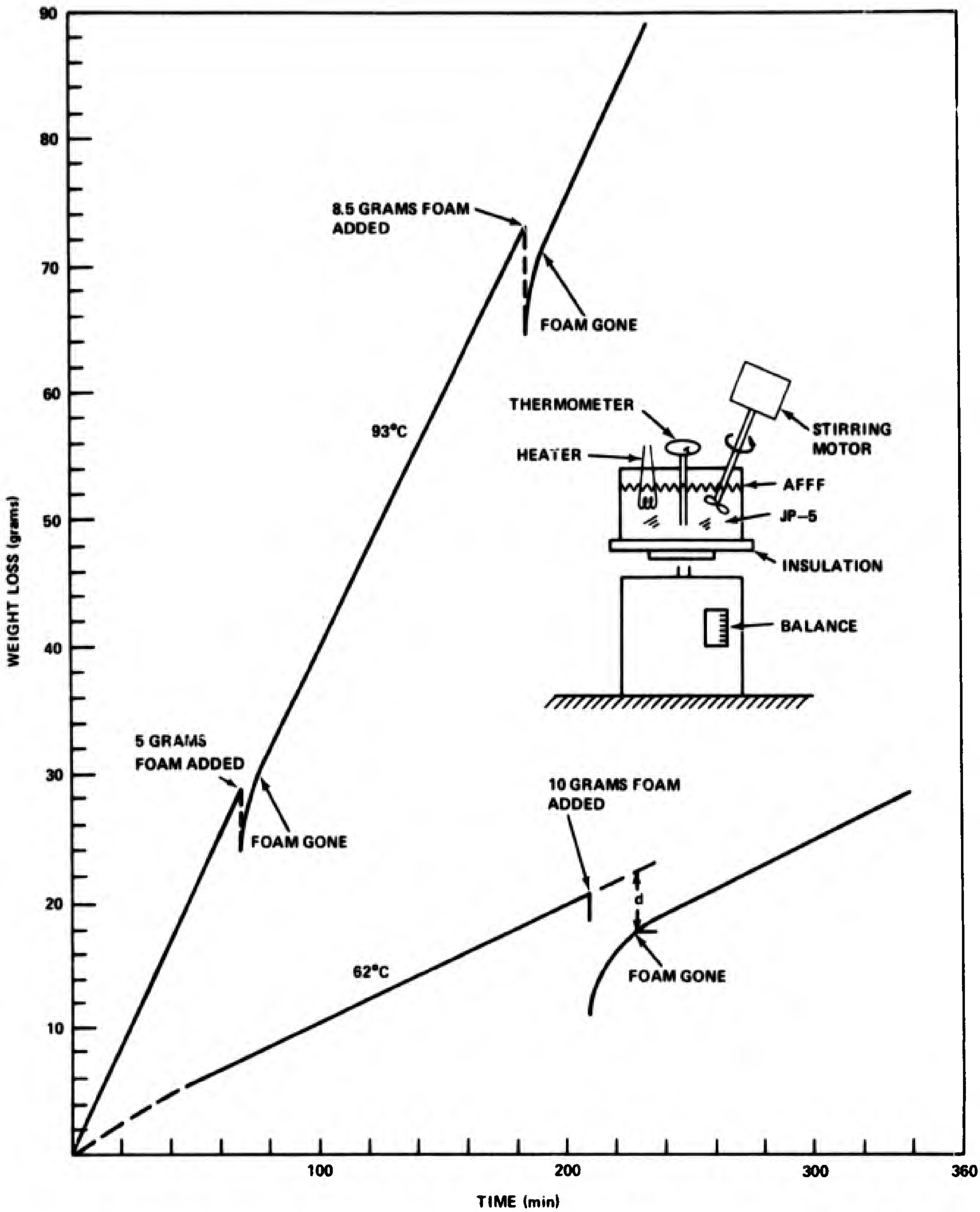


FIG 4.11 EVAPORATION CURVES FOR JP–5 AND JP–5 + AFFF

stopped fuel evaporation; however, undetected water absorption could undo this simple demonstration.

4.1.4 Critical Application Density

As defined in Table 2.1 the critical application density is the amount of agent that will just extinguish the fire. With AFFF all three suppression mechanisms are operating to reduce the fuel vapor reaching the combustion zone; therefore, the critical application density can be discussed in terms of the reduction in fuel evaporation rate required to reach the lower limit for combustion, namely the fire point. From this point of view, the central question is how much reduction in burning rate is required for extinguishment. One estimate of reduction is based on measured values of the burning rate and evaporation rate at the fire point. Under equilibrium burning conditions at a temperature of about 420°F JP5 evaporates at about 0.36 g cm^{-2} min^{-1}. At 144°F, which is about the flash point, the rate of evaporation drops to 5.8×10^{-4} g cm^{-2} min^{-1} corresponding to a decrease in evaporation rate of about 600. Another estimate of the decrease required for extinguishment, based on fires that extinguish themselves, e.g., fuel burning on substrates of sand or gravel. Looking briefly ahead to the next section, Figure 5.4 shows the weight loss curve for JP5 burning in a 10 foot diameter rock bed. A comparison of the rate at extinction, i.e., 0.0023 g cm^{-2} min^{-1} to the burning rate of a pool fire, 0.36 g cm^{-2} min^{-1}, leads to a factor of about 150 in the change of evaporation rate. If it is assumed that cooling the fuel surface to 212°F is necessary to maintain a barrier for either heat absorption or vapor retention, then for JP5 these other two modes of protection have only to contribute a factor of 6 to 10 at most, well within their capabilities. If it is assumed that for JP5 the critical application density will just cool the surface of the fuel to 212°F then for the conditions encountered in Figure 4.2, namely a fuel temperature ranging from 420 to 212°F over a thickness of about one centimeter and a specific heat of 0.6 calories g^{-1}°C, the required cooling water would be about 0.8 gallons per 100 ft^2. Based on numerous extinguishment tests on fires ranging from 10 to 50 feet in diameter, the observed critical application density is slightly under one gallon per 100 ft^2 for a fuel thickness of about 1/2 inch or less. Deep pools such as fuel storage tanks that have been burning long enough to heat a greater depth of fuel will require more cooling but such fires are not typical of promptly attacked aircraft crash situations.

JP4 has a higher critical application density despite its lower boiling range because the flash point has now dropped about 140°F below the JP5 value; consequently, considerably more reliance is placed on the vapor barrier action. Because of their low flash points both AVGAS and JP4 can generate secondary foam and under the proper ignition conditions can propagate a transient flame through the foam. These transient flames run through the foam creating a visual impression similar to sheet lightning playing in the clouds. The foam collapses on each passage of the flame and has to be regenerated by the evaporation of more fuel. In the field the critical application density for JP4 was about two gallons per 100 ft^2 for pool fires.

Putting aside possible theoretical interest in the critical application density, the practical value as a yardstick for evaluating agents, equipment, and application techniques makes this parameter very useful. For example, the evaluation of various foams should be based on their critical application density for extinguishing a standard test fire. To be valid, the test procedure must be designed to avoid application effects that can mask the density results. With some of the existing crash trucks, it is humanly impossible to move the turret fast enough to achieve the critical application densities for AFFF when the pumps are operating at maximum capacity; therefore, in agent evaluation tests, such trucks should be operated at reduced pumping rates. Obviously the critical application density provides the fundamental criterion for the design of foam trucks. The goal should be units that can apply foam uniformly at densities down to the critical value. Similarly, the critical application density provides a valuable yardstick for evaluating the performance of the fireman, particularly his development in a training program or his need for more training.

4.2 Foam Properties-Importance of

Conventional foam qualities, namely the expansion ratio, drainage rate, and percentage agent concentration, are measured by routine procedures as specified in NFPA 112. In this section we will look for correlations between these characteristics and the features playing an important role in extinguishment, i.e., cooling, thermal barrier, and vapor barrier as discussed in Section 4.1.

4.2.1 Expansion Ratio

In the laboratory experiments for foam survivability summarized in Figure 4.9 variations in the expansion ratio from 3 to 10, i.e., the extreme range encountered with foam generating nozzles, had no effect on the weight loss. As previously mentioned, the steam generated when the foam contacted the hot aluminum dish expanded the foam to several times its initial volume until the pan had cooled to 212°F at which time the steam condensed and the foam collapsed. This steam inflation controlled the contact to the pan and thus the cooling rate during the critical high temperature period. The thermal barrier to radiation and convection will improve with the number of bubbles present as should the barrier to escaping fuel vapors; however, the initial expansion ratio appears to have little effect on the ratio achieved after steam inflation. Although the low expansion AFFF foams were never superior to the higher ratios, the ratio usually had little effect; consequently this parameter can be adjusted for convenience in application of the foam. For example, when the ambient winds are low and the distance from nozzle to target is short, a high expansion ratio is advantageous because the large volume simplifies the application of a uniform coating. Conversely, when long trajectories are involved, the ratio can be reduced to provide a dense foam that is less susceptible to air currents and thermal updrafts.

4.2.2 Drainage Rate

Drainage rates measured at room temperature are useful in evaluating a foam making process where several batches of the same agent are compared, but not for comparing different agents. The stability of the fire fighting agents should be determined at elevated temperatures, preferably near the boiling point of water. For example, protein foam normally exhibits a lower drainage rate than AFFF under the NFPA test, but above 165°F the coagulated protein cannot maintain or form a foam. Consequently, as indicated in Figure 4.1, the AFFF is more stable than protein foam throughout the critical elevated temperature range. In summarizing the importance of the standard drainage rate test, it should be noted that fire fighting may involve two steps: extinguishment, and burn-back protection when the entire fire cannot be extinguished in a very short time. For extinguishment the high temperature properties of the agent are of paramount importance, but from time to time it has been argued that once the fuel and substrate have been cooled, the agent with the lowest drainage rate could exhibit better burn-back protection. In an effort to evaluate this assertion, Geyer (reference 4.2) compared the burn-back characteristics of protein foam and AFFF in a series of tests involving partial extinguishment followed by burn-back. During a typical 30-minute sequence control required six applications of AFFF for a total 664 gallons compared to four applications of protein foam involving 1,040 gallons, i.e., about 22 gpm for AFFF versus 34 gpm for protein. Apparently the overall advantage remains with the thermally more stable foam.

4.2.3 Percent Concentration

The ability of the FC-200 to withstand thermal insult was relatively independent of the agent concentration in the range from 2% to 6% as shown in Figures 4.9 and 4.10. Since these tests principally follow the evaporation of water, the lack of a concentration effect is not surprising. Agent concentration should be important where the vapor barrier is tested such as in extinguishment. In small laboratory suppressions, the same minimum critical application density was found for both 3% and 6% concentration; however, it was easier to reproducibly achieve extinguishment at the critical application density with the 6% foam.

4.2.4 The Ideal Agent Characteristics

Three factors are involved in a comparison of fire suppression agents.

1. Efficiency as measured by the critical application density.

2. Operational latitude and convenience.

3. Cost.

Obviously, the ideal solution will have the lowest critical application density, the maximum latitude and convenience in use, and the lowest cost. Where lives are in danger as in aircraft crash fires, the first two factors should determine the choice of agents.

In developing or selecting an agent, the efficiency will depend on the foam's ability to cool the fuel and to provide thermal and vapor barriers between the fuel and the flames. For cooling, water is an ideal material, because (1) of its exceptionally high heat of vaporization, i.e., the highest of all common materials and (2) because of the convenient boiling point, i.e., below the middle of the boiling range for the common aircraft fuels, AVGAS, JP4, and JP5. Since all foam solutions are more than 95% water, they have essentially the same potential cooling power; therefore, the only area for improvement involves keeping the water where it will be most efficient, mainly on or above the fuel surface. As outlined in Section 4.1, the agent must achieve good stability at the boiling point of water if the foam is to survive the initial cooling phase. A simple test that will provide a relative comparison of the high temperature stability of foams can be readily performed in the laboratory. For example, heat a small beaker of each agent to the boiling point of water while slowly bubbling air through the liquid. A stable solution should still form bubbles at 212°F and generate some transient bubbles due to steam inflation. This simple procedure will illustrate the substantial difference in stability between protein foam and AFFF.

For the thermal barrier against radiation and convective heating again a water foam provides a good material because water has good infrared absorption characteristics and the air bubbles in the foam both reflect light and provide excellent insulation. To maintain its effectiveness, the barrier must cover the fuel surface and not disintegrate at the elevated temperatures, i.e., the water should leave by evaporation outward and not by drainage into the fuel. Consequently, the stability requirements are the same as those required for cooling. Two factors of molecular architecture are important for the vapor barrier. First, the agent must have good surfactant characteristics so that a sealing layer of protective molecules will readily cover the fuel and, second, these molecules should exhibit a low vapor pressure so they will not evaporate along with the water at the elevated temperatures. Undoubtedly, the success of the fluorocarbons in these tests stems from good performance in both of these categories.

The qualities listed so far pertain to extinguishment; however, there are circumstances where complete extinguishment is not possible, then the question of burn-back protection becomes important. In Section 6.0 where a series of burn-back experiments are discussed, two general situations are encountered corresponding to flames moving downwind or upwind. In the first case, the flames lean over the foam producing an intense thermal load particularly at the leading edge of the foam. The water evaporates rapidly and the thin film of surfactant molecules is soon destroyed. Foam life in this situation is determined primarily by the amount of water available for evaporation. In the usual situation where the agent is applied from the upwind side of the fire, the flames lean away from the foam blanket and the thermal insult is less severe than in the preceding case. Now the drainage characteristics of the foam have time to exert their influence. As the AFFF foams age, fissures often develop when there are no longer enough bubbles to cover the entire surface. The burn-back pattern follows and expands these open areas. Under these circumstances, the drainage time for the foam becomes important and the ideal foam would have a long life in addition to the excellent extinguishment characteristics.

Several laboratory attempts were made to enhance the burn-back resistance of AFFF by incorporating glass micro-balloons in the solution to provide a permanent layer of bubbles. Unfortunately, the microspheres acted as foam breakers and prevented the normal entrapment of air. Another combination which incorporated the microspheres in an emulsion containing a 95% water solution of 6% AFFF had fair stability but the technique for generating a foam or applying a thin uniform emulsion layer appeared to be a problem beyond the scope of this project. If such combinations of water, and inorganic bubbles were to become practical, economics might dictate the use of sinispheres, the little hollow spheres formed in fly ash, in preference to the more expensive micro-balloons.

From the standpoint of operational latitude, the ideal agent should exhibit good extinguishment efficiency even though the application equipment and techniques cover a rather wide range of expansion ratios, application uniformities, and application patterns. For example, the 10 foot diameter JP4 and JP5 fires were readily extinguished with AFFF in droplet form and the aircraft carrier flight deck sprinkler systems tested at China Lake were effective without making appreciable foam. Finally, the ideal agent should be harmless to personnel and equipment both as the solution is applied and as products that may evolve through interaction with the fire.

4.3 Application Modes

The concept of ideal application implies equipment and techniques capable of (1) generating a good quality foam and (2) depositing a perfectly uniform layer of foam over the fuel surface without loss in transit. Application densities should be controllable down to the critical value. In practice uniform coatings are very difficult to achieve and, of course, some losses are always present; consequently, this section will be concerned also with how to minimize these problems. As indicated in Table 2.1 the existing modes of application can be divided into two categories (1) total coverage where the total fire area is suppressed simultaneously as in the case of sprinkler systems and (2) incremental coverage where at any instant the agent is applied to only a small part of the fire area, e.g., a monitor or handlines. In keeping with the ideal concept, the simplified extinguishment model employed here neglects all categories of foam loss. The model assumes extinguishment will occur when the agent applied per unit area reaches a threshold value which is independent of the rate of application, i.e., the critical deposition density. For the same total pumping capacity both modes of application will extinguish the fire in the same time; however, during extinguishment the appearance of the fire will be somewhat different in the two cases. In the total sprinkling mode, the burning area remains constant, but the specific burning rate must decrease with time. In the incremental mode, the burning area decreases and the specific burning rate remains essentially constant in the fire area.

4.3.1 Total Simultaneous Coverage

This mode of application is employed extensively on aircraft carriers, both on flight decks protected with AFFF discharged through the washdown nozzles inbedded in the deck and on the hangar decks where the agent is dispensed through overhead sprinklers. Overhead sprinklers are also encountered in aircraft hangars ashore. In both of these arrangements the foam trajectories pass through a hostile environment that generates substantial losses; consequently, the deposition parameters depart substantially from the simple application values developed below. If the losses can be approximated by a constant percentage of the applied agent, the relationship will have the same form as for the ideal case.

Starting with the pumping capacity R_p and the application area A the specific application rate

$$S_r = \frac{R_p}{A} \tag{4.2}$$

and the application density

$$S_d = tS_r = \frac{R_p t}{A} \tag{4.3}$$

if the critical application density equals S_{dc} then the extinguishment time

$$t_e = \frac{S_{dc}A}{R_p} = \frac{S_{dc}}{S_r} \tag{4.4}$$

In graphical form expression 4.4 leads to a family of hyperbolic curves i.e., one curve for each value of S_{dc} when the extinguishment time is plotted as a function of the pumping rate R_p or the specific application rate S_r. A family of straight lines is obtained when the total agent $G = R_p t_e = S_{dc}A$ is plotted as a function of R_p. Figure 4.12, which is reproduced from Reference 1.1 illustrates the hyperbolic relationship in Equation (4.3) as commonly presented in the literature.

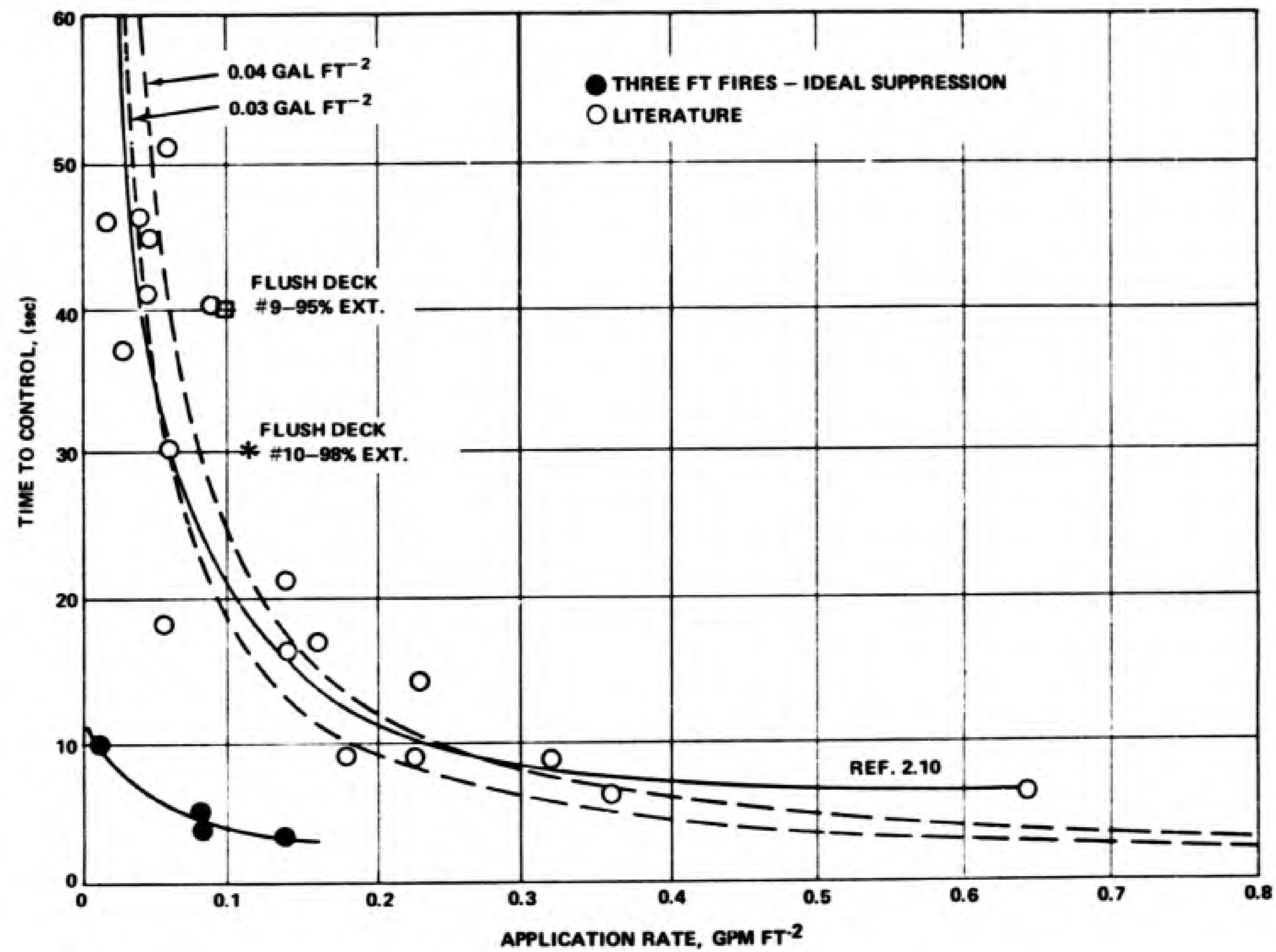


FIG 4.12 CONTROL TIME OF JET FUEL FIRES USING FC–194

4.3.2 Incremental Coverage

In the simple incremental mode illustrated in Figure 4.13 foam is applied uniformly over a rectangular foam print of length (L), width (W), and Area (a') which is moved at uniform velocity (V) along the sweep path to generate the desired application density. The instantaneous application rate S_i is proportionally related to the pumping rate R_p by

$$S_i = \frac{R_p}{a'} \qquad (4.5)$$

and the area uniformly covered with foam per unit time becomes

$$a = LV - a' \qquad (4.6)$$

Foam will be applied to any spot outside the initial print position for a time

$$t = \frac{W}{V} \qquad (4.7)$$

and the application density becomes

$$S_d = S_i t = \frac{S_i W}{V} = \frac{S_i a'}{LV} \qquad (4.8)$$

If the velocity is adjusted to V_c, i.e., a value that deposits the critical application density S_{dc}

$$LV_c = \frac{S_i a'}{S_{dc}} \qquad (4.9)$$

and the total fire area A will be extinguished in a time

$$t_e = \frac{A}{a} = \frac{A}{(LV_c - a')} = \frac{A}{a'(\frac{S_i}{S_{dc}} - 1)} \qquad (4.10)$$

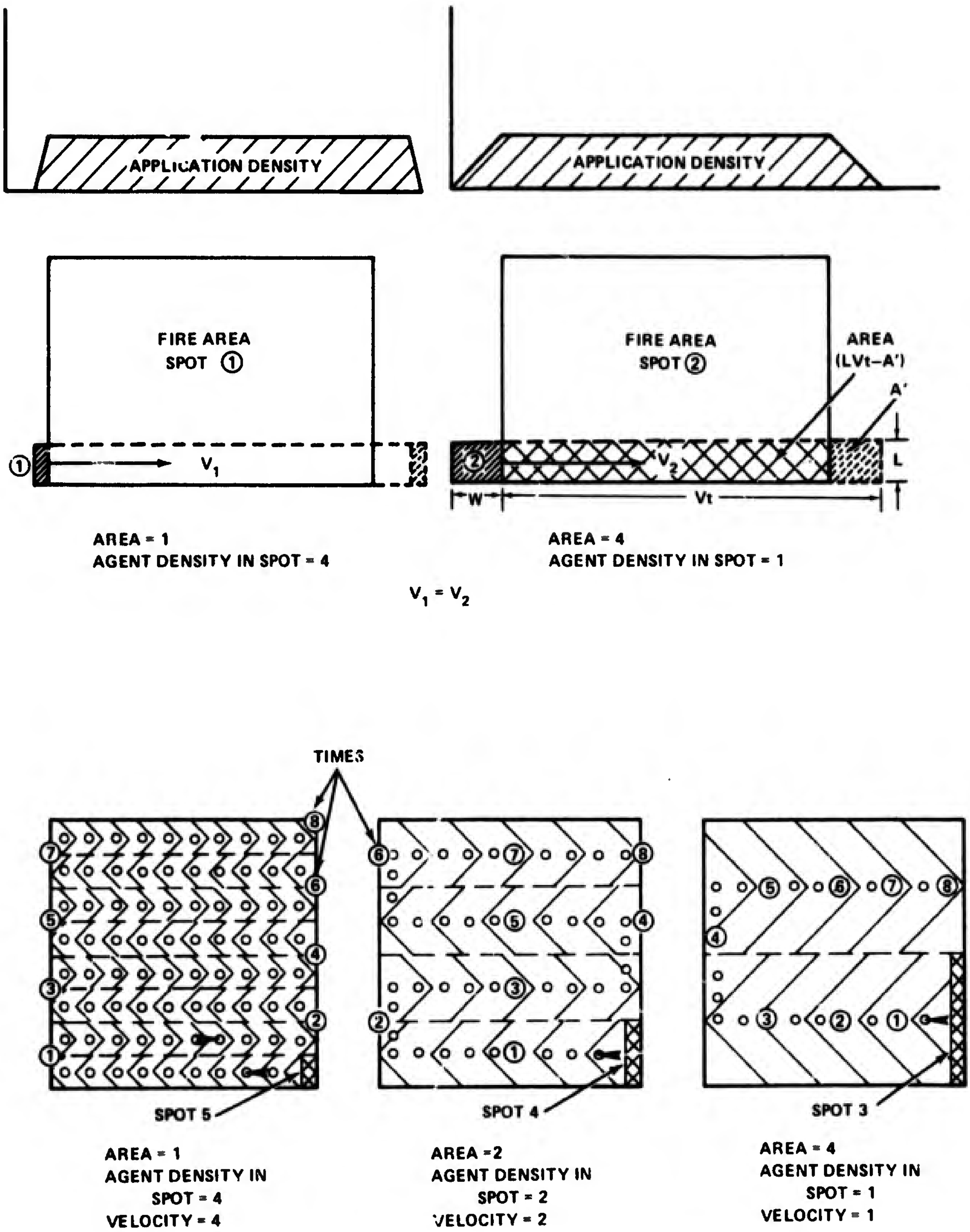


FIG 4.13 INCREMENTAL COVERAGE MODEL DIAGRAM

Graphically the extinguishment time (t_e) is a hyperbolic function of the area (a) as illustrated by the family of curves in Figure 4.14 where each fire area (A) corresponds to a different hyperbola. If the pumping rate is large or the foam print is small so that $S_i >> S_{dc}$ the extinguishment time reduces to

$$t_e = \frac{A\ S_{dc}}{a'\ S_i} = \frac{A\ S_{dc}}{R_p} \qquad (4.11)$$

i.e., the same hyperbolic relationship encountered in Equation (4.4) for total area extinguishment; however, the expression relating extinguishing time to application rate now involves the instantaneous application rate and the foam print size. This relationship is still hyperbolic, but now the ratio of fire area to spot area determines which hyperbola is involved and which parameter should be maintained constant if extinguishment data are to be compared. For example, in the China Lake and AGFSRS test A, S_i and a' were frequently changed simultaneously so in a plot of t versus S_i each point could fall on a different hyperbola. Furthermore t_e is now directly proportional to the fire area as it should be when a constant area is being extinguished per unit time.

If the foam print area a' is a large fraction of the fire area and the sweep path remains inside the fire area, the beginning and end of the operation leaves some non-uniformly coated areas, Equation (4.10) applies and the shapes of the curves are perturbed. In the drive-by technique employed in this study, this complication was avoided by starting and stopping the sweep path outside the fire area.

The other parameters of concern pertain to the mechanism of applying the agent. For example, what are the effects of spot size, more than one spot, and multiple versus single coats of agent on the extinguishment time, agent required, and freedom from reignition. The model permits some predictions regarding these parameters. For example, in the ideal case where no agent is lost and uniform application density is achieved, the number and size of spots have no effect as long as the pumping rate remains unchanged. If differences in performances are to be found, they must appear in the losses and the problems of achieving a uniform application density. Figures 4.13 and 4.15 illustrate the influence of spot size and shape on the losses. Several ground patterns from AGFSRS report 71-1 are reproduced in Figure 4.15. The straight stream patterns are approximately twice the length of the dispersed stream pattern.

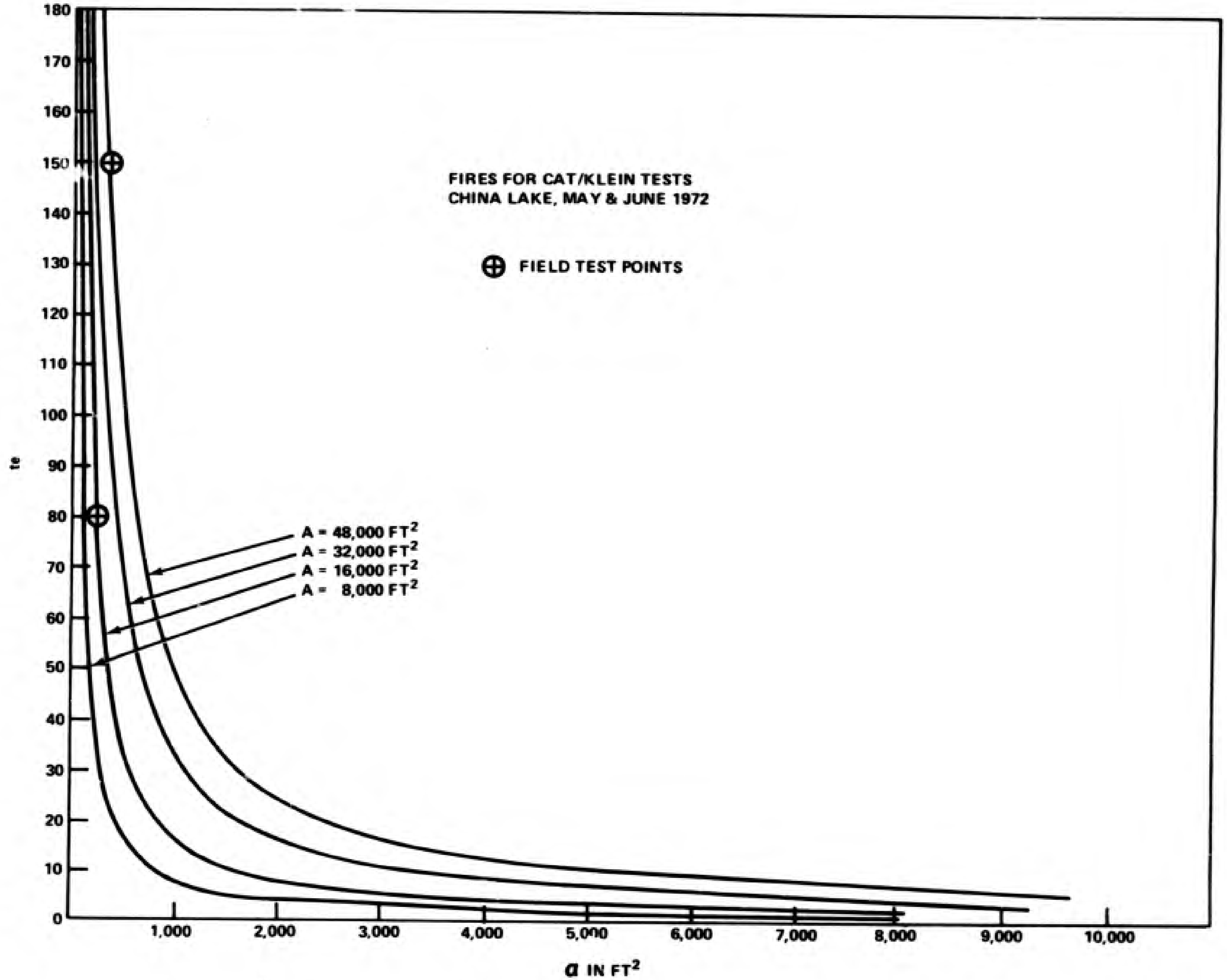


FIG 4.14 CONTROL TIMES OF LARGE FIRES BY CAT/KLEIN TRUCK

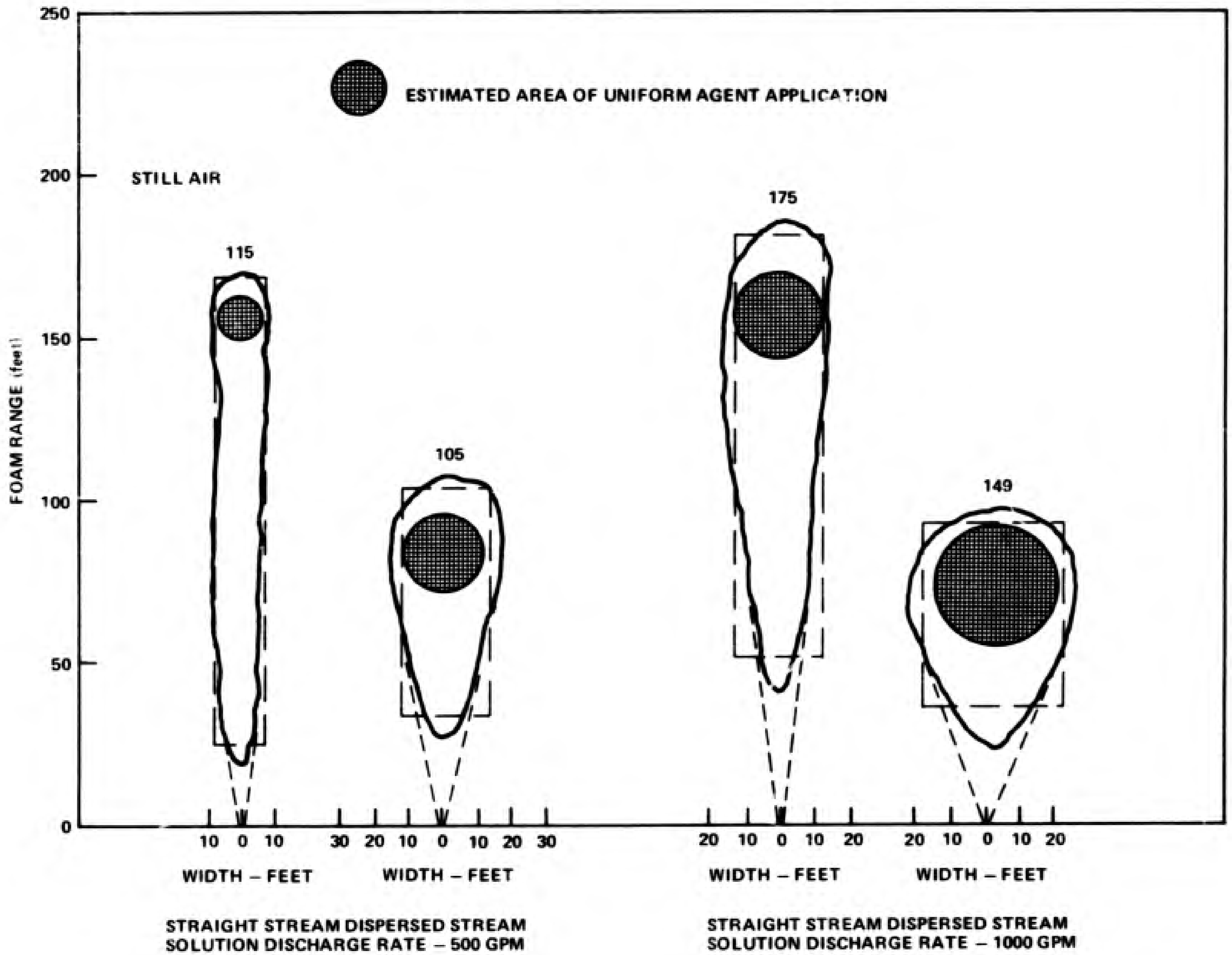


FIG 4.15 FOAM GROUND–PATTERNS PRODUCED BY NOZZLE A

However, there is less than 20% difference in the total areas. For our immediate purpose, the analysis will be simplified by three assumptions. First, the pumping rate remains constant. Second, the agent is uniformly distributed over the spot, which in reality, it is not. Third, the spot shape can be approximated by a rectangle as indicated in Figure 4.15. If these rectangles are moved as indicated in Figure 4.13, Equation (4.9) indicates that only the dimension (L) perpendicular to the direction of motion influences the velocity required to achieve a particular application density. Spot 1 has 1/4 the area, but the same length as spot 2. In one sweep across the fuel bed, both spots will deposit the same density of agent except at the ends where the densities will trail off more for the wider spot as indicated by the application density charts at the top of the figure. However, when spots 3, 4, and 5 are moved, the velocities will have to be inversely proportional to the spot lengths for the applications densities to remain constant. This velocity difference leaves the initially extinguished area for spot 3 exposed to the adjoining fire twice as long as for spot 4 and 4 times as long as for spot 5 before the returning sweep moves the fire back one spot length. If the destruction rates are the same for all of three cases, a thicker layer of protective foam will be required to provide the necessary protection times in spot 3. Presumably a reduction in the required specific application density could be achieved that would favor shorter spots either from the standpoint of minimizing the required agent or for maximizing the protection against reignition. Counteracting this effect is the greater foam front displacement distance with the longer spots which provide a greater reduction of thermal insult. Unfortunately, with existing nozzles the control of spots size, uniformity, and sweep pattern is not adequate to resolve these fine points of application. In the ideal paths employed in Figure 4.13, there are no overlapped or skipped areas as encountered in actual operation. With manual operation, the larger number of sweeps and the faster movement of the turret required by short spots would offer more opportunities for operator overkill and misdirected foam losses L_a L_m. However, with automatic indexed, motor driven turrets, these losses might be made independent of spot size.

When the question of single versus multiple turrets is examined in a similar manner, the model indicates that updraft and evaporation losses L_u L_e should be the same for any number of spots as long as the combined area of spots is modest compared to the size of fuel bed and the pumping rate is fixed and independent of the number of turrets, i.e., in a given time, the single fast moving spot would cover the same area as the multiple spots and the same suppression time would be required, at least for simple sweeps illustrated in Figure 4.13. When manual operation is considered there appears to be an advantage to a main turret for principal coverage with a small capacity spot in addition to extinguished areas missed by the main turret. A similar reduction in the L_a L_m losses might be achieved with automatic turret control since perfectly uniform application is virtually impossible to achieve manually. The question of building up the foam layer in a single versus multiple coats cannot be answered until better information is available about the reduction in burning rate for foam deposits below the critical application density and the rate of destruction for such foam concentration. With the sweep rates available in the drive-by type of application, the second coating could not be applied before essentially complete flame recovery had occurred and consequently, larger total application densities were required for multiple passes. With stationary vehicles and a sweeping turret it is normally difficult to achieve spot densities below the critical application value due to the inertia of the turret. Therefore until finer control is attained on spot size, uniformity and motion, the drive-by technique of extinguishing the fire in one pass appears to be the most efficient operation.

4.4 Critical Application Density Measurements

Critical application densities for the extinguishment of JP4 and JP5 with 6% AFFF were established for pool fires on water and rock substrates in the 10 foot pan. For these tests three forced-air foam nozzles were mounted on a pipe framework which was manually pushed over a set of rails alongside the pan. Uniform application was achieved by maintaining a uniform velocity over the pan area. Application densities measured by sampling pans were found to be in agreement with densities calculated from the pumping rate and the measured time to pass over the fire area. Although the foam quality was not as good as achieved with the larger conventional nozzles used in the vehicle field tests, there was no loss in fire suppression effectiveness.

Two sets of nozzles were required to achieve the application density range. The smaller nozzles produced an expansion ratio of 5.8 with a 25% drain time of 1.8 minutes. The larger nozzles gave an expansion ratio of 7 and a 25% drain time just under one minute.

Because of the experimental procedure, the data for JP5 fires in Table 4.1 and the JP4 fires in Table 4.2 include two or three values for each test number. A test number cor-

Table 4.1

EXTINGUISHMENT OF JP5 FIRES WITH UNIFORM FOAM APPLICATIONS

Test No.	Type Fire	Nozzle Velocity, ft/sec	Sampling Application Density gal/100 ft^2	Pumping Application Density gal/100 ft^2	Remarks (Extinguishment)
159	Pool	1.5	0.60	0.63	no
	Pool	1.0	0.90	0.93	yes
160	Pool	1.8	0.50	0.53	no
	Rock	1.9	0.47	0.51	no
	Rock	1.8	0.50	0.52	yes
161	Pool	2.1	0.43	0.45	no
	Rock	2.3	0.39	0.42	no
162	Pool	1.2	0.75	0.80	yes
	Rock	1.3	0.69	0.77	no
163	Pool	1.4	0.64	0.69	yes
	Rock	1.4	0.64	0.70	yes

Table 4.2

EXTINGUISHMENT OF JP4 FIRES WITH UNIFORM FOAM APPLICATIONS

Test No.	Type Fire	Nozzle Velocity, ft/sec	Pumping Application Density gal/100 ft^2	Remarks (Extinguishment)
164	Pool	1.0	0.78	no
	Pool	0.8	0.93	no
	Rock	1.0	0.78	no
165	Pool	0.6	1.40	no
	Pool	0.6	1.28	no
	Rock	0.6	1.40	no
166	Pool	1.0	2.97	yes
	Rock	2.0	1.59	yes
167	Pool	2.0	1.58	no
	Pool	1.5	1.82	no
	Rock	2.0	1.58	yes
168	Pool	1.7	1.73	no
	Rock	2.5	1.15	no
	Rock	1.3	2.30	yes
169	Pool	1.1	2.68	yes
	Pool	1.0	2.88	yes
	Rock	1.4	2.02	yes
170	Pool	1.4	2.10	yes
	Rock	1.9	1.53	yes

responds to a fresh supply of fuel that completely covered the rocks to form a typical pool fire for the first application of AFFF. If extinguishment occured the fuel was reignited otherwise burnback was allowed to reestablish the fire, then foam was applied again 30 seconds after full involvement or when sufficient fuel had been consumed to expose the desired area of rocks. As more rocks are exposed, the fuel surface area decreases, the total burning rate is reduced, the fire becomes less smokey, and less agent is required to extinguish a unit area of the fuel bed.

Figures 4.16 and 4.17 show the suppression results plotted according to the application density. In most cases the critical application density is well defined, i.e., for JP5 0.64 gal/100 ft^2 for 6% AFFF on a pool and 0.5 gal/100 ft^2 for approximately equal surface areas of fuel and rocks exposed to the flames. Similarly with JP4 the critical densities were about 2.1 gal/100 ft^2 for pool fires and 1.6 gal/100 ft^2 for the exposed rocks or about three times the requirements for the corresponding JP5 fires. These densities are comparable to the values found on the larger fires using crash trucks and the drive-by application tactics. The anomalous point for a rock substrate in Figure 4.16 has not been explained but obscuration by smoke and flames made it difficult to determine the area of rocks exposed and thus the time to commence suppression so as to maintain a constant burning rate from one test to the next. In summary it is concluded that fires on rock substrates become easier to extinguish as the fuel level sinks and exposes a larger rock area.

5.0 EXTINGUISHMENT WITH CONVENTIONAL EQUIPMENT AND TECHNIQUES

5.1 Total Area Extinguishment with Liquid Drops, i.e. Expansion Ratio = 1

5.1.1 Effects of Fire Size: 10 Foot Pan; LLL300 50 x 50 Feet; China Lake 93 x 90 Feet

Radiation control times for fires suppressed by the "uniform" and instantaneous application of light water solutions by means of spray nozzles show a hyperbolic relationship when plotted as a function of the spray application density in GPM/ft^2. Such a plot for 3 and 10 FT/dia and 50 - ft square pool fires of JP5 is shown in Figure 5.1 and the data are tabulated in Table 5.1. The reasons that larger fires require longer times to control at a particular specific application rate are exceedingly complex. The physical process in these experiments involves principally the interaction of drops of

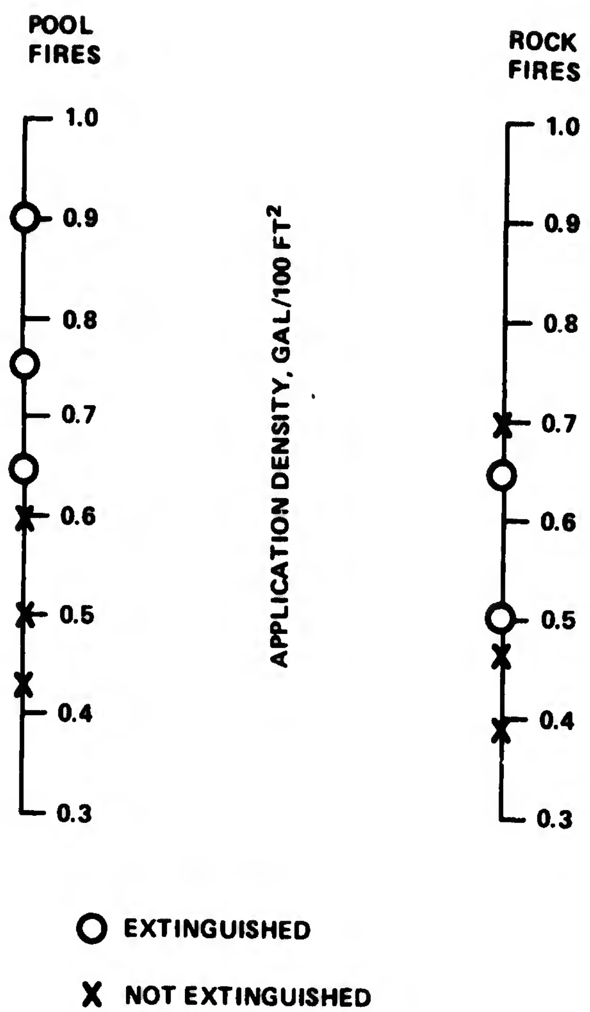


FIG 4.16 CRITICAL APPLICATION DENSITIES FOR 10' POOL AND ROCK SUBSTRATE FIRES OF JP–5

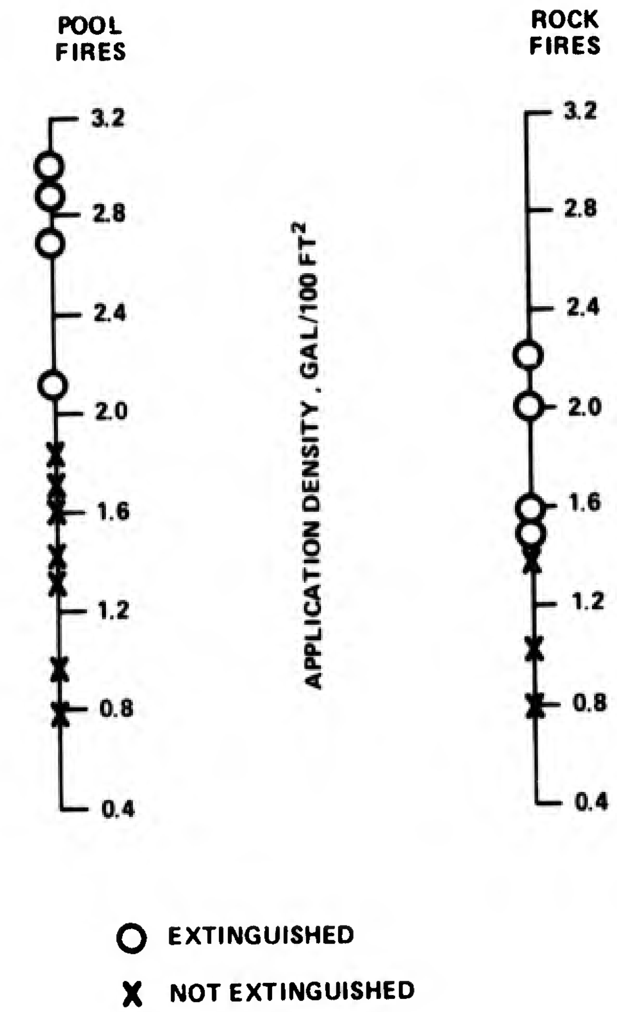


FIG 4.17 CRITICAL APPLICATION DENSITIES FOR 10' POOL AND ROCK SUBSTRATE FIRES OF JP–4

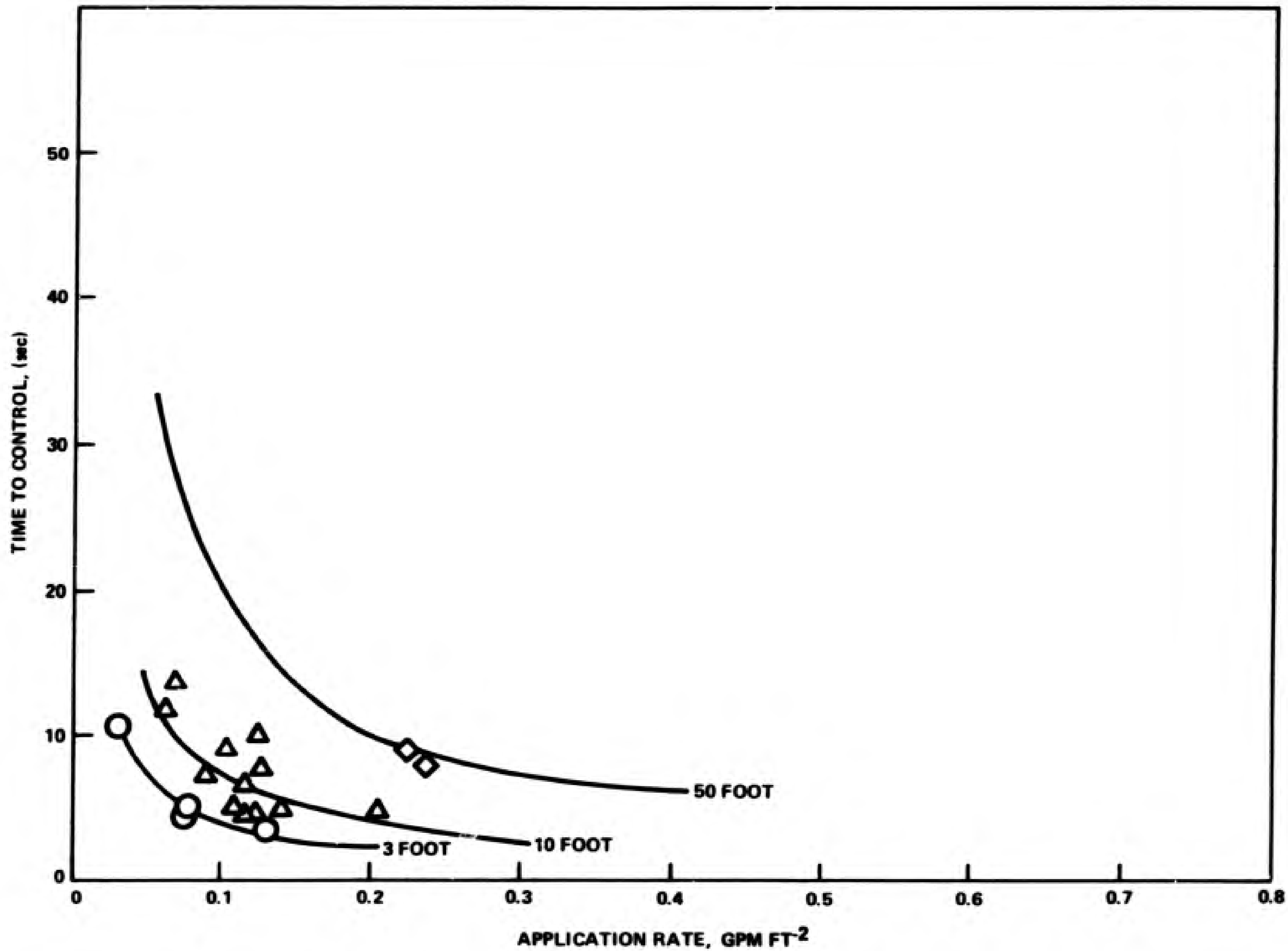


FIG 5.1 CONTROL TIME OF JP–5 FIRES USING FC–199 AND "IDEAL" SPRINKLER APPLICATION

Table 5.1

RADIATION CONTROL TIMES FOR JP5 POOL
FIRES SUBJECTED TO TOTAL EXTINGUISHMENT BY SPRINKLERS

Test No.	Fire Dia., Feet	Control Time, Sec.	$\frac{GPM}{FT^2}$
10	3	3.3	0.1319
8	3	4.5	.0795
9	3	3.8	.0799
7	3	9.9	.0311
19	10	5	.206
23	10	4.5	.116
24	10	5	.137
25	10	6.6	.113
26	10	11.6	.062
29	10	13.8	.066
30	10	7.3	.088
32	10	7.7	.126
33	10	10.2	.126
34	10	9.2	.103
35	10	4.2	.123
38	10	5	.109
75	50 x 50	8	.236
76	50 x 50	9.3	.225

light water solution with the flame zone and the fuel surface. Several variables of major importance are the cooling effect of the water impacting the fuel surface and the amount of agent stripped from the drop and remaining on the surface before the drop sinks to the bottom of the fuel layer. Both of these physical processes depend to a large extent upon the size and temperature of the drop which reaches the burning surface. Both temperature and drop size are a function of the path length through the flame zone and the gas velocity encountered during transit. Larger trajectories combined with the buoyant gas velocity of larger fires result in fewer particles impacting the fuel surface. Thus longer times are required to cool the fuel and establish a vapor barrier; i.e., actions which retard the fuel evaporation rate.

The suppression data for sprinkled fires has been correlated to the average path length through the combustion zone by the equation:

$$t_c\left(\frac{GPM}{A}\right)^{0.857} = 0.953X^{0.406} \qquad (5.1)$$

where $\frac{GPM}{A}$ = sprinkler rate, gal ft^{-2} min^{-1}

t_c = radiation control time, sec

x = average path length

Since Equation (5.1) was derived empirically from Figure 5.2, it should be considered specific for experimental conditions of wind and spray characteristics encountered in these tests. The average path length for circular fires is defined as the average path through the inclined flame zone to the fuel surface where the angle of inclination is defined as in Figure 5.3. The angle of the wind-blown flame was calculated from the Sleipchevich expression, defined earlier, and experimental data. Geometrical relationships derived to calculate the path length for a drop impacting a chord of the circular pan from zero length to the maximum path through the flames. These paths were then averaged by a computer program to cover a large number of chords.

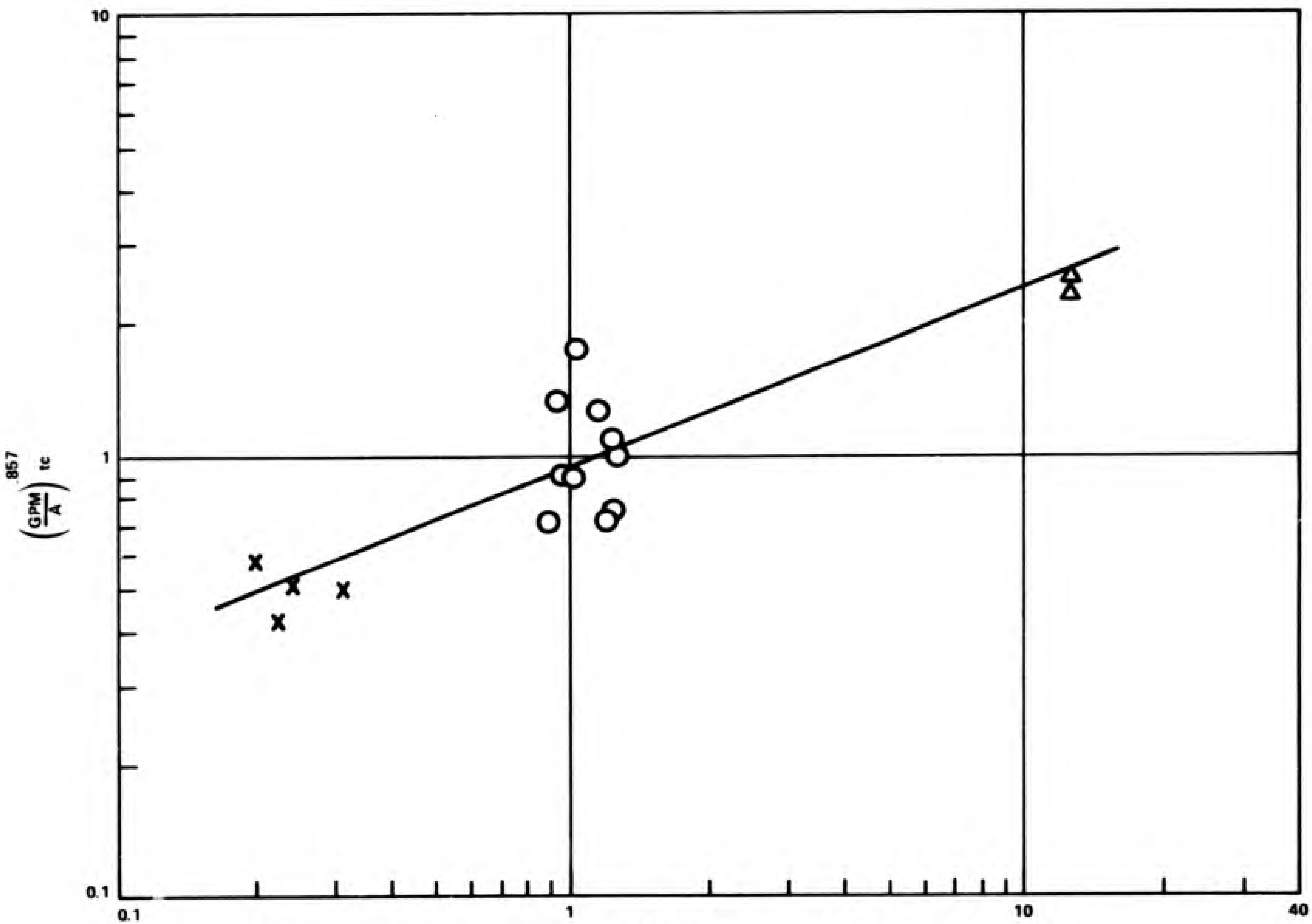
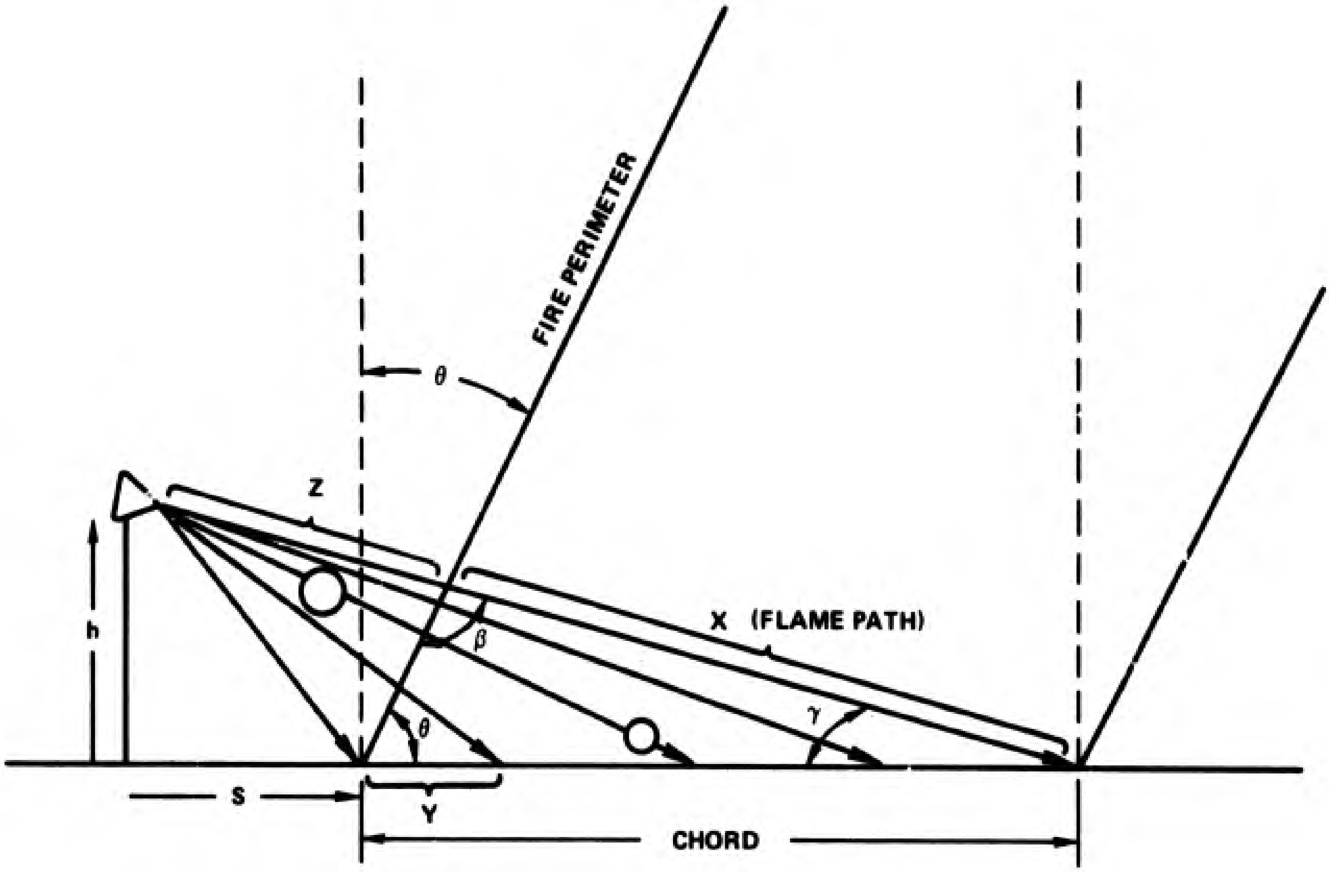


FIG 5.2 SPRINKLED FIRE SUPPRESSION



CALCULATE FLAME PATH FROM:

$$\left(\frac{h}{\sin\gamma}\right)^2 = h^2 + (s+y)^2 \qquad (1)$$

$$\sin\beta = \frac{Y}{X}\ \sin O' \qquad (2)$$

$$\beta = 180 - (\theta' + \gamma) \qquad (3)$$

FIG 5.3 ONE DIMENSIONAL FLAME PATH LENGTH FOR DROP TRAJECTORY

5.1.2 Effects of Environment: Substrate, Wind, Objects

Contrary to the experience with AFFF and incremental extinguishment cited in Figures 4.16 and 4.17, the JP5 fires on sand or rock substrates were harder to extinguish than pool fires when the agent was sprayed as liquid drops in this series of total coverage extinguishments. The ease of extinguishment depended strongly on the fuel level in the rocks at the onset of suppression. Initially the burning rates of fuels on these substrates are reasonably close to that of pool fires and as the substrate is exposed it tends to become hotter than the boiling temperatures of the fuel. In this condition, the fire is harder to extinguish and requires a greater amount of agent. However, eventually the fuel level is lowered sufficiently so that the mass burning rate is lowered significantly because of the drastic decrease in radiative heat transfer as a driving force. The fuel burning rate becomes conductively driven and appreciably lower. The weight loss curves for such an experiment are in Figure 5.4 where the initial fuel burning rate of 0.054 lb min^{-1} ft^{-2} tapers off to 0.0048 lb min^{-1} ft^2. The extinguishing times to control radiation for 10 foot and 50 foot x 50 foot JP5 fires on rock substrates are given in Table 5.2. Comparison of these results with the pool fire data in Figure 5.1 shows the extent of the difficulty in extinguishing fires where the exposed rock has heated above the boiling point of the fuel. After the fire level subsides because the burning mechanism is now limited by the conduction of heat through a rock layer, extinguishment becomes a relatively easy task accomplished by either foam or water.

In the CASS experiments of March 1970 on the 83 foot x 90 foot mini-deck at the Naval Weapons Center, China Lake, the experimental variables investigated included both the effect of wind and aircraft on the suppression times required by deck spray systems employing AFFF. If the amount of suppressant required to extinguish a unit area of fire remains constant regardless of the rate of application, the curve for the control time versus the specific application ratio becomes a hyperbola. The three hyperbolas shown in Figure 5.5 correspond to the normal application density for the CASS test which was 0.04 gal/ft^2 and the actual densities which range from 0.03 to 0.12 gal/ft^2. The control time in these experiments is defined as the time when 95% of the fire was extinguished. In Figure 5.5 most of the control times for the first 12 tests, shown as numbered points, fall near the boundaries set by .03 and 0.16 gal/ft^2 hyperbolas. When the run is represented by a single point, the mode of application remains constant up to the control time. In Tests 3, 7 and 8 where 2 points are connected by a line, the initial application rate indicated by the plus sign was increased part way into the test by hand lines which boosted the rate up to the values shown by a dot.

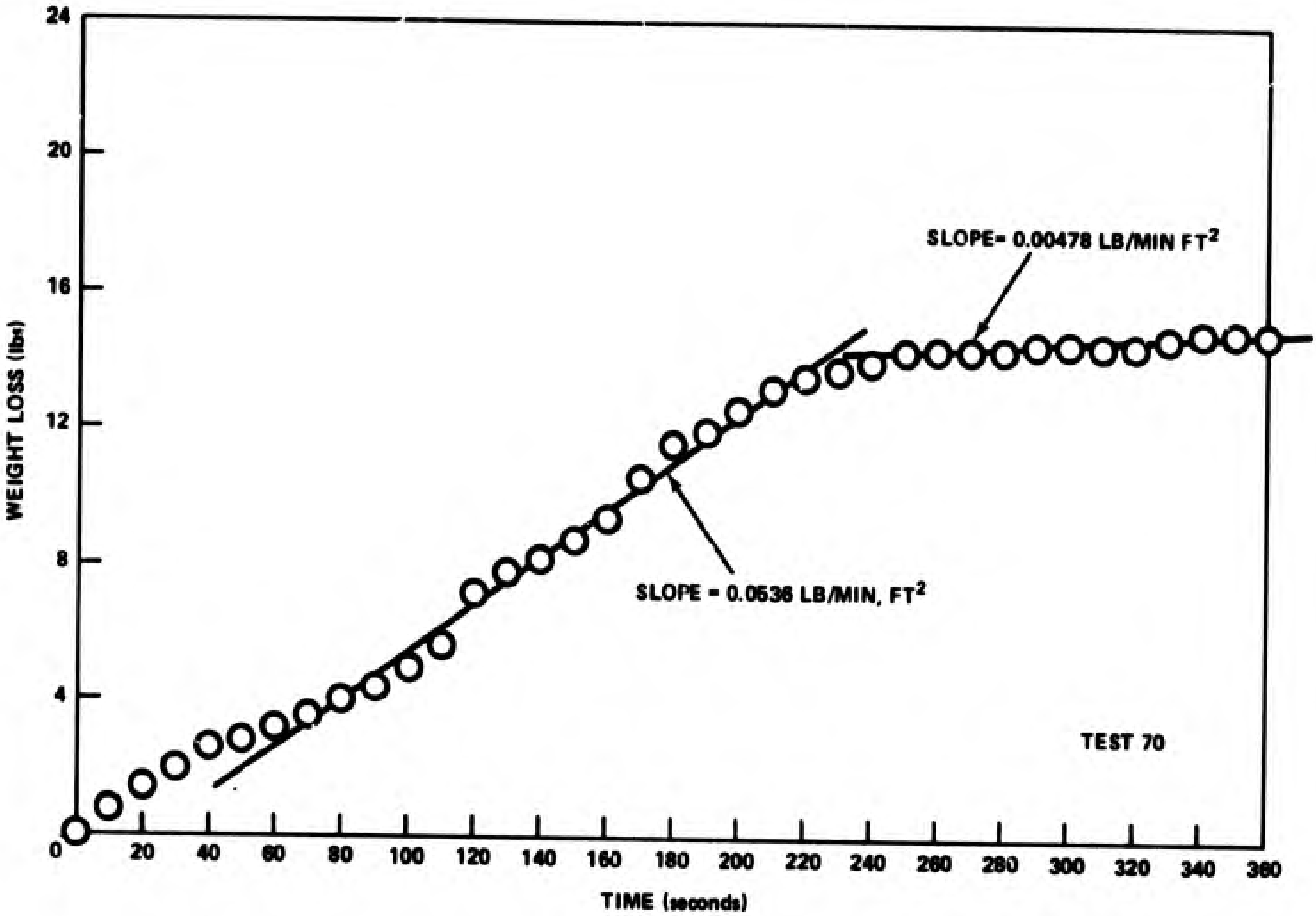


FIG 5.4 WEIGHT LOSS VS TIME FOR JP–5 BURNING IN ROCKS IN 10 FT PAN

Table 5.2

RADIATION CONTROL TIME FOR JP5 POOL FIRES OR ROCK SUBSTRATES SUBJECTED TO TOTAL EXTINGIUSHMENT BY SPRINKLER

Test No.	Fire Dia., Feet	Control Time Sec.	GPM Ft^{-2}
72	50 x 50	12	0.232
73	50 x 50	20.4	0.232
67	10	13	0.49
68	10	15.4	0.52
69	10	7.2	0.50
70	10	23	0.50
71	10	16	0.50

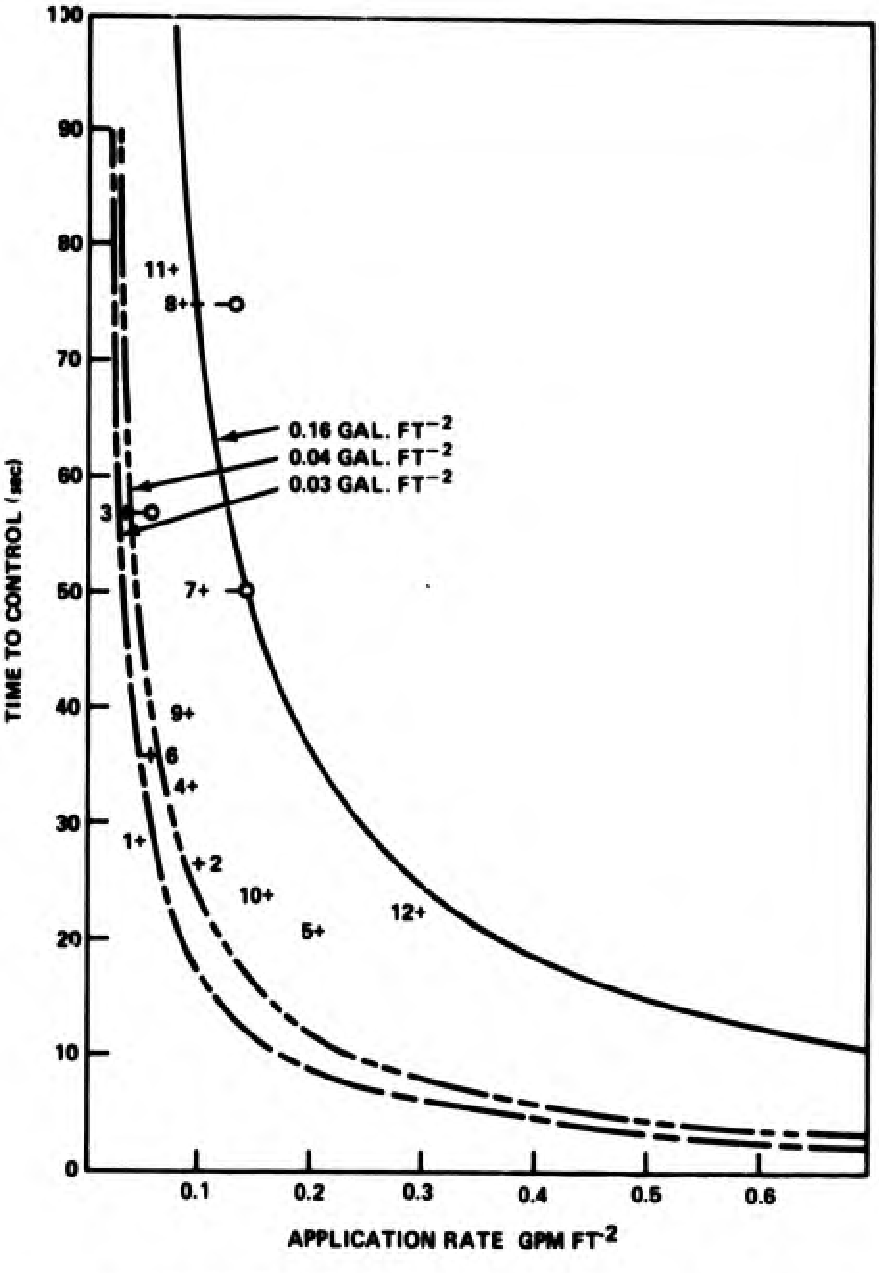


FIG 5.5 CONTROL TIMES FOR MINI–DECK FIRES AT CHINA LAKE

In the wind effects test, the initial application rate was held constant at about 0.1 gal/min, ft^2, but the control time decreased substantially with the air velocity from 75 seconds in still air for Test 8, to 50 seconds at 17 knots in Test 7 and 40 seconds at 30 knots in Test 9. Obviously the effect of wind was to aid the spread of AFFF over the fuel. The wind may also have increased the turbulent interaction of the spray drops with the surface thereby increasing the cooling rate. As indicated in Section 4.1.2, this cooling is a primary factor in reducing the evaporation rate of the fuel which feeds the combustion zone.

The aircraft parked on the mini-deck also caused a change in agent required for suppression. In general, the five planes parked on the deck increased the application density required for extinguishment, i.e., the points for Tests 7 through 12 are generally closer to the 0.16 hyperbola than Tests 1 through 6. Similarly Test 1 with a clear deck can be compared with Tests 2 and 4 which involved the mock-up. Again the obstruction moves the data to the right.

5.2 Incremental Suppression Tests with Fireman

5.2.1 Moffet Field and LLL Site 300 Tests with the MB-1

The basic assumption of the incremental suppressant model is that a single turret operated by a fireman will cover the fire area at a constant rate so,

$$\frac{dA}{dT} = a \text{ or } \frac{dt}{dA} = \frac{1}{a} \tag{5.1}$$

and

$$t = \frac{A}{a} \tag{5.2}$$

where t = time required to control fire, seconds

A = fire area, ft^2

$1/a$ = slope, sec/ft^2

This postulate leads to the requirement that the gallons of agent per unit area also be constant, therefore

$$G = S_{dc}A \tag{5.3}$$

where G = gallons of agent used to control point

S_{dc} = slope, gallons/ft^2

By definition

$$\frac{G}{tA} = \frac{GPS}{A} \tag{5.4}$$

where GPS = gallons of suppressant per second.

Rearrangement of these equations leads to;

$$\frac{GPS}{A} = \frac{S_{dc}A}{at^2} \tag{5.5}$$

We would predict from this approach that a constant rate of coverage of the fire area by any combination of turrets would give a hyperbolic relationship between the control time and the fire area extinguished per unit time, i.e., a restatement of Equation 4.10. The slopes a and S_{dc} can be determined by the appropriate plots and these in turn can be used to derive the conventional plots of control time versus application density expressed as GPS/A. Further, the model provides a positive means of comparing results from extinguishing tests where the rate of pumping (GPS) is changed, where different equipment is used or where new fire teams are being trained. It should be noted that this model predicts different curves for any experimental variable affecting the gallons of suppressant sprayed per second. This would include both equipment, foam and personnel variables.

The performance and efficiency of a fire truck is assumed to be a direct function of the rate at which a monitor or turret operator can cover the required fire area with suppressant. Thus, if extinguishment tests are performed by the same equipment on successively larger fire areas, and the operator extinguishes the fire at a constant rate, a plot of radiation (or visual) control time should be linear with fire area. Such a relationship is confirmed in Figure 5.6 by experimental data from testing the Navy MB-1 truck at Moffet Field and at LLL Site 300 on JP5 fires up to 2500 ft^2. In these experiments two different MB-1 trucks were used, practically every test was conducted with different operators, experienced and inexperienced and

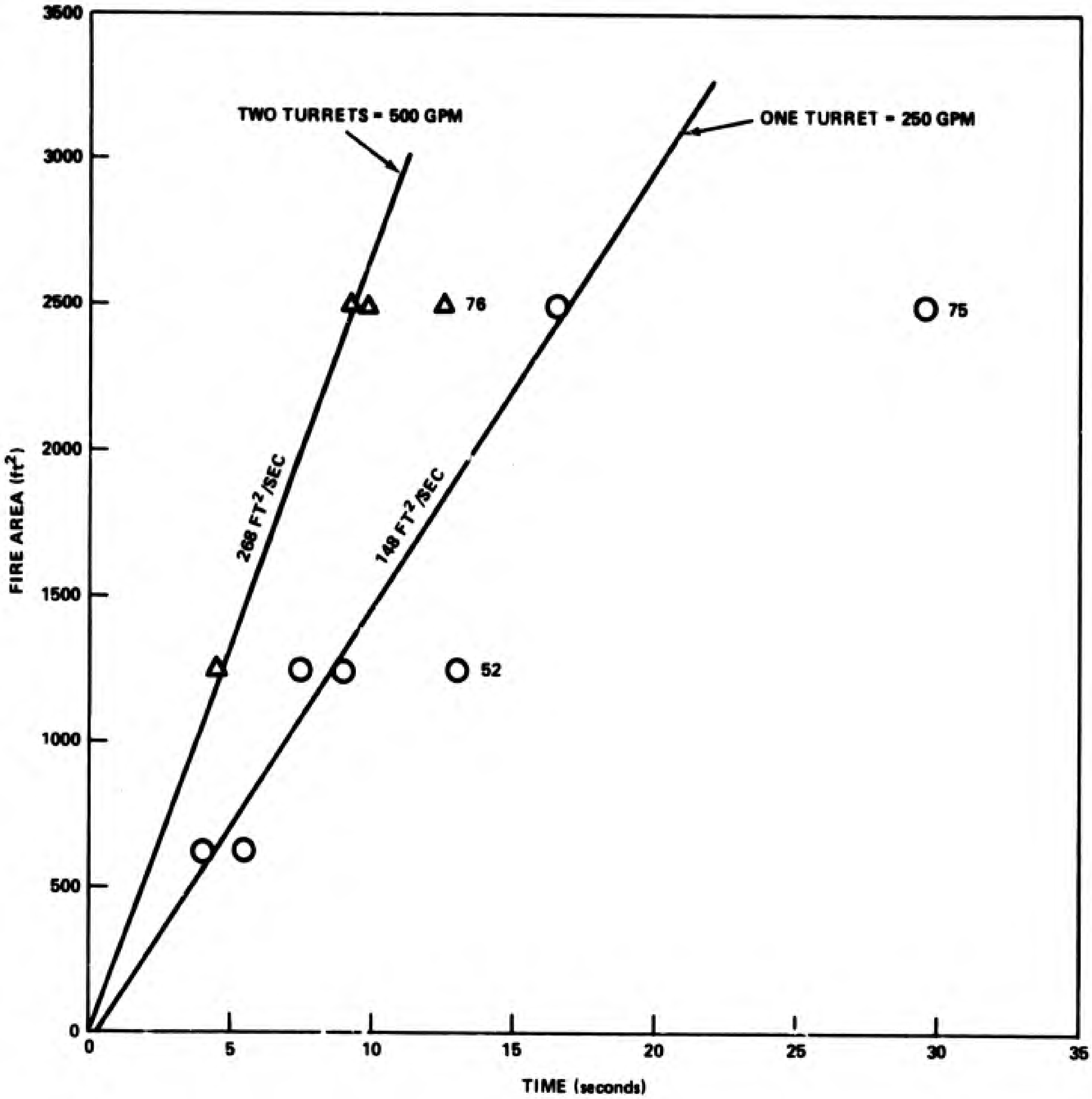


FIG 5.6 CONTROL TIMES FOR JP–5 FIRES USING 6% AFFF SOLUTIONS & MB–1 TRUCK

the fire sizes varied from 50 feet x 12-1/2 foot to 50 foot x 50 foot. The suppressant data from these tests are given in Table 5.3.

A number of factors should influence the consistency of the data presented in this way. Operator experience, suppressant flow rate, number of turrets operated, obstructions in the fire area and fuel behavior with respect to volatility and reignition are the primary variables in this respect. This method of data presentation also allows us to compare the performance of two competing trucks with regards to efficiency in suppressing fires and to do so with considerable sensitivity. An example arises in our data in the comparison of the performance difference between using one or two turrets on the MB-1 truck. With one turret the operator covered 148 ft^2 fire area per second to the control point signifying the reduction of radiation as measured by the method shown in Figure 5.7. With two turrets the coverage rate went to 268 ft^2/sec, or a factor of 81% over the single turret performance. The additional turret did not give an expected doubling of the single turret coverage rate. This may come about from the fact that these fires were of such small size that there was some overlap in coverage between the two turrets and some misdirected streams beyond the boundary of the fire area. This lack of coordination between the two turret operators is a training factor which could gain some increase in performance since the potential exists for doubling the area coverage rate in going from one to two turrets.

Those data points which do not fall near the majority curve can be attributed to inexperienced operators and a significant difference in the fire bed characteristics. At Moffet Field the fuel was floated on a water pool contained within dikes. At LLL Site 300 the fire bed consisted of rocks lined with corrugated sheet metal and this tended to make reignition easier. Such behavior was apparent from a study of the time-lapse film of the fires in question.

The development of "trained performance" curves of this type for specific apparatus allows us to evaluate the training of equipment operators where their times to control known areas of fire can be compared to the standard. A like argument can be made for the training of a two turret team where the object is to reach the doubling potential of the single turret rate of coverage.

Table 5.3

RADIATION CONTROL AND EXTINGUISHMENT TIMES FOR SUPPRESSION OF JP5 FIRES WITH NAVY MB-1 TRUCK

Test No.	Control Time, Sec.	Extinguishment Time, Sec.	Fire Dimension, ft.	Application Rate, GPM	Gal. to Control	Gal. to Exting.	GPM/A
46	5.5	10.3	12-1/2 x 50	250	22.9	42.9	0.4
47	4.0	8	12-1/2 x 50	250	16.7	33.3	0.4
50	4.5	10.5	25 x 50	500	37.5	87.5	0.4
51	7.5	16.5	25 x 50	250	31.3	68.8	0.2
52	13	16.5	25 x 50	250	54.2	68.8	0.2
53	9	11	25 x 50	250	37.5	45.8	0.2
54	9.3	12	50 x 50	500	77.5	100	0.2
56	18	21	50 x 50	250	75	87.5	0.1
74	9.7	15.3	50 x 50	500	80.8	127.5	0.2
75	29	50	50 x 50	250	121	208.3	0.1
76	12.5	20.2	50 x 50	500	104	168.3	0.2

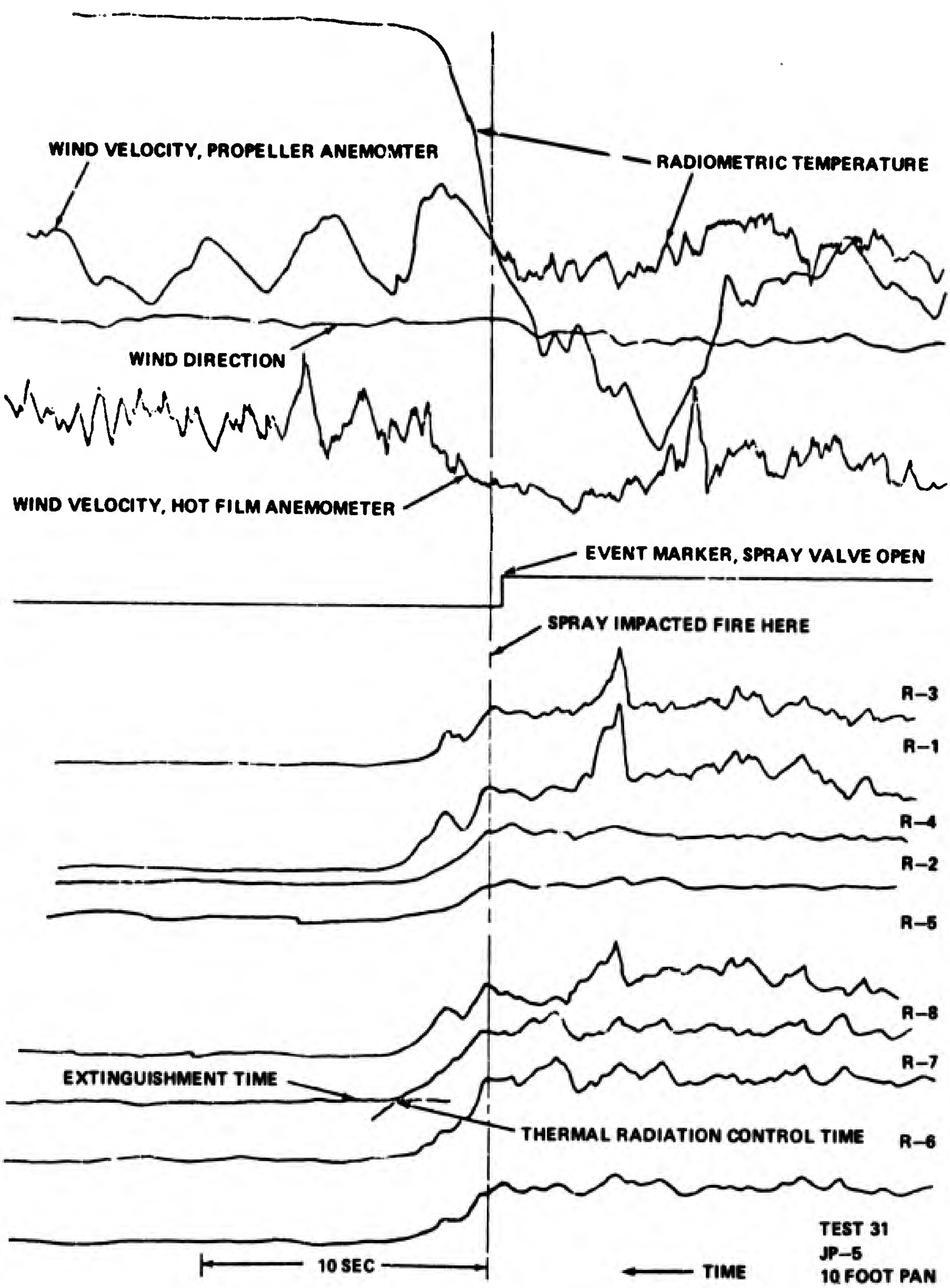


FIG 5.7 FIRE CONTROL TIME FROM THERMAL RADIATION MEASUREMENT

When the fire area extinguished is plotted against the time required, as in Figure 5.8, the data scatter emphasizes a number of responsible factors and conclusions. In the first place the wasted time in completing the extinguishment process results in the rate of coverage being reduced to almost half of that found when considering just control time. This points up again that as the fire area grows smaller, the wasted motions tracking the last remaining traces of fire increase. In our plot we have drawn the curve through points denoting the most efficient extinguishment. The action in terms of feet covered per second of one crew using two turrets was nearly twice that of the one turret operators being trained for this job. However, in 50% of the sample the two turrets did no better than one in extinguishing the fire.

We can only conclude from our data that the value of extinguishing time as a measure of efficiency is rather limited probably because it is a mop-up operation after control is achieved. Its importance is primarily in that it does have to be accomplished, and it therefore consumes water and agent. If shut-down is called for after control is achieved, the fire will spread again to its full size and burn until all the fuel is consumed. Perhaps the best strategy during this time interval is to reduce the GPM being used during mop-up operations in order to conserve suppressant.

A second requirement imposed by this model is that the gallons of suppressant per ft^2 of fire also be constant. Such a plot for the Moffet Field and LLL Site 300 tests is shown in Figure 5.9. Again the data appears to support the assumptions in the model.

Since one of the purposes of this analysis is to show the relationship between the model hypothesizing a linear rate of suppressant coverage (constant ft^2/sec) and the hyperbolic relationship between control time and GMP/ft^2, the data have been plotted in this way in Figure 5.10. The curve drawn through the experimental points was calculated from Equation (5.5) using the slopes from the linear relationship in Figures 5.6 and 5.9 and the experimental pumping rates. Tests 52, 75 and 76 are believed to be outliers primarily because the crews operating the MB-1 truck on these tests were doing so for the first time. A secondary reason in the case of Tests 75 and 76 is the type of fire bed construction, i.e. the use of rock versus a water substrate.

When fire tests are designed with this basic model in mind, the correlations may be extrapolated to larger fires under the same operating conditions (constant dA/dt) with considerable confidence, up to a point. The use of a single experimental test might lead to erroneous conclusions unless

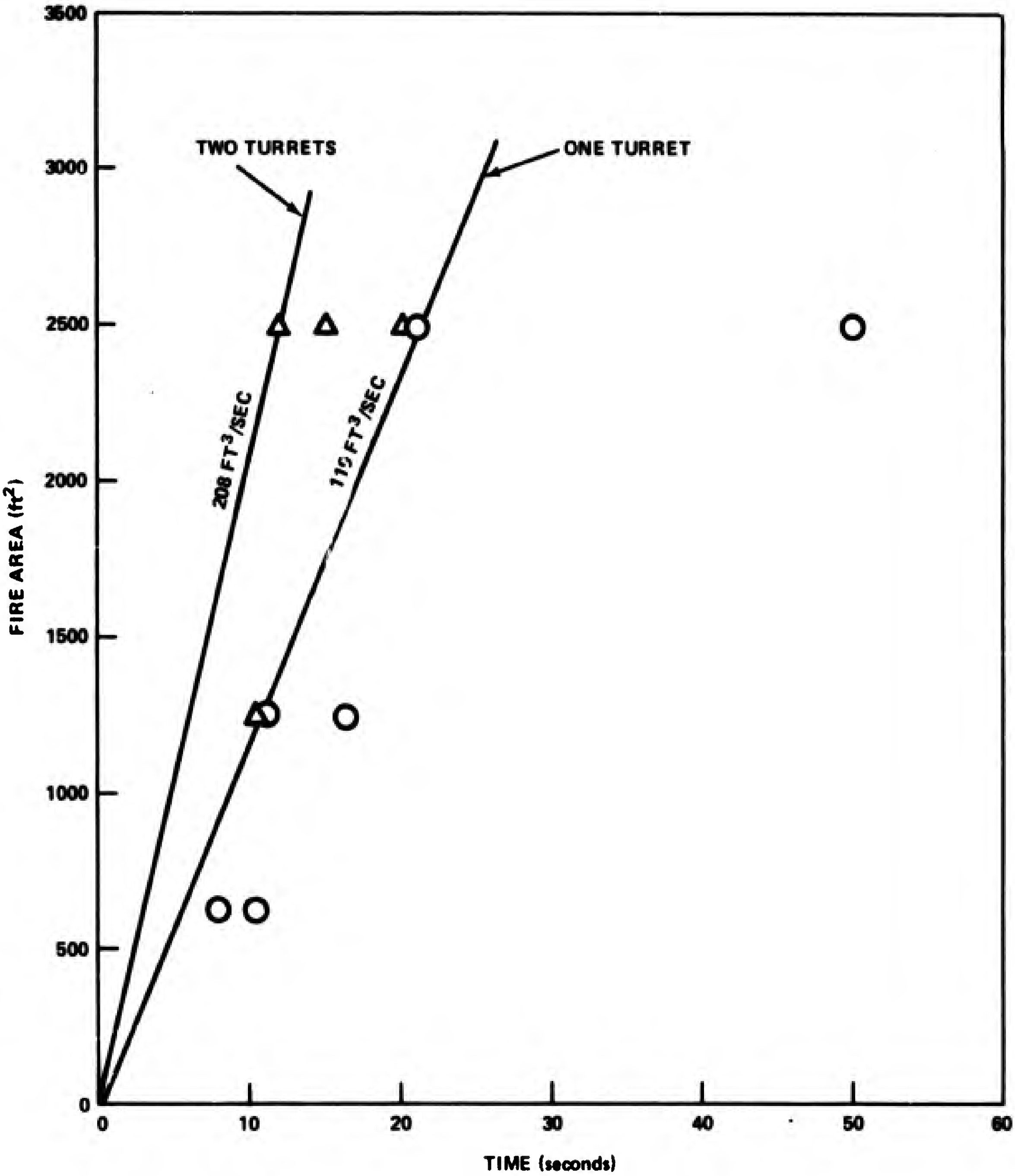


FIG 5.8 EXTINGUISHING TIMES FOR JP–5 FIRES USING 6% AFFF SOLUTIONS—MB–1 TRUCK

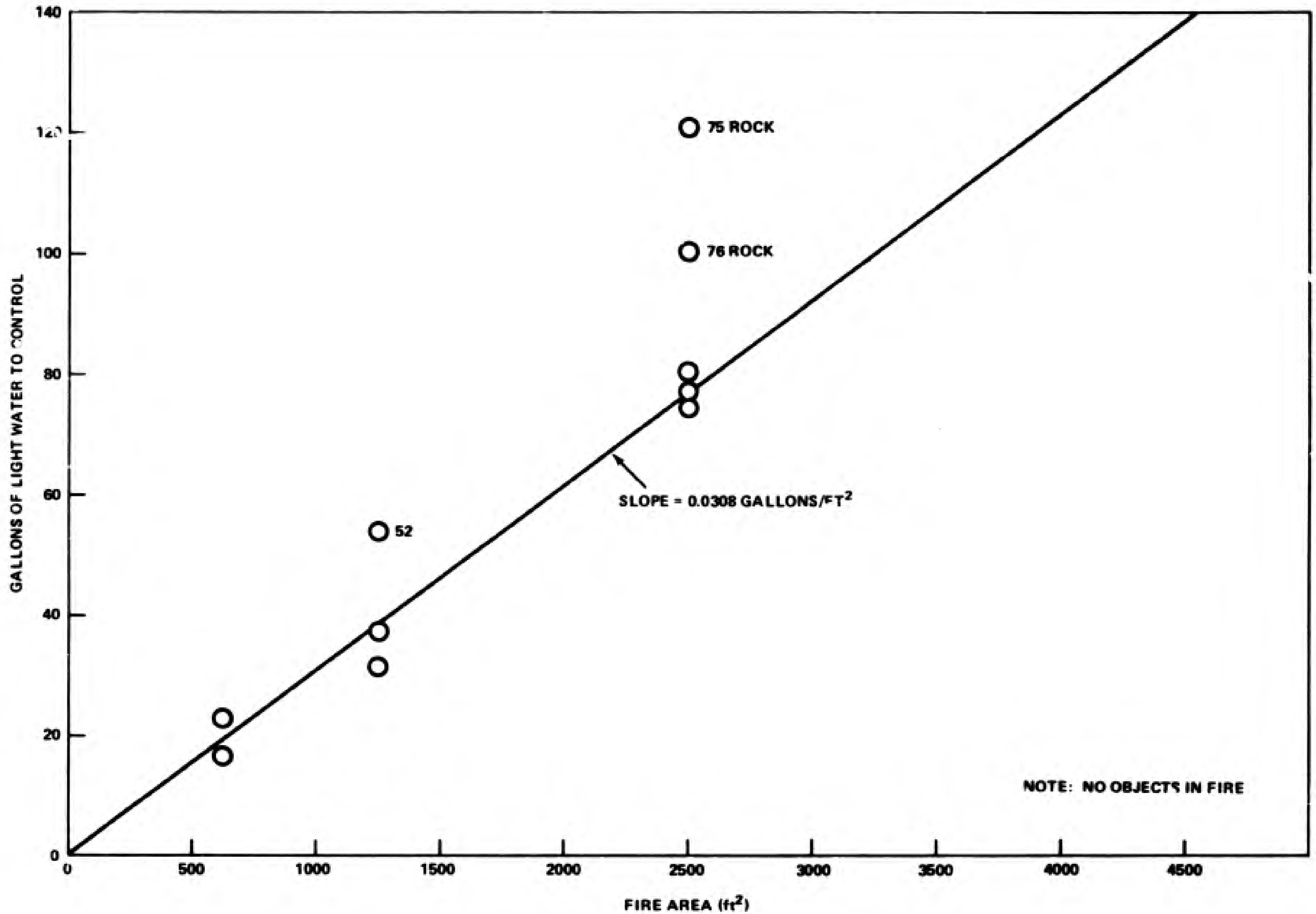
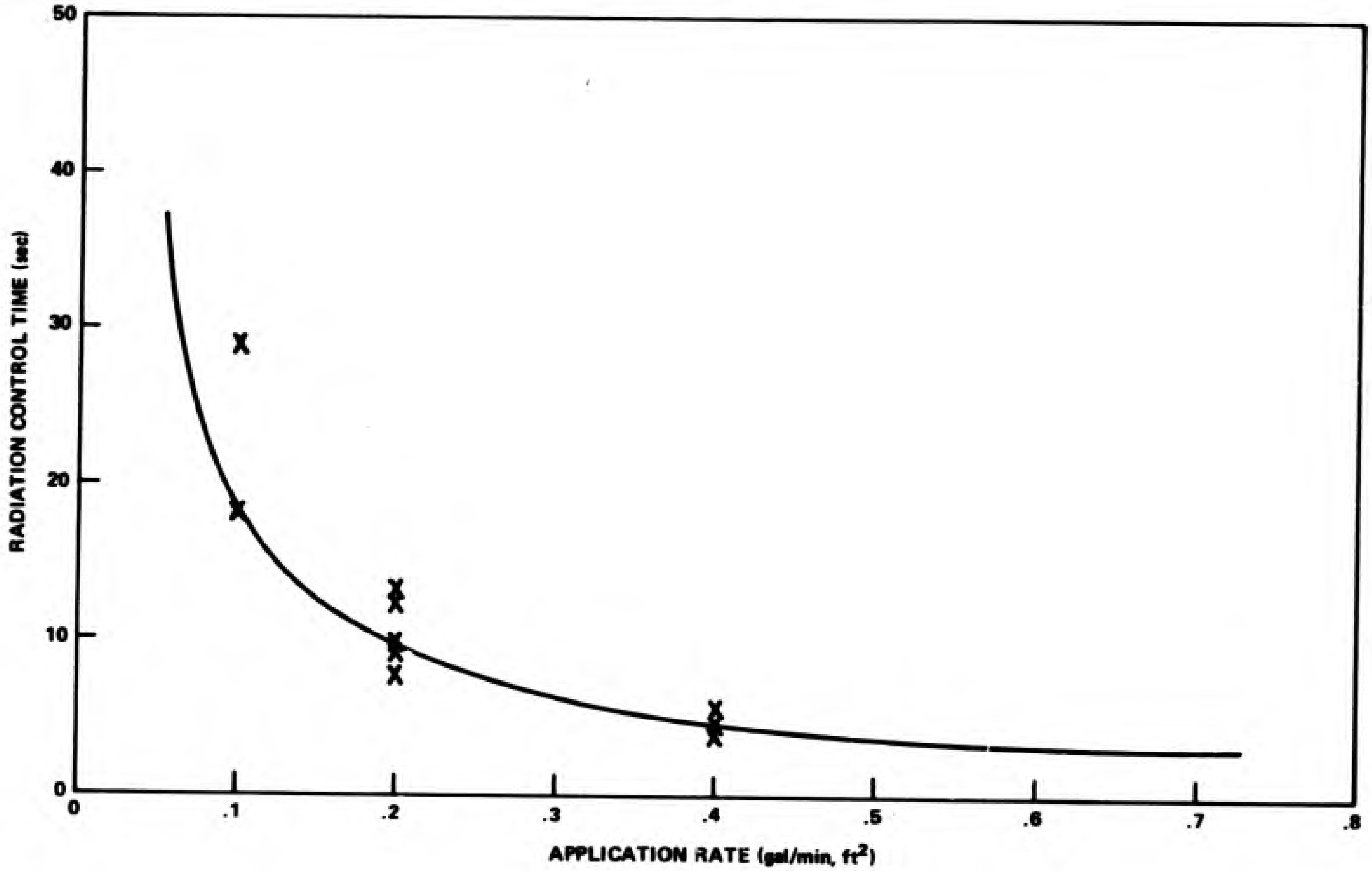


FIG 5.9 GALLONS OF 6% AFFF SOLUTIONS REQUIRED TO CONTROL JP–5 FIRES – MB–1 TRUCK



FI 5.10 RADIATION CONTROL TIME FOR JET FUEL (JP–5) FIRES USING AFFF WITH MB–1 TRUCK

it is verified that dA/dt is indeed relatively or explicity constant. There is also a boundary imposed on extrapolating to larger fires by equipment limitations where the suppressant stream from the turrets cannot reach the fire.

5.2.2 China Lake, CAT/Klein Tests

With these limitations in mind we have analyzed the experiments at NWC where an experimental fire truck was tested for capabilities in controlling large aircraft fuel fires such as those which might relate to a C-5 crash situation. The fire-fighting truck is referred to in this report as the CAT/Klein truck. The analysis is made using the single test result from increasingly larger fires which the apparatus was tested against. The data used in this analysis are in Table 5.4. The diagrams in Figure 5.11 shows the area covered by the fire in relationship to the C-5 mock-up made of sheet metal arrayed in a three dimensional structure to simulate the fuselage and wing sections of the C-5. The radiation control times from these tests are plotted in Figure 5.12 as a function of the fire area. Note carefully that both GPM and the method of attacking the fire were changed as the fire size was increased. On the same curve we show the visual control times taken in the field during the tests. This is to emphasize that there is a difference between radiation and visual control times. Our preference is to use the former because it is dependent less upon the human element which might inject an appreciable variable between independent investigators.

The corresponding curves of total gallons of suppressant versus fire area are in Figure 5.13. The slopes of these curves and the experimental pumping rates were used to prepare the curves in Figure 5.14 correlating the radiation control time against the application rate density in GPM/ft^2. Keeping in mind that we have developed a predicted performance curve from one test without confirmation that the basic assumption of our model of constant ft^2/sec is reasonably true, we may attach a provisional interpretation to the data. The crew operating the CAT/Klein truck did improve their efficiency on the larger fires. The smaller 8000 ft^2 fire was attacked using only one turret pumping at 878 GPM. This is the primary reason for its lower rate of coverage in ft^2/sec. The other three fires were also attacked in a more efficient manner which gave increased coverage rates in each case as the fire size was enlarged. Two turrets operating at 1470 GPM were used on the 16,000 ft^2 fire. In this situation the truck approached from upwind and movement was restricted to moving forward toward the fire in a straight line. The lateral range to the far end of the fire was 200 feet. The 30,000 and 48,000 ft^2

Table 5.4

RADIATION AND VISUAL CONTROL TIMES FOR SUPPRESSING JP4 FIRES WITH CAT/KLEIN TRUCK

Fire Area ft^2	Radiation Control Time Sec	Visual Control Time Sec	Application Rate Gal/min	GPM / ft^2	Gal. to Control	dA/dt_r ft^2/sec	dA/dt_r ft^2/sec	dG/dA gal/ft^2
8,000	49	55	878	0.110	717	163	145	0.0896
16,000	52	80	1466	0.092	1270	308	200	0.0790
32,000	75	110	1493	0.047	1866	427	291	0.0583
48,000	82	160	1454	0.030	1987	585	300	0.0414

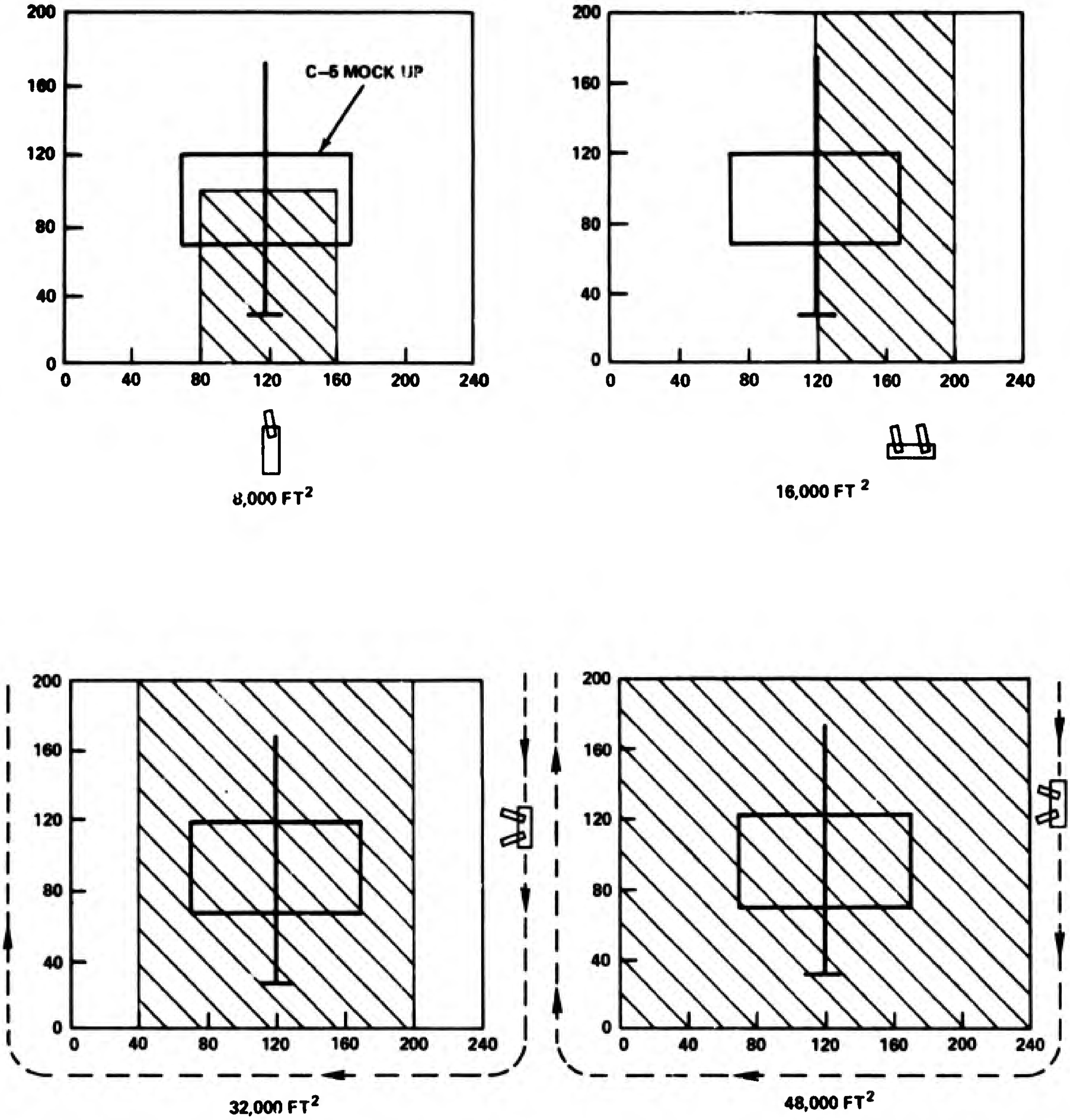


FIG 5.11 TEST LAYOUT FOR CAT/KLEIN TRUCK EVALUATION

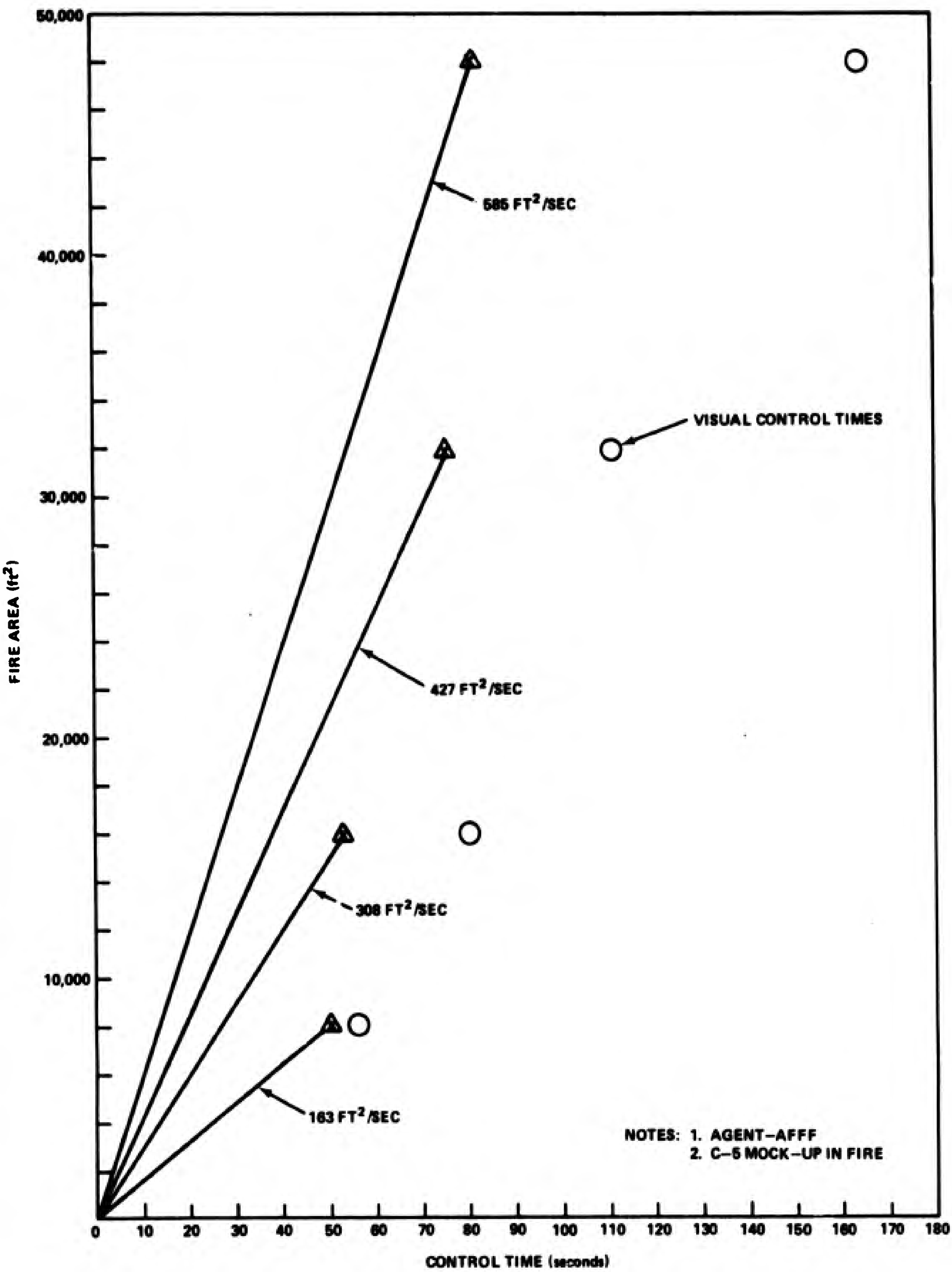


FIG 5.12 CONTROL TIMES FOR JP–4 USING THE CAT/KLEIN TRUCK

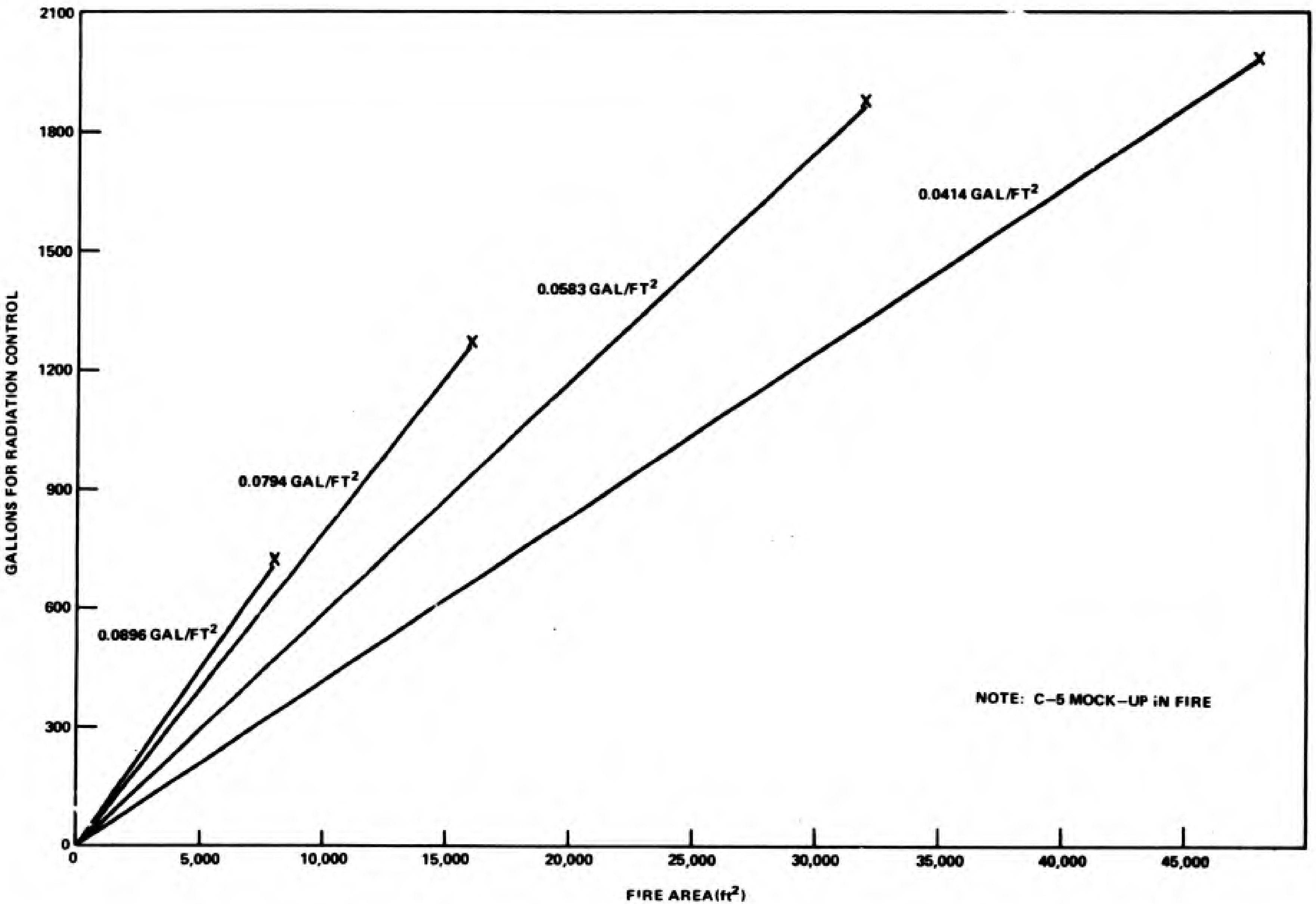


FIG 5.13 GALLONS OF AFFF REQUIRED TO CONTROL JP–4 FIRES CAT/KLEIN TRUCK

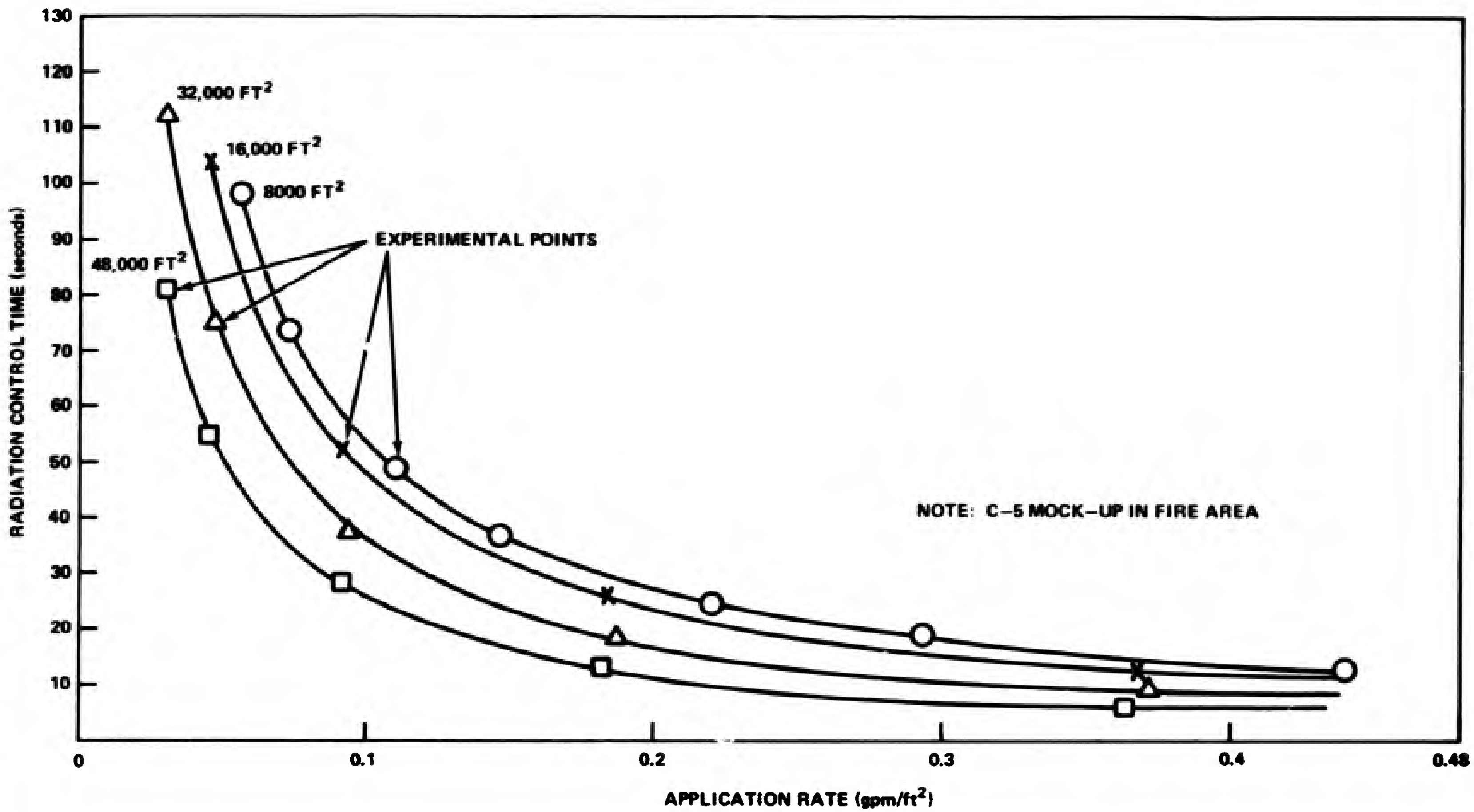


FIG 5.14 RADIATION CONTROL TIME FOR JP–4 FIRES USING AFFF & CAT/KLEIN TRUCK

fires were attacked by driving at increasing speeds around the fire perimeter while spraying continuously from both turrets. The 32,000 ft^2 fire was basically two 80 x 200 foot rectangles on each side of the C-5 mock-up. The maximum distance from the edge of the mock-up to the fire perimeter was 120 feet. The 48,000 ft^2 fire was two 120 x 200 feet areas separated by the C-5 mock-up. Figure 5.11 illustrates each fire area and the method of attack.

The utilities of adapting this extinguishment model are many. There are also words of caution. The primary advantage is the minimization of experimental tests required to characterize a piece of fire fighting equipment. If our assumption of constant rates is applicable, several tests are all that would be required to evaluate a particular equipment configuration. This method could also evaluate equipment options such as higher pumping rates, more efficient or multiple nozzles, training progress and allow extrapolation to larger fires. The latter option cannot be done if other constraints such as maximum range of the nozzles becomes a critical variable.

5.3 Effect of Foam Quality on Fire Suppression

The ability to determine the effect of foam quality on fire suppression when using conventional equipment and techniques is seriously hampered by the experimental variability introduced by the human element, the fireman. The method of attacking any test fire is included within this definition. If in any experimental design proposed to investigate foam quality parameters the experimenter changes the suppression pumping rate or the rate of suppression in ft^2/sec (human element), then the foam variables are hopelessly confounded unless such statistics are taken into account in the analysis procedure. In the experiments about to be described, the fire size was limited to 50 feet x 30 feet with JP5 as fuel. The pumping rate was maintained constant and the human element was all but eliminated by using the drive-by technique with stationary nozzles pointed to impact the fire area so as to totally control the rate of suppression in ft^2/sec. A sketch of the "test" vehicle is in Figure 5.15. Two water tanks, a standard Navy 250 hand billy pump, associated valves and fittings, and three handline nozzles from the MB-1 crash truck converted a dump truck into an aircraft fire suppression test vehicle. Its capacity of 400 gallons of premixed agent could be discharged at a nominal rate of 90 gpm.

In Figure 5.16 a plot of thermal flux versus time shows the effect of suppressing 1500 ft^2 JP5 pool fires with 6% AFFF using the drive-by technique. The pertinent foam and suppression parameters are given in Table 5.5. The major variable

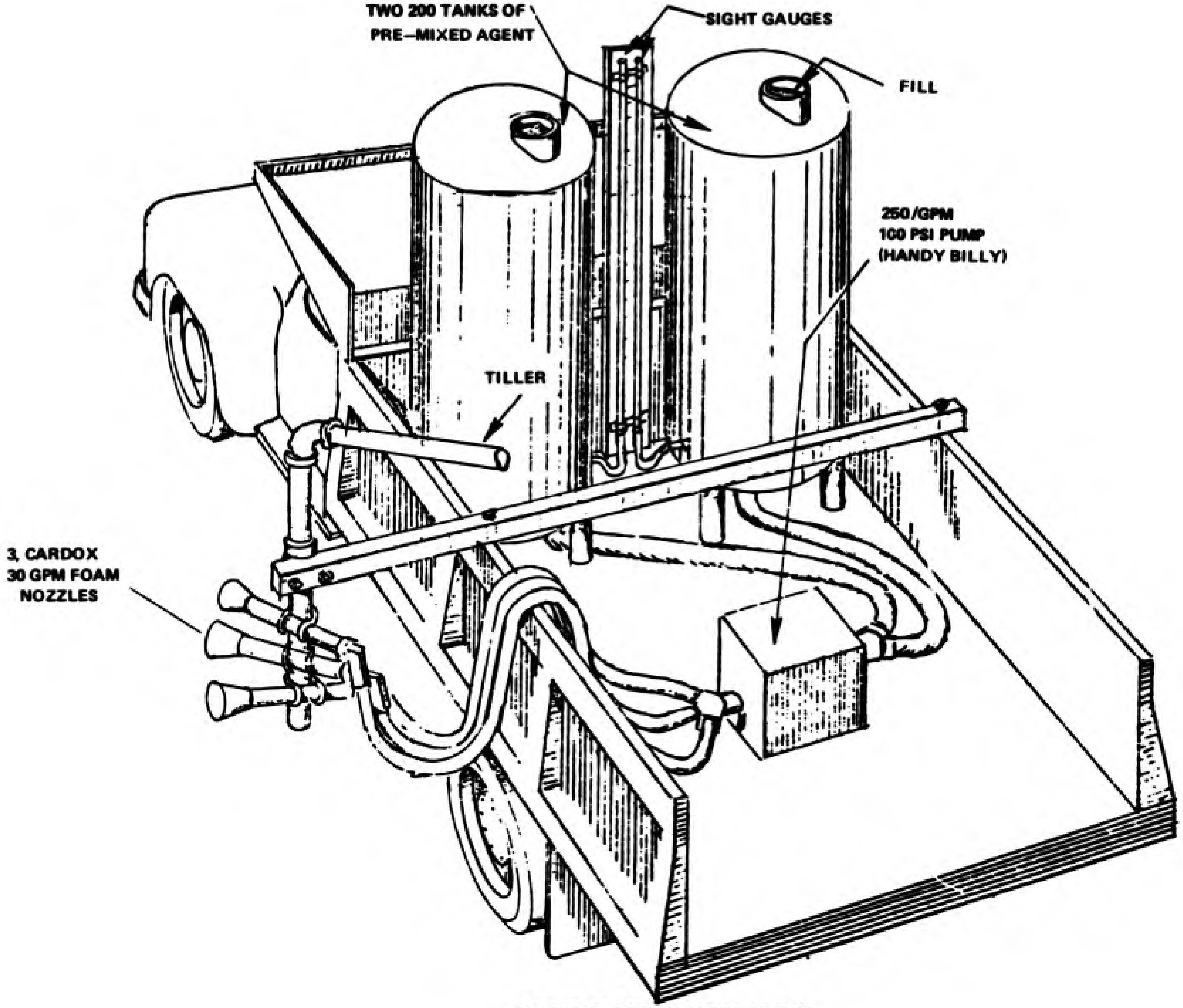


FIG 5.15 DROMEDARY FIRE TRUCK

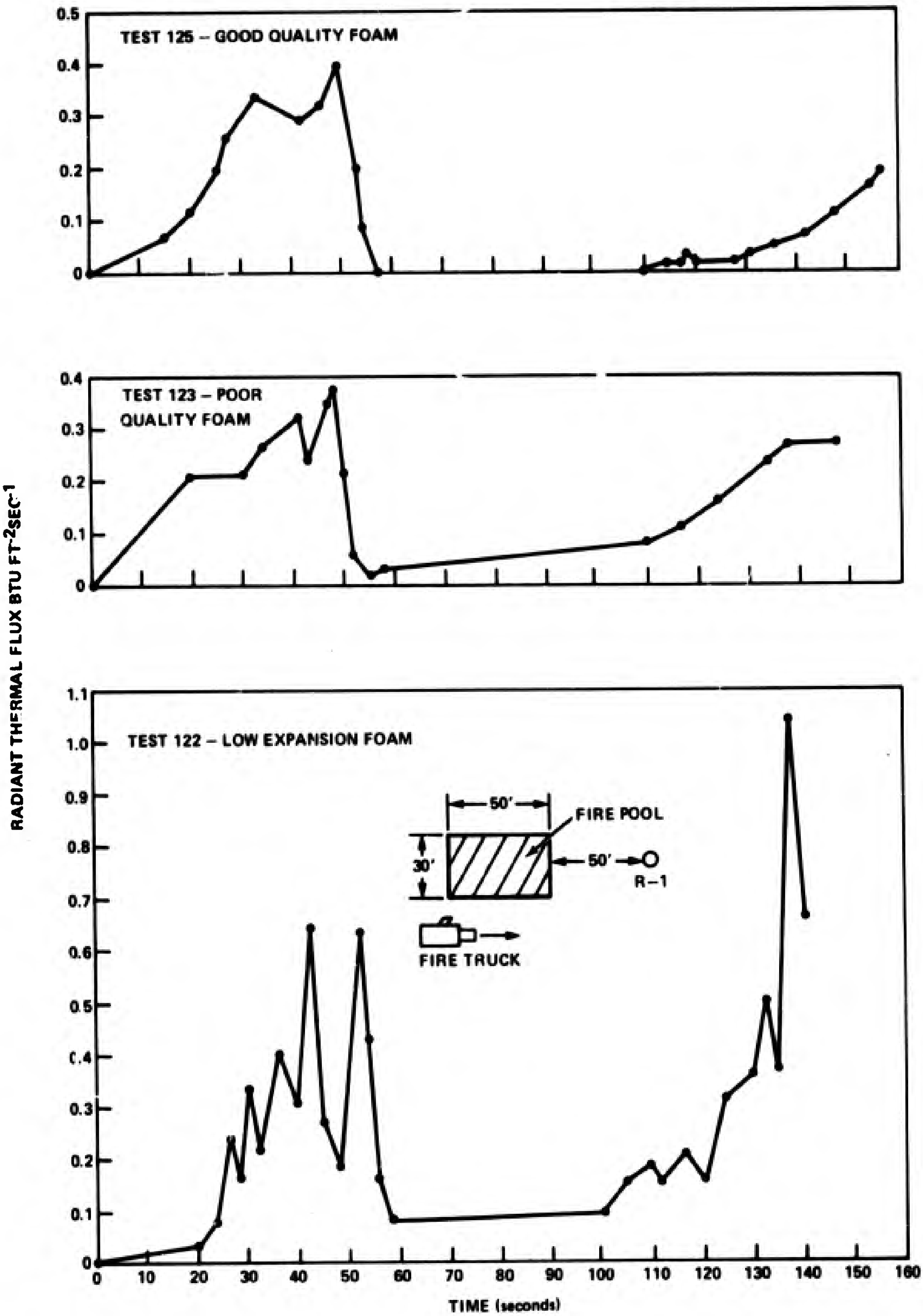


FIG 5.16 RADIATION VS TIME FOR SUPPRESSION OF FIRES WITH VARYING QUALITY AFFF FOAMS

Table 5.5

COMPARISON OF THE EFFECTS OF FOAM QUALITY ON SUPPRESSION

Test	Foam Parameters			Suppression Parameters		Time to	Control	
No.	Expansion Ratio	Drain Time, Min.	Application Density, Gal/ft^2	Total Gal Applied	Area Covered, ft^2	Cover Test Area, Sec.	Times, Sec. $t_{0.1}$	$t_{0.25}$
122	1	0	0.015	90	1000	9.2	0	43
123	5	2.7	0.007	80	1950	8.9	4	62
125	10	4.2	0.009	98	1750	10.7	62	92

$t_{0.1}$, $t_{0.25}$ Time in seconds with the thermal flux (Q) at one diameter from fire controlled to below 10% or 25% of Q equilibrium before suppression.

was the foam quality where the expansion ratio was varied from 1 to 5 to 10. The effect of quality on suppression is shown by the two control times given, i.e. $t_{0.1}$ when the radiation level was below 10% of the average thermal flux before suppression and $t_{0.25}$ when it was below 25% of the average flux before suppression. These experiments showed that in all cases the knock-down power of AFFF solutions with regards to reducing thermal radiation was exceptionally good. However, low expansion foams and liquid drops did not exhibit the burn-back resistance of normal expansion foams and consequently the fires attacked with less than the best foam tended to recover faster.

5.4 Effect of Application Characteristics

The 011-B Fire Truck was used to measure the effects of application rate, sweep pattern and speed on the critical application density and burn-back resistance for AFFF foam on JP5 fires. Several devices were attached to the truck as measurement and control aids. Water consumption was measured with a manometer clamped to the rear of the truck, truck speed was monitored by the voltage produced by a small electrical generator attached to a rear wheel, and the turret position and motion were guided by a fixture attached to the hydraulic controls in the truck cab.

Table 5.6 lists values of the experimental variables for each of the 13 fires and 26 extinguishments. As in the tests described above, two extinguishments were obtained for each fire by permitting complete burn-back between each pass with the truck. The pattern designations are (1) = fixed nozzle, (2) = vertical oscillations and (3) = horizontal oscillations. In all cases the nozzle was aimed about 45° to port. Initially the test plan called for a series of extinguishments with 6% and 3% AFFF concentrations; however, periodic plugging of the proportioner lead to a random assortment of low-quality foams.

Some observations from the 011-B tests supported also by evidence from other field tests and the laboratory experiments of Section 4.2 are as follows:

1. The critical application density for JP5 burning on water or rock substrates is about one gallon per 100 ft^2 for the uniformity achieved in these experiments with a 30 second preburn. With a very uniform coating of foam, .5 gallon per 100 ft^2 would probably be sufficient. Low agent concentration and low expansion ratio foams gave the poorest extinguishment results.

Table 5.6

TESTS OF 011B FIRE TRUCK AT SITE 300

1500 FT^2 JP5 FIRES

Test No.	Pass	Truck Speed M.P.H.	Pump Rate GPM	% Concentration	Nozzle Pattern	Substrate	Area Extinguished %	Burn-Back Time Sec.	Aug. Application Density	Nozzle Motion
128	1	15.7	200	~5	Foam	H_2O Pool	15	30		Stat.
128	2	7.5	200	~5	Foam	H_2O Pool	70	X		Stat.
129	1	8.1	200	~5		H_2O Pool	55	>60		Stat.
129	2	3.8	200	~5		H_2O Pool	95	X		Stat.
130	1	14.9	200	~5		H_2O Pool	50	25		Vert-2*
130	2	7.4	200	~5		H_2O Pool	80	63		
131	1						0			Vert-2
131										
132	1	7.4	200	~5		H_2O Pool	90	>177		Vert-2^3
132	2	4.3	200	~5		H_2O Pool	100			Vert-$2^{\sim 5}$
133	1	7.1	200	~5		H_2O Pool	65	50		Vert-2
133	2	6.9	200	~5		H_2O Pool	50	35		Vert-2
133	3	6.2	200	~5		H_2O Pool	90	>168		Vert-2
134	1	15.5	400	~5		H_2O Pool	50	11		Vert-2
134	2	6.6	400	~5		H_2O Pool	98	115		Vert-2
135	1	14.2	400	~5		H_2O Pool	75	66		Stat.
135	2	7.3	400	~5		H_2O Pool	100			Stat.

Table 5.6 (Continued)

Test No.	Pass	Truck Speed M.P.H.	Pump Rate GPM	% Concentration	Nozzle Pattern	Substrate	Area Extinguished %	Burn-Back Time Sec.	Aug. Application Density	Nozzle Motion
136	1	7.6	200	6		H_2O Pool	90	26		Horizontal
136	2	3.2	200	6		H_2O Pool	100			Horizontal^{6}
137	1	14.9	400			H_2O Pool	50	39		Horizontal
137	2	7	400			H_2O Pool	95	X		Horizontal^{2}
138	1	6.8	200			Rock	75	100		Horizontal$^{2-1/2}$
138	2	2.9	200			Rock	85	X		Horizontal^{10}
139	1	7.5	200			Rock	75	30		Horizontal^{3}
133	2	3.2	200			Rock	98	X		Horizontal^{6}
140	1	13.6	400			Rock	5	14		Stat.
140	2	7.5	400			Rock	50	19		Stat.
140	3	3.1		~3		Rock	60	X		Stat.

X = Ran out of fuel before burned back
* = oscillations 1 per sec

2. The burn-back resistance is strongly influenced by the expansion ratio and concentration of the foam. As would be expected, burn-back occurs most rapidly in areas covered by the thinest layer of foam.

3. With the present trucks, large diffuse patterns are more efficient than the dense straight stream patterns because the nozzle will not move fast enough to apply a uniform critical application density. For example, the maximum oscillation frequencies are about 42 CPM vertically and 62 CPM horizontally. At 15 mph, the truck speed corresponding to a critical application density of about one gallon per 100 ft^2, the foam left a sinusoidal path on the fuel bed and extinguished less than a quarter of the fire.

4. With the present visibility from inside the cab, operators cannot see well enough to direct two nozzles that are close together. A master nozzle for a main extinguishment accompanied by a small clean-up nozzle should be effective.

6.0 BURN BACK PROTECTION

6.1 Effects of Foam Quality and Environmental Factors

AFFF burn-back resistance was measured as a function of the foam quality parameters in a series of 10 foot diameter JP5 fires on water and rock substrates. Figure 6.1 illustrates the experimental procedure. First, the one-inch thick layer of JP5 was heated by burning for 30 seconds at full involvement, then the flames were extinguished by drawing a galvanized sheet metal snuffer over the pan as indicated in Figure 6.1. Unfortunately, the size and fit of the snuffer did not always completely extinguish the fire, particularly at the higher wind velocities; consequently, a few flames around the edge were suppressed with AFFF. Next the fuel was divided in half by lowering the guillotine, foam was sprayed or pre-mixed foam was poured over the upwind half of the pan, and the unshielded fuel was ignited. After the unprotected area was fully involved in flames, the guillotine was lifted to expose the foam to the heat from the fire. The time for complete foam destruction was measured as a function of agent concentration, 2% and 6%; expansion ratios, 3x and 10x; and application densities of 1, 2, and 4 gallons per 100 ft^2. Drainage time could not be controlled and varied from under one minute to over four minutes; so the influence of this uncontrolled variable is unknown.

Destruction times in seconds are shown in the experimental matrix of Figure 6.2 along with wind directions and velocities. These wind variables substantially influence

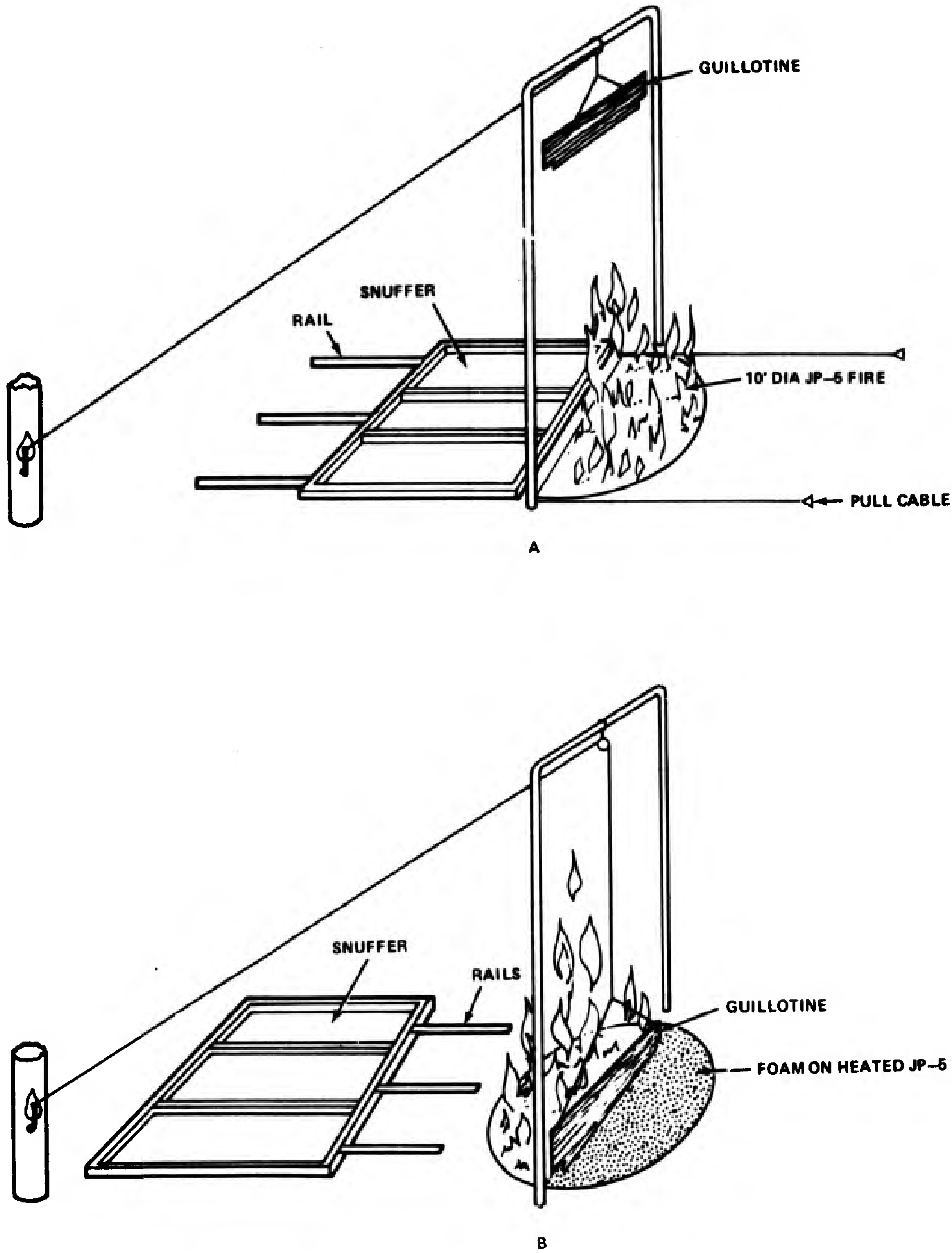


FIG 6.1 EXPERIMENTAL ARRANGMENT FOR BURN BACK TESTS

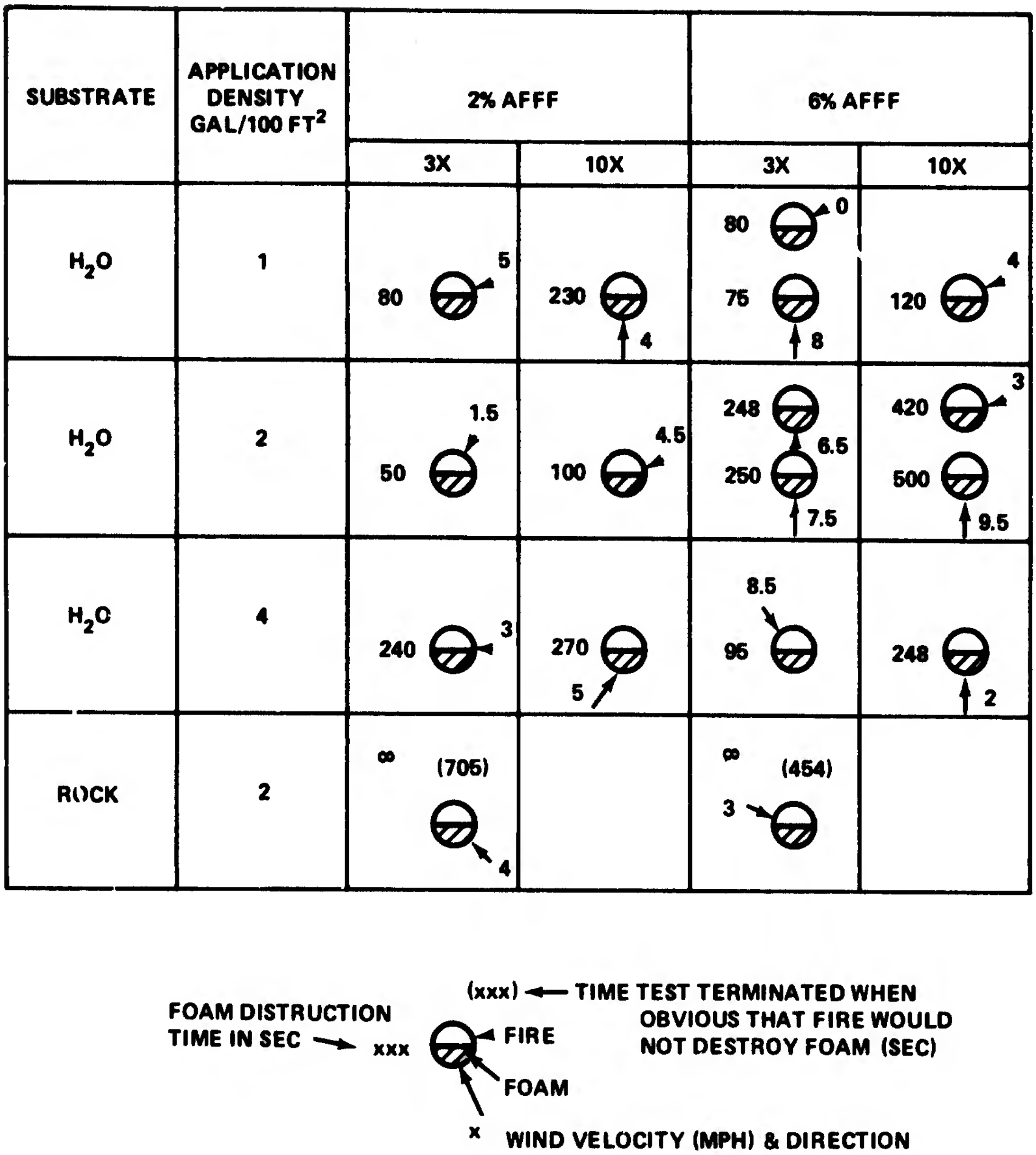


FIG 6.2 BURN BACK RESISTANCE AS A FUNCTION OF FOAM QUALITY

the radiation intensity encountered by the foam, i.e., the velocity affected the fire plume angle and the direction determined whether the plume leaned over the foam or not. It appears from the burn-back times that there is little difference between 2% and 6% FC-200 foams. Probably the wind direction influenced these results signficantly, so that under actual adverse fire fighting conditions the concentration probably would not effect the survival of the foam to a significant degree.

With the techniques of Figure 6.1, the volume of foam produced for an application density of one gallon per 100 ft^2 and an expansion ratio of 3x did not completely cover the area to be protected; consequently, the fire spread through the unprotected areas and destroyed the foam in short order. Fairly uniform coatings of foam were achieved and burn-back resistance was much improved at densities of 2 and 4 gallons per 100 ft^2 especially if an adverse wind blows the fire plume over the foamed area.

The effect of expansion ratio on burn-back resistance was probably the most pronounced of all the control variables in the experiment. All destruction times for the 10x foams exceeded those for 3x foams. Wind direction does not appear to bias this conclusion although destruction times were shorter when the wind blew the flame plume over the foam. It will be recalled that in the laboratory experiments on the effects of foam quality i.e. Section 4.2.1, the expansion ratio had little effect on the survivability of the foam. However, those tests involved surfaces whose temperatures exceeded the boiling point of water and the steam inflated the foam to several times the original value. With the heating ritual illustrated in Figure 6.1 it was impossible to go through the evolution and apply the foam before the JP5 temperature dropped below 212°F. Typical fuel temperatures ranged from 122 to 176°F, consequently no steam was generated to expand the foam. Some expansion due to steam generated by radiation from the flames was observed at the flame-foam boundary as the flame front moved across the test area after the guillotine had been lifted. This expanded region ranged from several inches to a foot wide depending on the flame orientation.

6.2 Effects of Fuel Temperature and Substrate

The burn-back tests described in Section 6.1 permitted the fuel to cool appreciably between the snuffing operation and the application of the protective foam layer; consequently, the foam did not experience the same thermal insult encountered in a conventional extinguishment. This limitation was eliminated by combining the spray rig described in Section 4.4 with the guillotine. In the tests reported here, the fire was allowed to reach its equilibrium burning rate with the guillotine positioned in the fuel pan, then a spray rig moved forward to extinguish half the fire, and the guillotine was raised to expose the foam to the flames. Burn-back rates were observed as a function of foam application density, substrate material, and wind conditions. A 6% concentration of FC200 with an expansion ratio of 5 and a 25% drainage time of 2-1/2 minutes was used throughout the test. The steel pan contained about two inches of gravel and about one inch of water. For pool fire tests, the fuel level covered the rocks sufficiently to permit extinguishment and burn-back before the fuel dropped below the surface of the rocks. In the rock substrate fire test, the fuel was allowed to burn down until rocks occupied about 50% of the surface area, then extinguishment and burn-back was commenced.

Table 6.1 is a brief summary of the results obtained by visual observation. The results show that the wind and substrate material are more important than the application density in controlling the burn-back rate. Three general wind conditions are of interest (1) steady winds that tilt the flames away from the foam, (2) calm conditions so that the flames go straight up in a symmetrical plume, and (3) winds that tilt the flames over the foam surface. Since heat transfer from the fire to the foam is principally responsible for the destruction of the foam, the fire plume with the best view factor will be the most damaging, i.e., 1, 2, 3, in order of increasing view factor.

Both JP4 and JP5 (runs 171 and 172) exhibited longer burn-back periods than recorded for similar application densities in the previous guillotine tests because of the strong breeze. When the guillotine was raised in run 171, the wind blew foam into the flame area and extinguished most of the fire as indicated by the flame front positions at various times shown in Figure 6.3. Runs 173, 174 and 176 in calm air, exhibited short burn-back times of less than one minute. In all cases, the radiation levels experienced by the observers and the radiometers on the foam side of the pan were substantially higher in tests 172 and 171. Under wind conditions 1 and 2, energy is transported back to the foam principally by radiation. When the wind tilts the flames over the foam, i.e., condition 3, the radiated heat transfer increases because of the increased view factor and some convective heating becomes possible. The only illustrations of the convective effect observed in these tests occurred when the flame fronts in tests 171 and 172 developed pincers that surrounded an island of foam. Under these conditions the turbulent air motion

Table 6.1

BURNBACK TESTS ON 10 FT DIAMETER JET FUEL FIRES

Burn No.	Fuel	Type of Fire	Foam* Application Density gal/100 ft^2	Flame Tilt Condition	Time for Complete Burnback min
171	JP4	Pool	2.9	1	12.5
172	JP5	Pool	2.8	1	9
173	JP5	Pool	1.3	2	0.5
174	JP5	Pool	1.3	2	0.9
175	JP5	Pool	1.8	2 and 1	~2.5
176	JP5	Pool	2	2	0.5
177	JP5	Rock	1.2	mostly 2	11.5
178	JP5	Pool and Rock	1.2	2	0.3
179	JP5	Pool and Rock	2.2	1	>8

*Agent = FC 200, 6 percent solution, pumping rate 19 gpm.

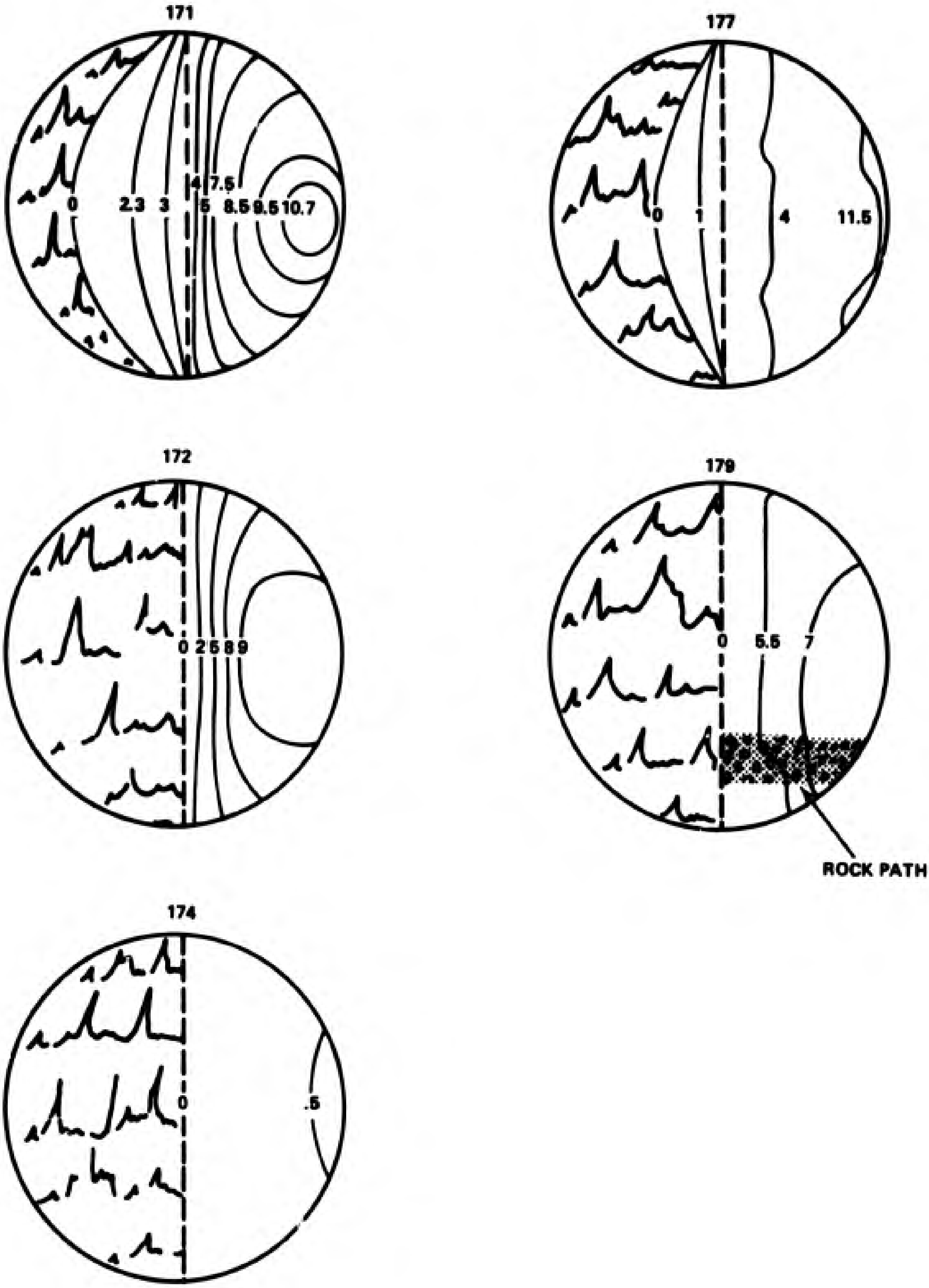


FIG 6.3 FLAME FRONTS VS TIME IN MIN. DURING BURNBACK

brought hot air and combustion products in contact with the surface of the foam; consequently, the foam was very short lived.

The rock substrate burn number 177 and the combination exposed rock and pool tests numbers 178 and 179 illustrate the advantage of fighting fires on a rock base. A very thin layer of agent provides substantial protection. At least part, if not most of this effect stems from the reduced radiation level encountered in the rock-base fires. When the fuel burns down below the surface of the rock, e.g., rocks exposed over 50% of the surface, the burning rate decreases, flame heights are reduced, and the flames are no longer opaque. Consequently, both the view factor and the radiation intensity decreases. Such fires are easy to extinguish and the burn-back rate is modest even in the absence of a visible foam layer.

Tests 178 and 179 represent attempts to create a difficult yet realistic substrate for a foam to protect, i.e., pool fire with a rock path bridging the foam. A two-inch high path, 16 inches wide was laid from the guillotine to the pan rim along the direction of the burn-back. Presumably the large pool area would provide a high radiation field and the rocks would leave a thin path in the foam due to the greater evaporation required to cool hot rocks. With the thin foam layer (test 178) burn-back was so rapid the rock path was inconsequential. With the heavier layer in test 179, burn-back in the rocks did exceed the main pool area rate for a while but eventually the fuel bed dropped into the rocks and the influence of the bridge disappeared. The breeze that developed during Test 179 probably had more influence on the burn-back rate than the rock bridge.

6.3 Effects of Fuel Type and Amount

The primary concerns at Site 300 were the critical application density for AFFF on JP4 fires, burn-back resistance of the foam, and the influence of the substrate on these parameters. In eight of the burns, the Dromedary unit was equipped with the Batel nozzle. The remaining extinguishments were made with three Cardox 30 gpm nozzles mounted as in previous tests. Figure 6.4 illustrates the drive-by test procedure employed in all of the Site 300 tests. Results for the critical application density and burn-back tests are summarized in Figure 6.5 and Table 6.2. Figures 6.5 and 6.6 show the uniformity of application densities at various positions sampled by the pans on either side of the fire. A comparison of Table 6.3 with these figures shows that when the application density falls below one gal/100 ft^2 in parts of the fire, not all of the flames are extinguished and burn-back can be quite rapid. For example,

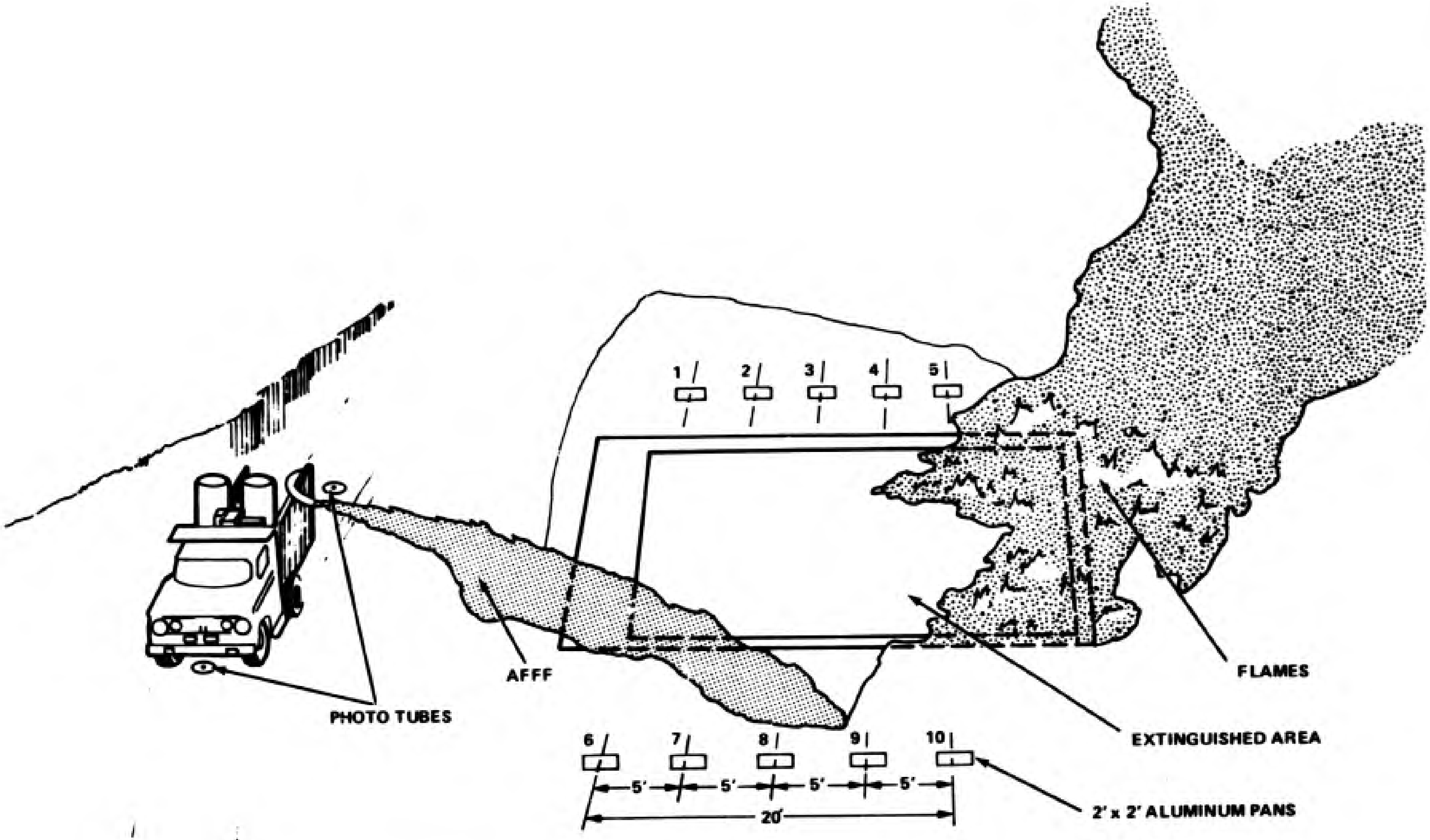


FIG 6.4 1–1/2" FOAM NOZZLE IN "DRIVE BY" EXTINGUISHMENT TESTS WITH AFFF ON 1500 FT^2 JP–4 FIRE

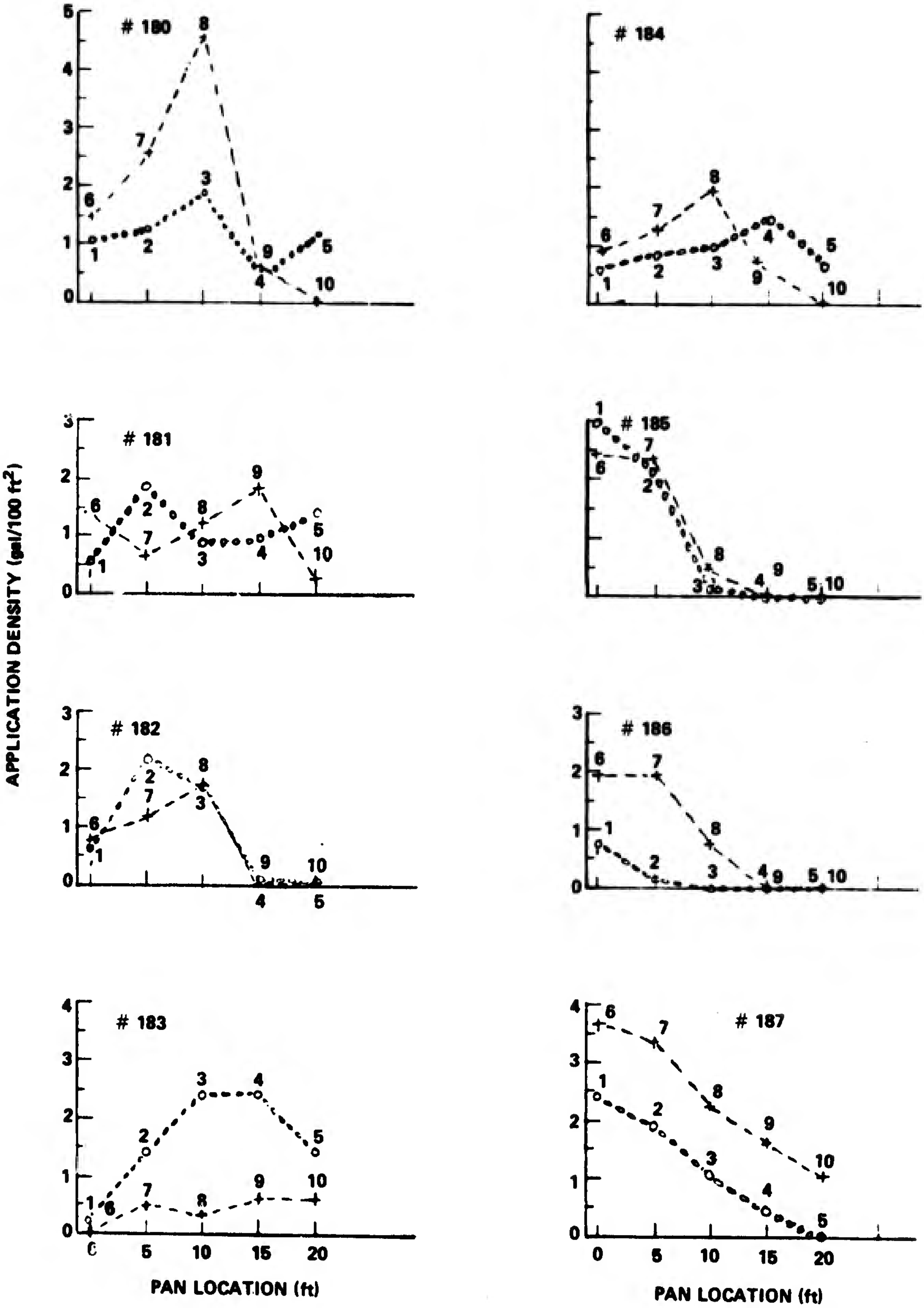


FIG 6.5 UNIFORMITY OF APPLICATION DENSITIES AT VARIOUS SAMPLING POSITIONS IN THE "DRIVE BY" EXTINGUISHMENTS

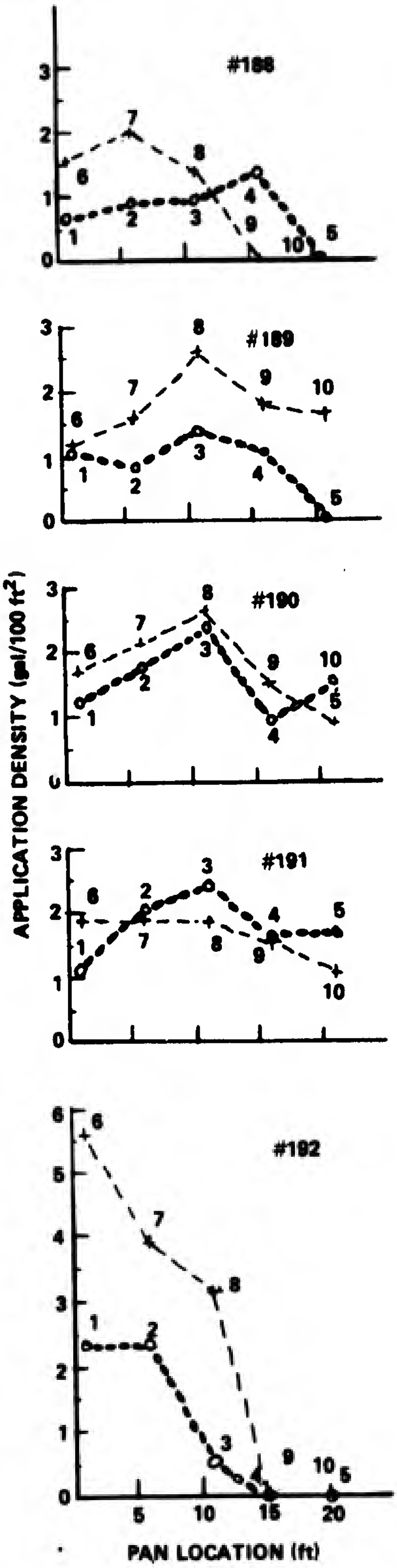


FIG. 6.6 UNIFORMITY OF APPLICATION DENSITIES AT VARIOUS SAMPLING POSITIONS IN THE "DRIVE BY" EXTINGUISHMENTS

Table 6.2

APPLICATION DENSITIES AND BURNBACK TIMES FOR JP4 FIRES

Test No.	Substrate	Application Density (Pans) gal/100 ft^2	Application Density Pumped Agent Foamed Area gal/100 ft^2	% of Foamed Area Not Extinguished %	Location of Burning Areas in Foam	Time for Flames to Cross Foam at one point	Remarks
180	Pool	1.7	1.6	0	--	--	Burnback 4 ft in 9 min then fuel exhausted.
181 First Pass	Pool	1.2	1.2	10	Up wind edge	20 sec	
Second Pass	Pool		.8	0	--	--	1.8 min - fuel exhausted
182 First Pass	Pool	1.4	.6	30	Up wind edge	20 sec	
Second Pass	Pool		1.1	0	--	--	1.5 min - fuel exhausted
183	Pool	1.2	.7	5	Up wind and middle	18 sec	
184	Pool	1.1	1.0	11	Up wind and middle	15 sec	
185	Pool	1.8	1.4	0	--	--	Burnback 4 ft in 2 min then fuel exhausted.

Table 6.2 (Continued)

Test No.	Substrate	Application Density (Pans) gal/100 ft^2	Application Density Pumped Agent Foamed Area gal/100 ft^2	% of Foamed Area Not Extinguished %	Location of Burning Areas in Foam	Time for Flames to Cross Foam at one point	Remarks
186	Rock	1.0	1.8	0	--	--	Burnback 8 ft in 2 min then fuel exhausted.
187	Rock	1.9	3.3	0	--	--	Burnback 4 ft in 3.3 min then fuel exhausted.
188	Pool	1.3	1.3	25	Up wind edge	7 sec	
189	Pool	1.4	1.0	90	--	--	
190	Pool	1.7	1.9	15	Up wind edge	20 sec	
191	Rock	1.7	2.2	1	Up wind and	3-1/2 min	
192	Rock	3.1	3.2	.1	Up wind and middle	5 min	

in test 180, 185, and 187 no flame areas were left inside the foam and burn-back did not destroy the foam before the fuel was consumed. By contrast, runs 181 to 184, 188, and 189 had residual fires along the upwind edge where the density dropped below the one gal/100 ft^2 line, and in these cases rapid burn-back developed. Tests 91 and 92 illustrate the observation that burn-back is slower in rock substrates than for pools. Very small pockets of flames were left in the foam blanket in tests 91 and 92, but the fires did not progress through the foam before the fuel was exhausted. The lack of uniformity in the foam layer complicates the measurement of the critical application density. However, for JP4, it appears to be between 1 and 2 gal/100 ft^2 and is slightly less for rock substrates than for pool fires.

6.4 Effect of Application Density

Drive-by tests with the MB-1 vehicle were used to determine burn-back resistance and the critical AFFF application density required to extinguish JP5 pool fires with dimensions of 50 feet x 30 feet. Figure 6.7 shows the test arrangement and illustrates the procedure. A fairly uniform layer of AFFF is applied to the shaded area by driving the MB-1 past the fire at a constant velocity while the locked turret sprays foam on part of the fire. The destruction of the foam is monitored photographically. From this data it is possible to develop curves such as in Figures 6.8, 6.9, and 6.10 of the foamed area remaining as time and the fire front progresses. The progress of the average fire front can then be matched to the application densities measured by the sampling pans. Such plots are shown in Figures 6.11 through 6.14. Finally the average application density (from the leading and trailing pans) can be related to the foam protection time as shown in Figure 6.15. Right away it is obvious that application density is not the only variable affecting the protection time. In this case, the missing variable is the thermal flux acting to destroy the foam. All of the fires which remained after the drive-by pass of the MB-1 were of different sizes and therefore radiated different thermal fluxes to the foam blanket. This flux also increased differently with time as each fire recovered to the full 50 foot x 30 foot size; consequently, if a measure of this heat flux were available it is likely that the protection time could be better correlated by an equation such as

$$t_p = AQ^nD^m$$

where Q = thermal flux received by the foam

D = application density

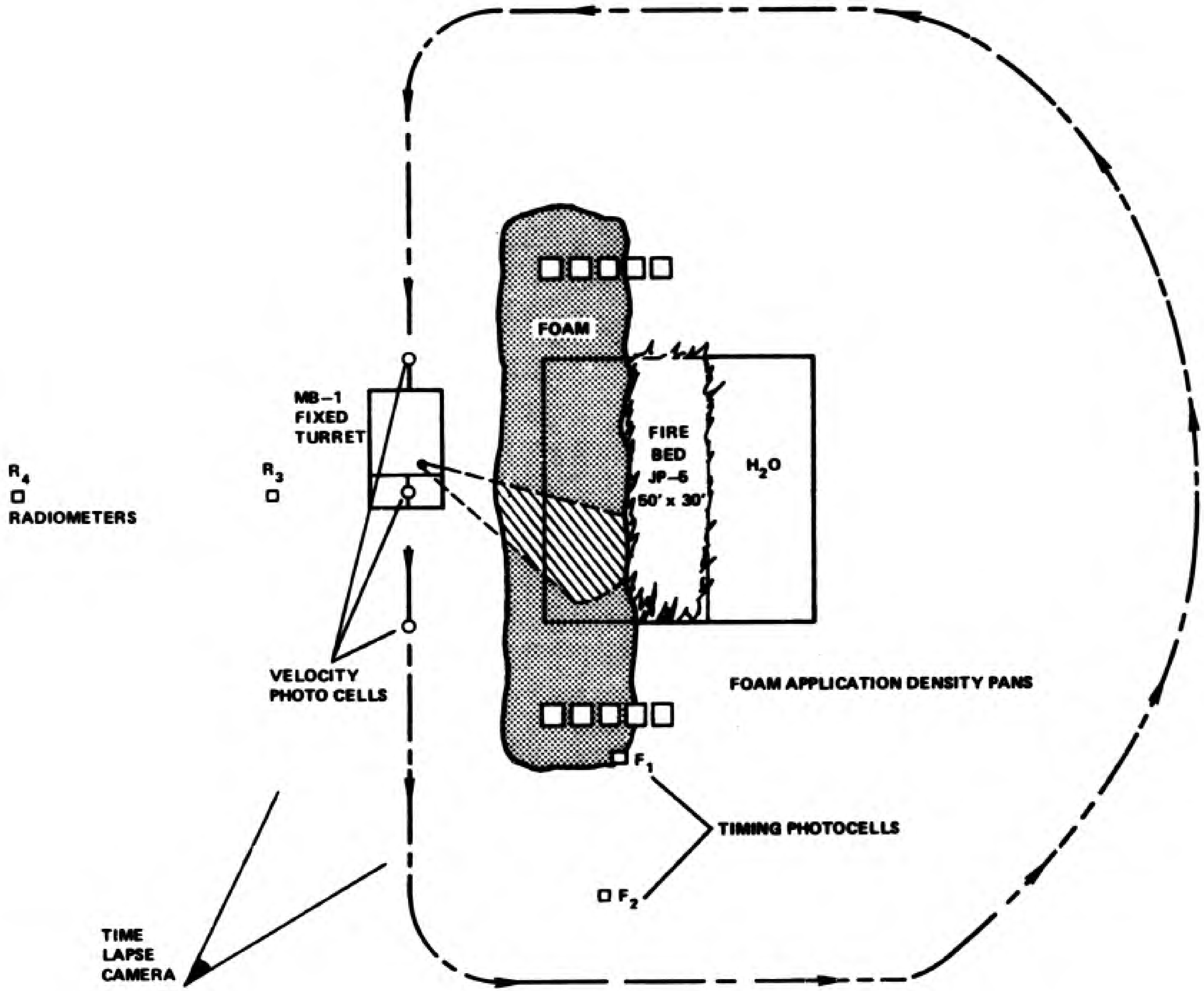


FIG 6.7 SITE LAYOUT FOR BURN BACK TESTS WITH MBI

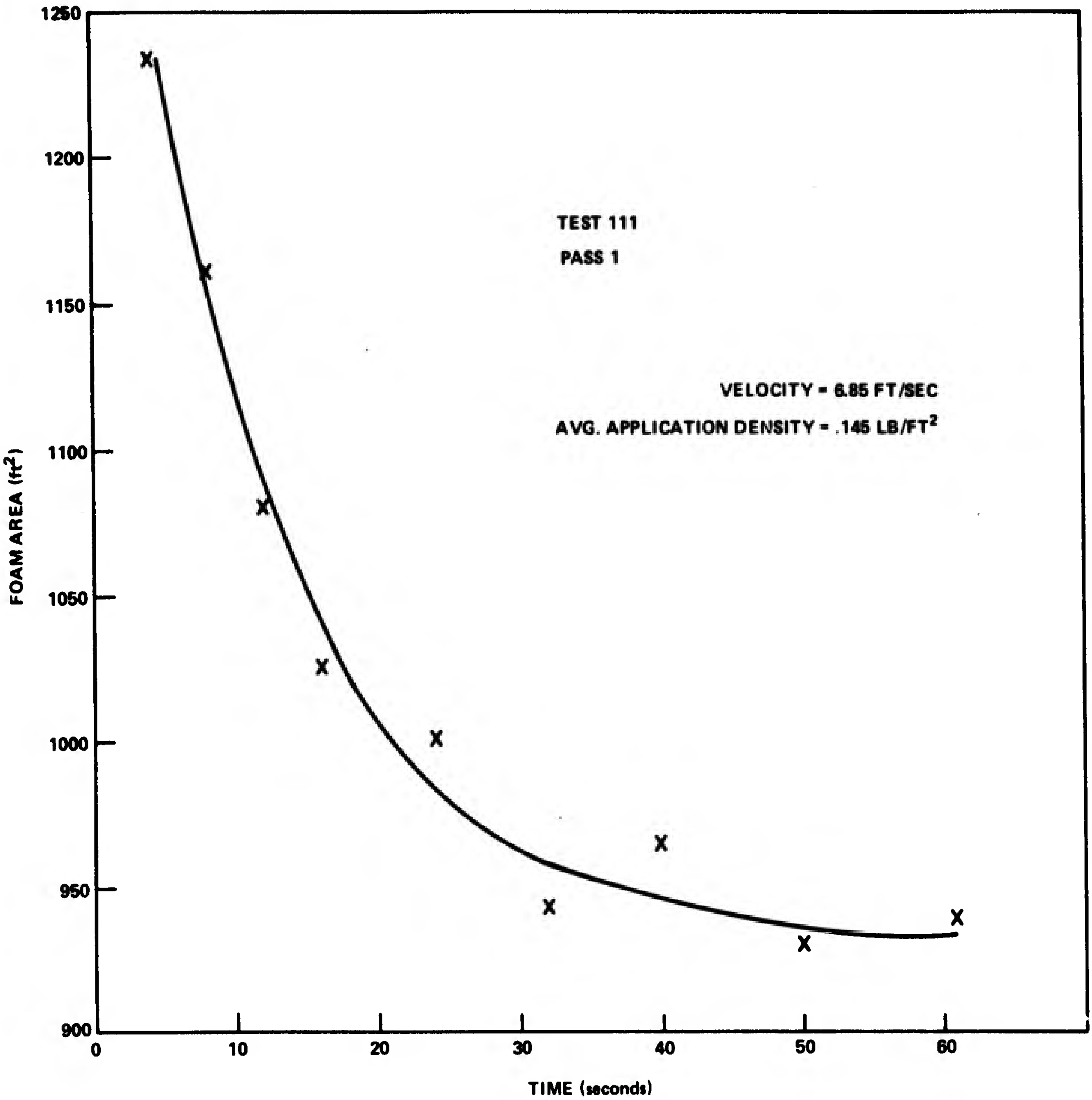


FIG 6.8 DECREASE IN FOAM AREA AS FIRE BURNS BACK

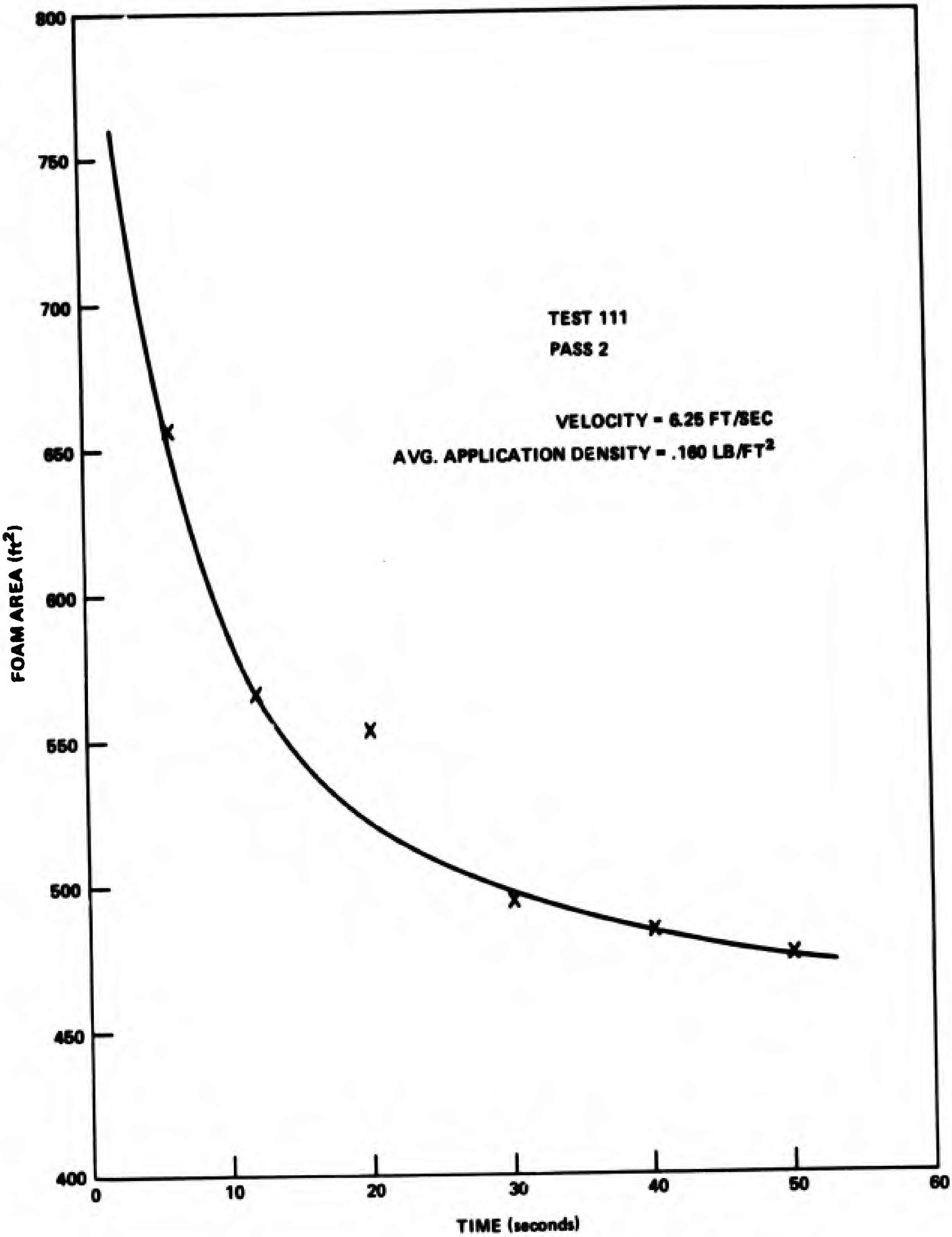


FIG 6.9 DECREASE IN FOAM AREA AS FIRE BURNS BACK

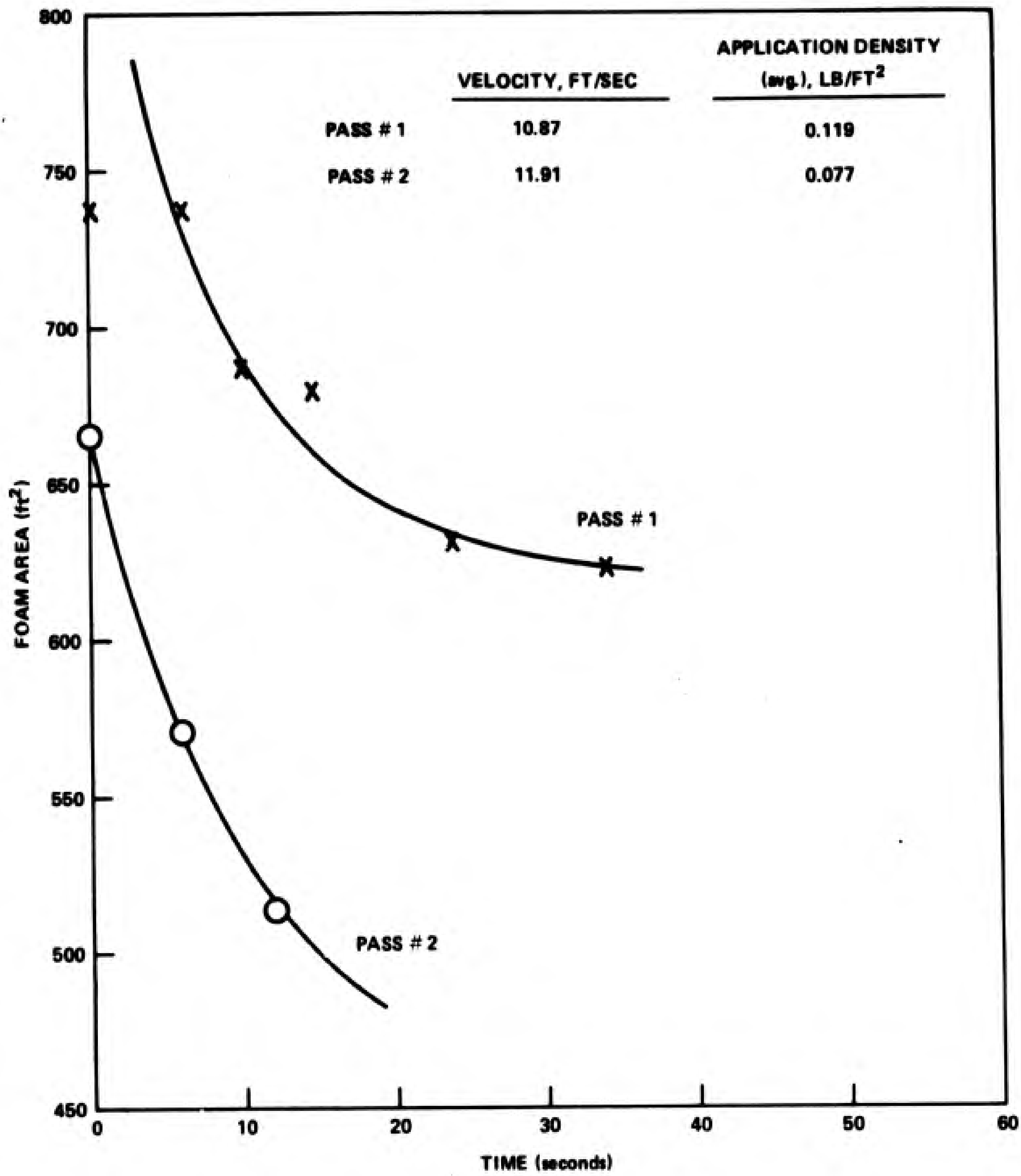


FIG 6.10 DECREASE IN FOAM AREA AS FIRE BURNS BACK TEST 112

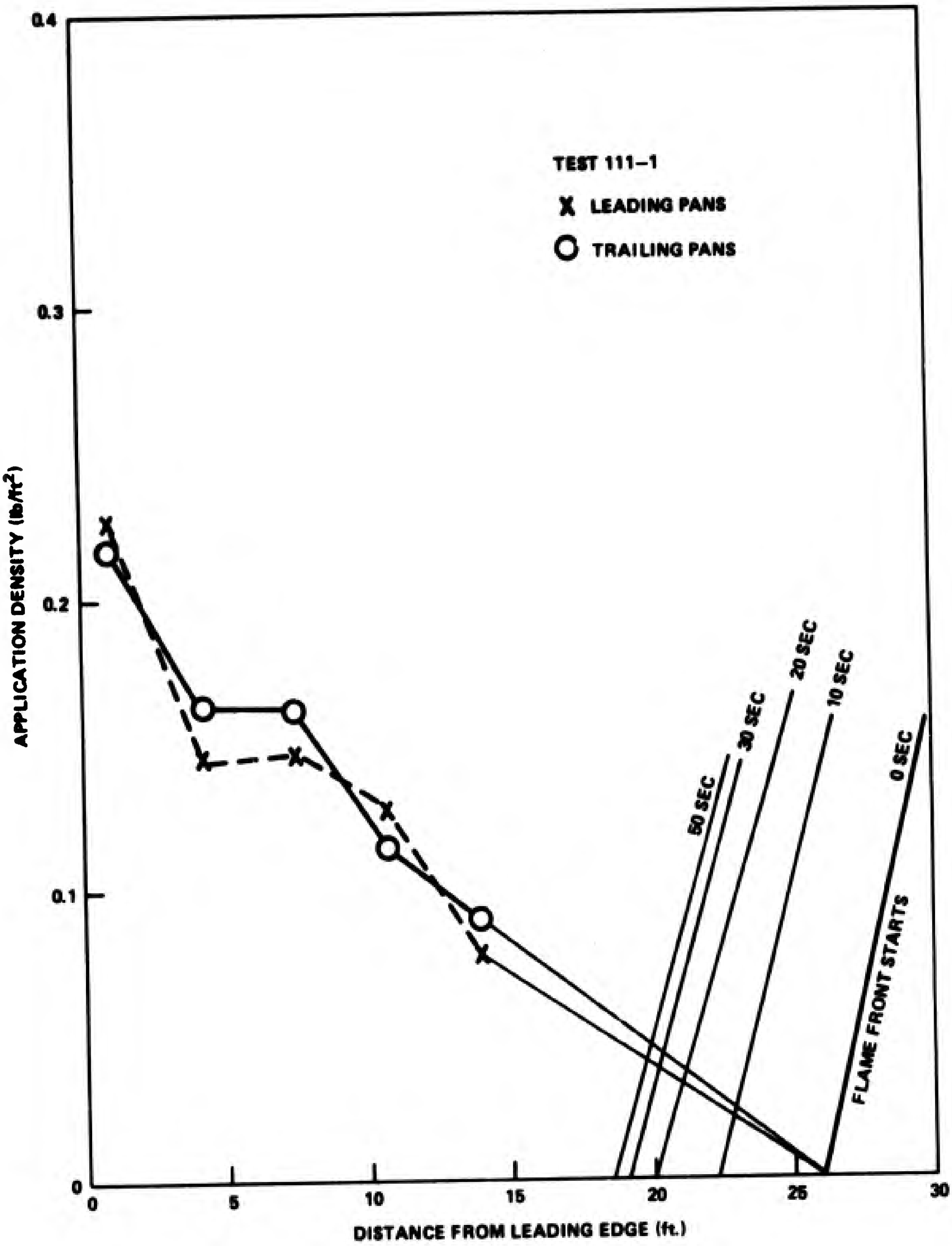


FIG 6.11 APPLICATION DENSITY DISTRIBUTION FOR TEST 111–1 BY DRIVE–BY TECHNIQUE

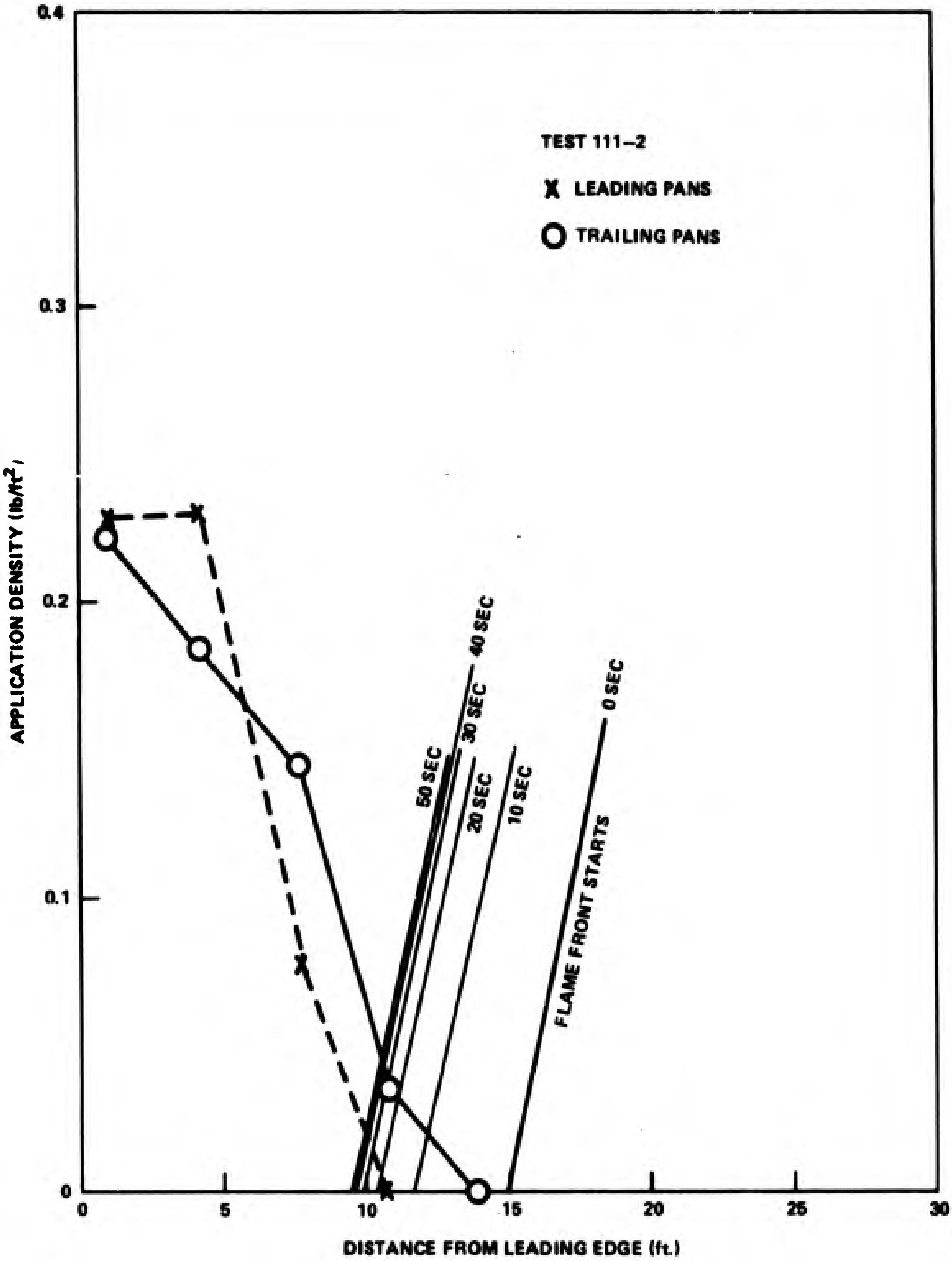


FIG 6.12 APPLICATION DENSITY DISTRIBUTION FOR TEST 111–2 BY DRIVE–BY TECHNIQUE

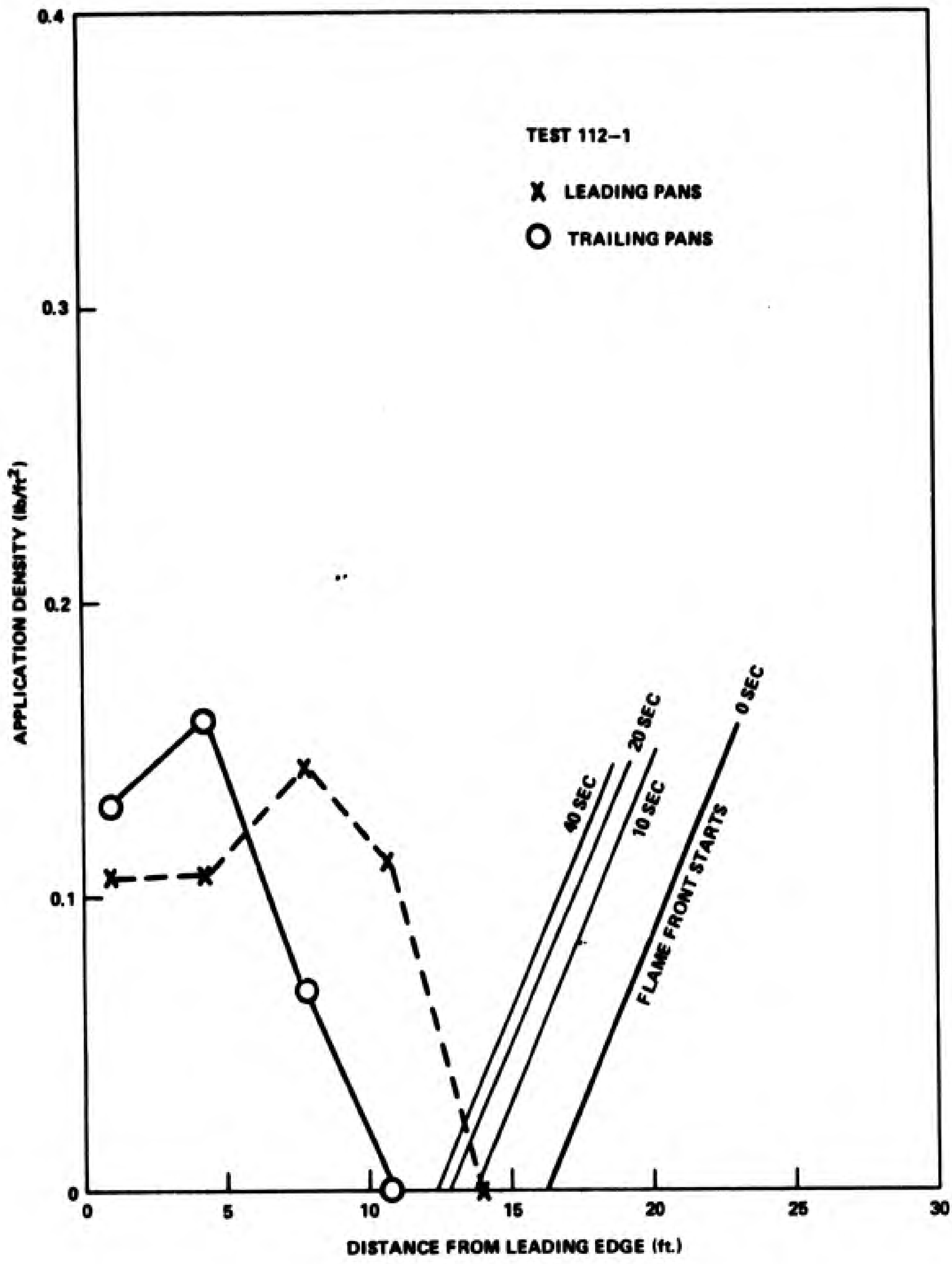


FIG 6.13 APPLICATION DENSITY DISTRIBUTION FOR TEST 112–1 BY DRIVE–BY TECHNIQUE

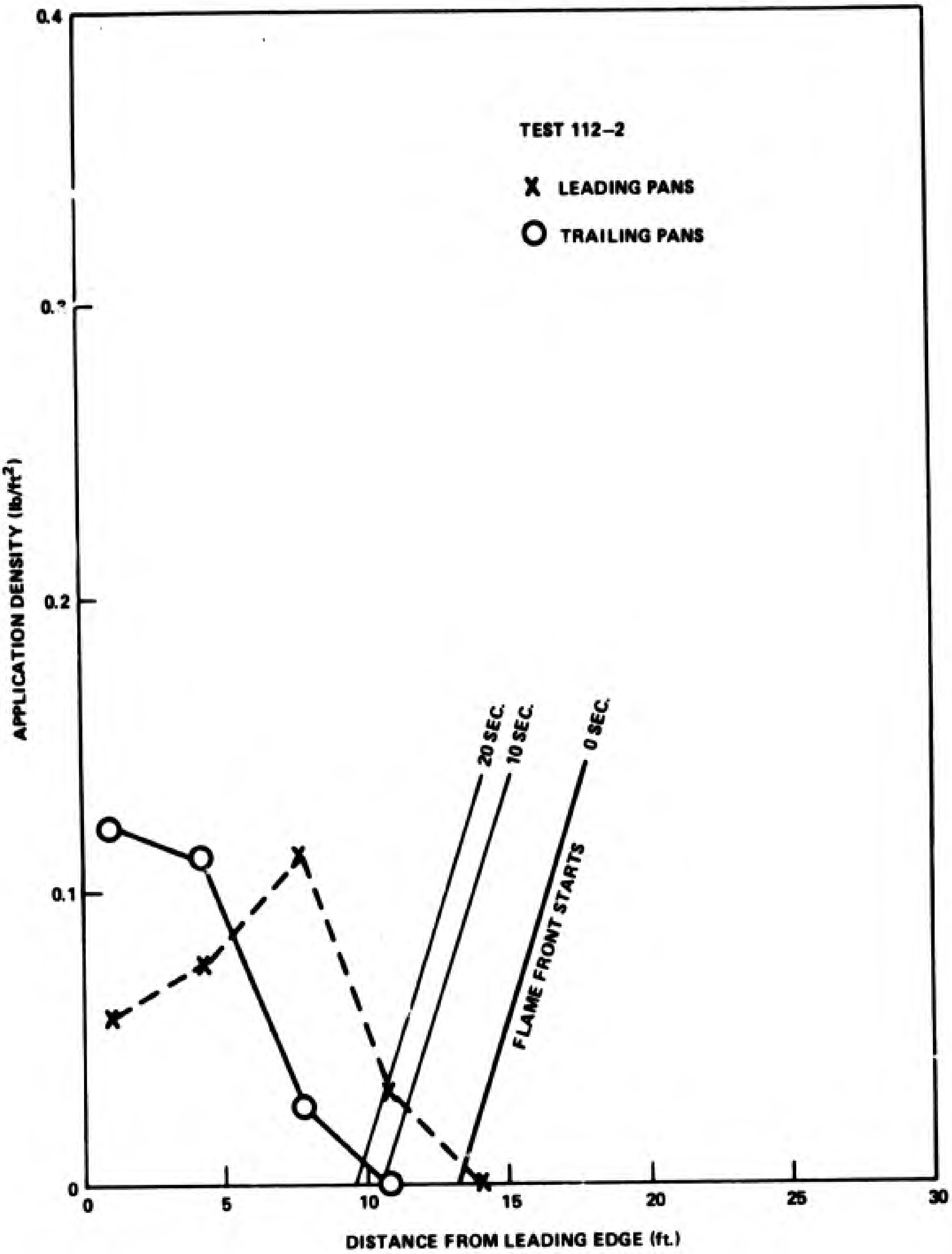


FIG 6.14 APPLICATION DENSITY DISTRIBUTION FOR TEST 112–2 BY DRIVE–BY TECHNIQUE

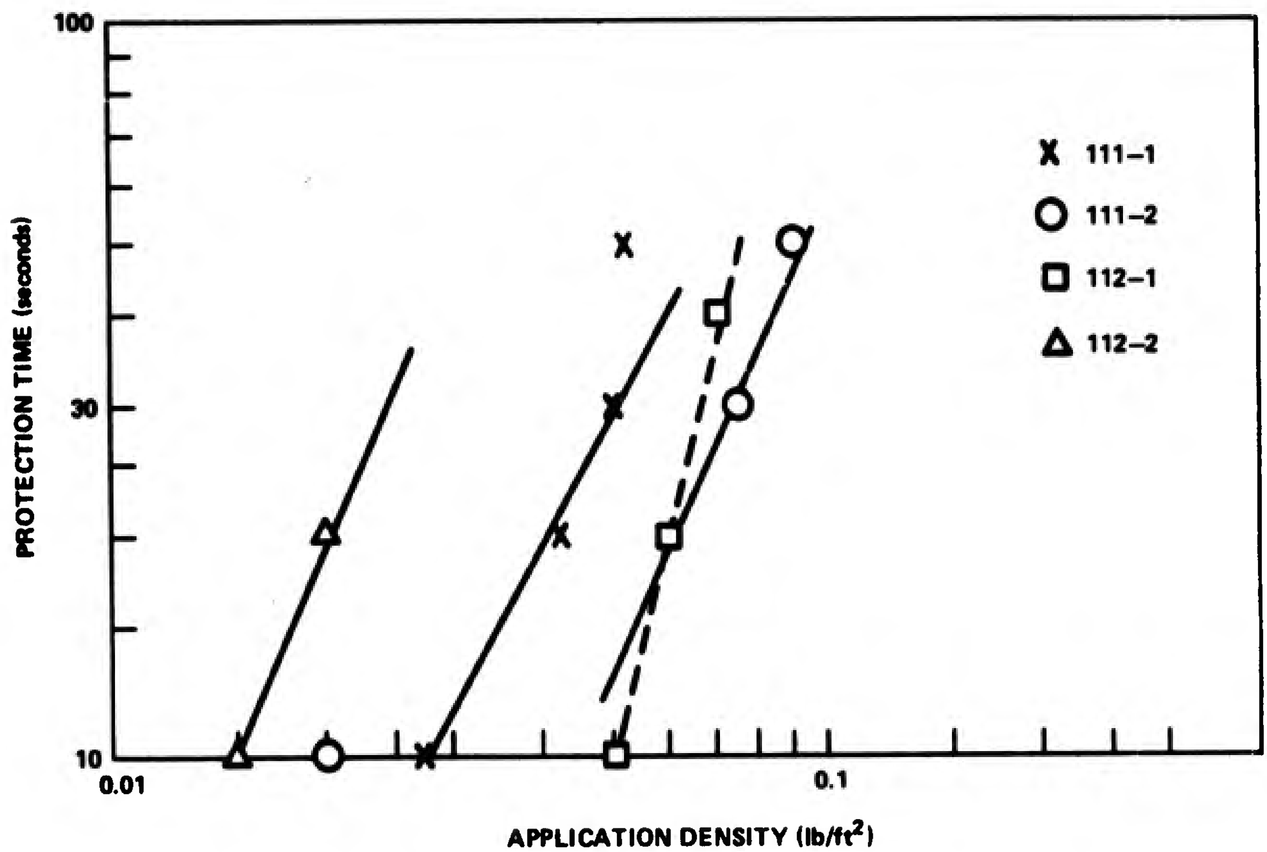


FIG 6.15 PROTECTION TIMES GIVEN BY AFFF

To establish a critical application density by the drive-by technique a series of tests were made both with the MB-1 and "Dromedary" vehicles. When the deposition pattern was fairly uniform and covered the complete fire area, application densities of AFFF as low as 0.62 gal/100 ft^2 successfully extinguished JP5 fires completely. Foam applications in the range of 0.50 gal/100 ft^2 were ineffective because the fire recovered quickly.

A few additional burn-back measurements were made on 10 foot fires using application densities approximately an order of magnitude greater than the critical value. Figure 6.16 shows the swinging gate and dike arrangement that replaced the Guillotine of Figure 6.1 and Table 6.3 tabulates the results. Again the wind direction was the dominant factor controlling the rate of burn-back. Without assistance from the wind burn-back was slowed to the point where the fuel was exhausted before the foam disappeared.

7.0 MODELING, SCALING AND PREDICTIONS

7.1 Fire Characteristics and How They Scale

7.1.1 Burning Rate

Once the radiation thickness for absorption of thermal flux feeding back to the fuel surface is exceeded, the burning rates of hydrocarbon fuels become constant. This occurs when the fire diameter is roughly three feet. Thus, the fuel burning rate of large fires is adequately predicted by the Blinov and Khudiakov relationship shown in Figure 3.1. It has also been confirmed in this program that the flame height/fire diameter ratio is relatively constant for fires with dimensions larger than 3 feet diameter.

7.1.2 Radiation

Thermal flux at distances from D/2 to 2D for JP4 pool fires varying from 40 feet x 100 feet to 200 feet x 240 feet may be predicted within a value of 47% by the regression Equation (3.4) in Section 3 of this report. For JP5 pool fires with dimensions from 3 feet in diameter to 83 feet x 90 feet, the regression Equation (3.5) should be used. Besides the variation of radiation with the dimensionless distance (X/D) it also depends upon the mass burning rate of the fuel (Fm) expressed in lbs/sec. Generally, these equations account for a variable wind velocity and direction within the percentage variations given in this report. Other experimental programs may well develop different predictions for different

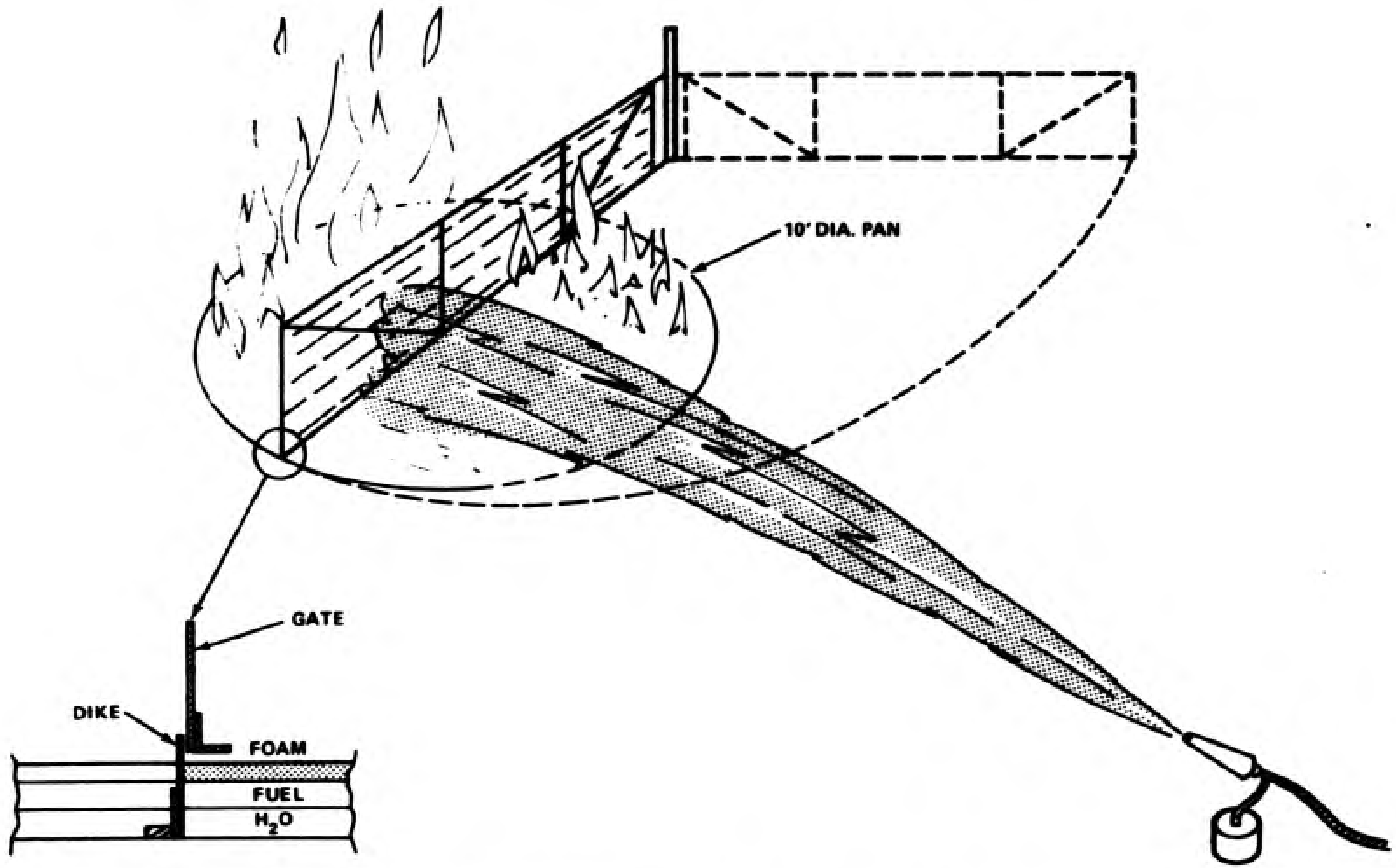


FIG 6.16 SWINGING GATE AND DIKE ARRANGEMENT FOR BURNBACK TEST

Table 6.3

BURN BACK TESTS WITH AFFF ON 10 FT DIAMETER JP5 FIRES
WATER SUBSTRATE

Burn Number	Pump on Time sec	Agent Discharged gal	Approximate Application Density gal/100 ft^2	Wind Tilt Condition ø	Burn Back Time*	Remarks
**193a	13	15	†	3	85 sec	
**193b	12	13.8	†	3	72 sec	
194	4	4.6	5.9	2	∞	Foam leaked through barrier and extinguished the entire fire.
195	6	6.9	8.8	2	∞	Foam leaked through barrier and extinguished the entire fire.
196	5	5.7	9.7	2	>14 min	Fuel exhausted at 14 min. Foam still effective, at 3 min flames started to die down due to lack of fuel.
197	4	4.6	5.9	1 and 2	∞	Extinguished entire fire.
198	3	3.5	5.9	1 and 2	10 min	Flames started to die down at 4-1/2 min due to lack of fuel.

* Measured from time of full recovery of flames on the fire side of barrier.
† Wind blew agent over wide illdefined area.
**Nozzle mounted on dromedary unit ~50 ft from fire, all other tests were made with nozzle hand held on 1-1/2 inch hose line.
ø Wind tilt condition: 1 = Flames blown away from foam
2 = Calm, i.e., flames straight up
3 = Wind tilts flames over foam.

environmental test site conditions. It is our intention to point out that wind variables are of major importance when measuring radiation at given distances from fires.

A major finding of this program is that radiation from larger fires per unit emitting area (as evidenced by flux measurements as a function of X/D) decreases as the mass burning rate increases. This is believed to be caused by a lower combustion efficiency in larger fires causing a higher number of carbon particles per unit volume of fire plume and lower temperatures.

7.2 Prediction of Suppression Requirements

The drive-by technique has been established as a fairly operator independent technique for evaluating the suppression capabilities of various agents in terms of the critical application density. These densities, when measured for particular combinations of fuel and environment, provide a basis for estimating the minimum agent requirements to extinguish similar fires of other sizes. Two factors determine how close this prediction will approach the actual requirements; (1) the losses, i.e., (La) overkill, (Lm) misdirected, (Le) evaporation, and (Lu) updraft defined in Table 2.1 and (2) the difference in fire characteristics between the model or test fire and the actual emergency. Since the losses are primarily a function of application factors, the magnitude and reproducibility will depend on the method of extinguishment. For example with total area application as with the flight deck sprinklers in the CASS tests, the losses should be modest, reproducible, and relatively independent of the fire size. Similarly, overhead sprinklers should exhibit good reproducibility for a specific sized fire but the updraft losses are large and could introduce considerable variation from one fire size to another; e.g., in a series of hangar deck fire simulations with foam sprinklers over a 10 foot fire, about 50% of the agent was lost in the fire plume. This large fraction is expected to increase somewhat in the stronger updrafts from larger fires; therefore a linear extrapolation of agent requirements with fire size appears more reliable for sprinklers in the deck than overhead.

In contrast, the incremental extinguishment technique can achieve minimal updraft and evaporation losses; however all of the losses depend strongly on the operators skill, i.e., a very individual factor. When the capabilities of a given crew have been established, a linear extrapolation to other fire areas should be adequate.

The second factor, i.e., departure of the real fire from the model, particularly when aircraft wreckage introduces flowing or spilling fuels or class A fires in the fuselage, requires information beyond the scope of this study. Existing philosophy in NFPA, FAA, and ICAO introduces auxiliary agents to cope with some of the special situations once the pool fire has been controlled with foam.

8.0 RECOMMENDATIONS FOR IMPROVING EQUIPMENT AND TECHNIQUES

8.1 Goals in Agent Development

In Section 4.2.4 the ideal suppressant was discussed in terms of three factors; (1) efficiency as measured by the critical application density, (2) operational latitude and convenience and (3) cost. The FC-196 and 200 agents used throughout this study deserve a high rating in both categories 1 and 2 for flat horizontal fuel base fires. Agents with comparable efficiency for flowing, spraying, moving, etc., fuel fires in the open are sorely needed. Cost is still a deterrent in the use of AFFF agents for extensive training programs, particularly on large test fires; therefore, research should continue for less expensive molecules with suitable surfactant and high temperature stability characteristics. If necessary a slight sacrifice in performance could be tolerated for training purposes, but the behavior of the agents should be sufficiently similar so that inefficient application techniques will not be encouraged; e.g., the relatively slow turret motion appropriate for pushing a thick layer of protein foam over the fire area is very inefficient when applying AFFF.

Additional stability is always a desirable goal particularly just below the boiling point of water where such stability would enhance burn-back protection. Here the goal is to generate a thicker more impervious vapor barrier when the water evaporates or drains out of the foam, i.e., the concept behind using bubbles like the micro-spheres or cenospheres.

Since an agent that is ideal for all fires does not exist, it would be desirable to have an agent whose characteristics both physical and chemical could be modified during the course of the fire fighting operation to meet the ever changing requirements. Present capabilities permit change in concentration and expansion ratio, although not too conveniently and controllably, and the twin agent nozzle for PKP powder and foam is a first step toward controlling the chemical properties. Other tempting possibilities for future work include control of foam stability, adhesion, and expansion time; e.g., foam with a modest expansion ratio is desired at the impact point to prevent penetration of the fuel, but a low expansion is required for long trajectories. Either timed or triggered expansion agents might be incorporated to supply this control.

8.2 Criteria for Application Equipment

The main criteria for application equipment are (1) adequate application rate and capacity to cope with anticipated fires, (2) safety for the operators, and (3) efficiency. As the aircraft have increased in size and fuel capacity, the fire protection industry has generated larger nozzles, pumps, and trucks to meet the threat of big fires. Our experience with the CAT/Klein, 011B, and other vehicles indicates that the size and capacity of existing turrets already exceed human capabilities for efficient control; i.e., it is impossible to avoid substantial losses of the L_aL_m variety. Typically, application densities required to extinguish test fires are an order of magnitude larger than the critical application density. Obviously, doubling the efficiency should be as effective as doubling the capacity and hopefully the efficiency approach would be more economical. Therefore, the emphatic plea is for more emphasis on efficiency. If better efficiency is to be achieved, we must have nozzles and nozzle controls capable of applying a very uniform layer of foam over the fire bed.

Two general design approaches are available. One involves an appreciable stand-off distance which minimizes the hazard to men and equipment but requires long trajectories with the foam and the attendant control difficulties. The other minimizes the stand-off distance, i.e., the device follows or if necessary, can enter the flames to minimize the foam placement problem at the expense of risk to men and equipment. Existing crash trucks were designed according to the first approach and as nozzle ranges are extended to deal with larger fires, it becomes more difficult to achieve uniform coatings. Several remotely controlled mobile monitors fall in the second category; however, they are still in the developmental stage and their extinguishing efficiencies are not known. Most of these experimental units start out with a single monitor which may well be the hard way to approach uniform coatings. It may be time to turn to the farmers who have had many years experience in applying uniform coatings of various agents to large areas, i.e., multiple nozzles and wind blown sprays look promising for uniformity, particularly if short trajectories are acceptable. In either approach the operator should be able to select the desired application density and have the articulated motion of the nozzle or nozzles be controlled automatically to match the setting. Finally, the well known problem of visibility still remains. The remotely controlled nozzles need not cover the operators' windows with foam.

8.3 Applications Techniques

While waiting for the ideal equipment to evolve, efforts should be made to improve the operating efficiency with existing trucks. Efficiency requires careful attention to the four losses listed in Table 2.1, i.e., over-kill where agent lands in already extinguished areas (L_a), misdirected foam that lands outside the fire bed (L_m), evaporation losses in transit through flames (L_e), and updraft losses where foam is carried away by the fire plume (L_u). Two problems are encountered in minimizing L_a and L_m. First, it is difficult to produce a uniform coating of foam and, second, the application density is seldom preselected on the basis of the characteristics of the fire and environment. Solving both of these problems requires extensive training with the agents and vehicles. As indicated in Section 1.0, questions of economics and pollution generally limit such training so that optimum skills are not developed. A technique nicknamed the "Cold Bed Tests" employed in setting up experimental procedures for Section 5.0 enhanced our ability to reduce L_a and L_m at a modest cost. Foam application was practiced over a simulated fire bed covered with black sheet plastic, equipped with sampling pans to measure the uniformity of foam layer and the density of the coating. After each test, the foam was swept into a sump where the liquid settled out and was pumped back into the fire truck for reuse. After sufficient control had been developed, the foam was ultimately expended in a "hot bed" test, i.e., a regular fire. At a fire fighters training school, a permanent "cold bed" could provide both exercise in the use of equipment and a measure of the trainee's performance. Practice should continue until various specified patterns and application densities could be reproduced upon demand, then when the trainee engages in a "hot bed" test, trained reflexes should enable him to lay down a reasonably uniform coating of the prescribed density.

The drive-by technique illustrated in Figure 6.4 is another approach to minimizing L_a and L_m. Present practice usually involves approaching the fire head on and dispensing the foam from a parked truck. As the flame front recedes, the truck may move to a new position, but the truck motion is not used to control the foam pattern. When adequate room is available, the drive-by technique greatly simplifies the application of uniform coatings; therefore, operators should be instructed in this technique as well as in the conventional operation.

L_u and L_e can be minimized by keeping the foam trajectory through the fire plume as short as possible, i.e., the foam should always be applied at the edge of the fire. This procedure is automatic in the drive-by approach, but often violated in the manual turret operation.

9.0 SUMMARY AND CONCLUSIONS

9.1 Fire Characteristics and Evaluation Parameters

For extinguishment purposes, a two dimensional class B fire is best characterized by the fire size and specific burning rate. The specific burning rate has a strong impact on the suppression efforts required and the total burning rate derived from the specific value and the fire area establishes the radiation field around the fire as shown in Section 3.1. Extrapolations from one fire size to another are simplified by the constant specific burning rate exhibited by fire larger than about three feet in diameter as demonstrated in Figure 3.1.

The critical application density discussed in Sections 4.1.4 and 4.4 is a very useful parameter or yardstick for evaluating extinguishing agents, equipment, and technique. When various types of fire fighting foams are to be compared, the physical and chemical stability at temperatures up to the boiling point of water becomes a very important factor as described in Section 4.1.

9.2 Impact of Experimental Variables

As indicated in Table 2.2, the fuel type and area are the principal factors governing the fire characteristics. Environmental variables such as wind velocity and substrate characteristics can exert moderate to strong effects on the fire characteristics and suppression requirements. For example, it is difficult to generate two identical outdoor fires because of minor fluctuations in these variables. With the exception of the rarely observed gigantic fire whirls, the most severe two-dimensional fires occur with a pool configuration burning under no wind conditions. In the context employed here, severe means largest specific burning rate, flame area, and radiation field. Winds and porous substrates such as rock or sand reduce burning rates and generally simplify suppression when the fire can be approached from the upwind direction; e.g., Section 5.1.2.

9.3 Suppression Principles

AFFF exercises three important mechanisms in extinguishing a class B pool fire; (1) it cools the fuel quickly down to the boiling point of water, (2) it provides a barrier to heat coming from the combustion zone, and (3) it forms a barrier to evaporating fuel. Cooling is essential if barriers are to remain on the fuel surface. In this respect, the principal advantage of AFFF over protein foams stems from superior high temperature stability.

The critical application density originally employed as a yardstick to compare the performance of agents, equipment, and techniques was found to be comparable to the agent required for cooling the fuel.

The two extinguishment models "total area" and "incremental" developed in Section 4.3 provide useful bases for planning suppression tests and presenting test results. The simplified models indicate how the experimental variables are related and how they should be varied for the two modes of extinguishment.

9.4 Suppression Equipment and Techniques

Comparisons of the application densities required by various firemen employing conventional equipment and techniques while extinguishing a "standard" test fire reveal a substantial range of efficiencies. Furthermore, all of the values for application density from a stationary truck were substantially higher than the critical application density indicating that there is considerable room for improving the efficiency of application. The principal problem is to apply a uniform coating of foam over the fire bed. Improvements in nozzles and actuating mechanisms are needed to overcome this difficulty. Ultimately, it would be desirable to lay down a foam layer with the desired density and uniformity on the first pass.

In this report, considerable emphasis has been placed on values of critical application density as yardsticks for evaluating the performance of men and equipment. It is realized that in real emergencies a safety factor will normally be added to provide burn-back protection and to allow for departures from a simple two dimensional fuel bed. We may train firemen to attack a test fire in a certain manner and measure their efficiency; however, their performance under actual crash situations is very dependent upon the crash site, transit time, type of aircraft, weather, and how as individuals they react to personal danger. These factors may increase suppression requirements by orders of magnitude, e.g., our research results show suppression times in the range of 15 to 30 seconds while actual crash fires often take from 15 to 30 minutes.

In the evaluation of human performance, we have shown that the firemen cannot fully utilize the present crash truck fire equipment because of his limitations in response time. With existing high capacity turrets, the reliance on visual feedback as the only basis for controlling the application pattern and density leads to an inefficient use of foam. Two techniques are suggested to enhance efficiency (1) the drive-by technique described in Section 5.0 and the "cold bed" technique for training firemen to apply pre-specified application densities as considered in Section 8.3.

REFERENCES

1.0 Alger, R. S. and Capener, E. L., "Aircraft Ground Fire Suppression and Rescue Systems - Basic Relationships in Military Fires, Phases I and II", AGFSRS Technical Report 72-1, Apr 1972

1.1 Alger, R. S. and Nichols, J. R., "A Mobile Field Laboratory for Fires of Opportunity", NOLTR 73-87, 3 Oct 1973

3.1 Blinov, V. I. and Khudiakov, G. N. (Reviewed by H. C. Hottel), "Certain Laws Governing Diffusion Burning of Liquid", Fire Research Abstracts and Reviews, Vol. 1, p. 41, 1959

3.2 Fu, T. T., "Aviation Fuel Fire Behavior Study", AGFSRS Technical Report 72-2, Feb 1972

3.3 Sliepcevich, C. M., Rein, R. G. and Welker, R. J., "Radiation View Factors for Tilted Cylinders", J. Fire and Flammability, Vol. 1, p. 140, Apr 1970

3.4 Graves, K. W., "Fire Fighter's Exposure Study", AGFSRS Technical Report 71-2, Dec 1970

3.5 Steward, F. R. and Masliyah, J. H., "Radiative Heat Transfer from a Turbulent Diffusion Buoyant Flame with Mixing Controlled Combustion", Combustion and Flame, Vol. 13, Dec 1969

3.6 Steward, F. R., "Prediction of the Height of Turbulent Diffusion Buoyant Flames", Combustion Science and Technology, Vol. 2, p. 203, 1970

3.7 Sliepcevich, C. M. and Welker, J. R., "Bending of Wind-Blown Flames from Liquid Pools", Fire Technology, Vol. 2, p. 127, May 1966

4.1 Moran, H. E., Burnett, J. C. and Leonard, J. T., "Suppression of Fuel Evaporation by Aqueous Films of Fluorochemical Surfactant Solutions", NRL Report 7247, 1 Apr 1971

4.2 Geyer, G. B., "Evaluation of Aircraft Ground Firefighting Agents and Techniques", AGFSRS Technical Report 71-1, Jul 1971

☆U.S.Government Printing Office: 1975 — 657-023/661