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EVALUATION OF AIRCRAFT GROUND FIREFIGHTING AGENTS AND TECHNIQUES

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TRI-SERVICE SYSTEM PROGRAM OFFICE
FOR AIRCRAFT GROUND FIRE SUPPRESSION AND
RESCUE, SMF
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Final Technical Report, Project 1598
(Period: August 1967 - July 1971)

Prepared by
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Final Technical Report
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for Aircraft Ground Fire Suppression and Rescue, SMF
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FORWARD

This final technical report describes the results of an analysis concerning aircraft ground crash firefighting extinguishants and equipment. The program was a joint effort by the Tri-Service System Program Office for Aircraft Ground Fire Suppression and Rescue (AGFSRS), Wright Patterson Air Force Base (WPAFB), Ohio, and the Systems Research and Development Service (SRDS), Federal Aviation Administration (FAA), Washington, D.C.

The program was conducted under WPAFB Contract No. F33657-67-F-1538 (Project No. 1598 and System 414N) and FAA Project No. 450-701-10X.

Messrs, Charles V. Bailey and Herman D'Aulerio were project monitors for AGFSRS and SRDS, respectively.

The program was carried out by the Propulsion Section, Aircraft Branch, Test and Evaluation Division, National Aviation Facilities Experimental Center, Atlantic City, N. J. under Project No. 910-003-19X during the period of August 1967 through July 1971.

PUBLICATION REVIEW

This document was submitted by the author in March 1972. It is published to reflect the data obtained by the author from a literature survey and from laboratory and full-scale experiments. This report has been reviewed and approved to the extent that the findings and conclusions are supported by the available data as published in the report.

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ABSTRACT

An analysis of aircraft crash fire fighting systems was made through a survey of known and newly developed agents, both blanketing and auxiliary, and of dispensing equipment. Laboratory studies were conducted to ascertain the most acceptable agents and equipment for use in performing full-scale fire fighting tests. Experiments were performed principally upon those agents which were manufactured in conformance with a Federal or Military specification or were listed and approved by a recognized testing laboratory. Full advantage was taken to avoid duplication of effort by accepting all published data which was considered reliable by reason of its source. Large-scale fire tests were conducted only with those agents considered worthy of additional testing. Full-scale tactical fire fighting experiments were performed with medium size aircraft (B-47 Stratojet Bombers) to determine the effectiveness of each fire fighting agent and the validity of the techniques and agent application rates employed.

CONTENTS

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Continued)

Section Page

APPENDICES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

I. INTRODUCTION

Purpose

The project objective was to study and test both current and new agents, equipment, and techniques to produce the most effective aircraft ground firefighting and rescue capabilities.

Background

The development of larger military and commercial aircraft has emphasized the need for improved post-crash firefighting capabilities to effectively control the fire hazards associated with an increase in the quantity of fuel on board. The technology of fire suppression and extinguishment must therefore advance equally to meet the problems of these increasing hazards. This required a program to investigate current and newly developed firefighting agents and application techniques, in an effort to determine those which best meet current and future demands.

An extensive body of firefighting literature encompassing many different foam agents and dispensing systems has been developed over the past several decades (Reference 1), but the most dramatic advances to increase the scope of firefighting technology have been made within the last 5 to 6 years.

Recent efforts directed toward developing a better understanding of the aircraft fire environment were undertaken by the Federal Aviation Administration (FAA) at the National Aviation Facilities Experimental Center (NAFEC) (Reference 2). Full-scale fire tests were conducted on a Boeing C-97 aircraft which yielded information on the time available for passengers to escape or survive an aircraft crash fire. The values obtained were influenced by the type of fire condition employed in terms of the continued spilling and spread of fuel and fire subsequent to ignition of small pre-wetted areas. In another project (Reference 3), full-scale tests were performed under fixed fire conditions employing air-aspirating foam nozzles and dry chemical powder dispensing equipment, in which six different foam agents and three different dry chemical powders were evaluated, both alone and in combination. The time required to control circular pool fires of 40, 60, and 80 feet in diameter, containing an obstacle and a three-dimensional fire, was determined. Other project work was performed (Reference 4) in which a mathematical model was formulated which permits a calculation to be made of the time required for damage to occur to the aluminum skin covering an aircraft fuselage when it is exposed to maximum spill fire conditions. From a knowledge of the fire damage time to an aluminum fuselage, which is closely related to the survival or escape time available to the aircraft occupants, an estimate can be made of the fire fighting equipment, in terms of the discharge rates and quantities of agents required, to prosecute a successful rescue mission.

To determine the availability of established and newly developed firefighting agents, a survey was made which, through manufacturers' claims and other knowledgeable sources, showed promise as improvements over those currently employed for the control and extinguishment of fires such as those associated with aircraft crash and ground operations. The agents considered were foam blanketing and auxiliary (complementary) agents. The names of the manufacturers or distributors of these products are summarized in Appendix A.

To develop the most meaningful tests and evaluation, it was considered essential to establish the mechanism whereby each agent is capable of achieving fire control and extinguishment of hydrocarbon fuel fires. To this end the agents selected for evaluation were categorized in two major groups, depending upon their principal function in the extinguishment of Class B fires (reference 5) these are: foam vapor-securing and blanketing agents and auxiliary firefighting agents.

II. LABORATORY EXPERIMENTS AND SMALL-SCALE FIRE TESTS

Foam Vapor Securing and Blanketing Agents

General:

The project effort was programmed in a manner which permitted the elimination of unacceptable agents prior to conducting full-scale fire tests. This was accomplished by an analysis of the dispensing system and the agent's properties, by reviewing reports and manufacturers' specifications for the agent, and by conducting relatively small-scale laboratory-type experiments which had a direct bearing upon the agent's end performance capabilities.

There are two types of foam vapor securing and blanketing agents available for use; these are (1) chemical foam, in which the bubbles are filled with carbon dioxide gas produced by the chemical reaction between the bicarbonate ion and the hydrogen ion in the presence of a foam stabilizer, and (2) mechanical foam, in which bubbles are filled by mechanically entrained air in a dilute solution of a foam stabilizing agent. Chemical foam has found only limited use in combating large aircraft fires, mainly because of the mechanical and logistic problems involved, such as those associated with the storage and handling of large quantities of chemicals and premixed solution. Therefore, this agent was not evaluated in the laboratory study. However, comparative large-scale fire tests were performed with chemical and protein foams on water base and traprock base JP-4 fuel fires with diameters of 50.5, 72.75, and 103 ft. The results of these experiments are presented under Section IV of this report.

Mechanical foam is the most widely employed agent in post-crash aircraft rescue work and the various types were considered in detail.

The protein base and synthetic detergent (syndet) type mechanical foam agents develop their firefighting properties when employed on Class B fires through the formation of a vapor-securing blanket of foam which floats on the surface of the fuel and excludes oxygen from the fire environment. The thermal decomposition of the aqueous foam also produces a significant quantity of steam, under certain conditions, which aids in the progressive control of the fire during extinguishment by reducing the oxygen supply available for combustion as well as by cooling the fuel.

Discussion:

Protein Foam Agents -

A. Type 6-Percent Protein Agents - The 6-percent type agent is in general use by the Federal Government and is procured under a federal specification (Reference 6). There are, at present, four different manufacturers producing liquids, in conformance with the federal specification, that are listed on the Qualified Products List (QPL).

The protein-base agents are considered to be of the low-expansion type, with foam expansion ratios from 8:1 to 15:1, depending upon the type of equipment employed for their production. With air-aspirating foam nozzles, expansion from 8:1 to 10:1 may be obtained with 25-percent drainage times ranging from 4 to 5 minutes. When the foam-pump system is employed, foam expansion ratios may be varied over a wide range, but in practice they are usually limited from 10:1 to 15:1 with drainage times of 20 to 30 minutes.

The 6-percent protein agent is the most widely used and its firefighting performance under various fire conditions was used as a basis for comparison of the newer agents such as the aqueous film forming foam (AFFF) developed by the U.S. Naval Research Laboratory (NRL) (Reference 7) and the fluoroprotein agents developed by the U.S. Naval Applied Science Laboratory (NASL) (Reference 8) with the participation of industry.

B. Type 3-Percent Protein Agents - The 3-percent agent is of the low expansion type and is recommended for use in air aspirating and other equipment for proportioning at a concentration of 3-percent by volume. At present, there is no federal or military specification for procuring this agent because of its failure to meet all of the fire test requirements similar to those established for the 6-percent agent.

The 3-percent agents are, however, recognized by the National Fire Protection Association (NFPA) (Reference 9), and they are listed for commercial use by Underwriters' Laboratories, Inc. (UL) (Reference 10). Most of the commercial production of 3-percent protein liquid is consumed by industry in the protection of hydrocarbon fuel storage tanks and related applications.

The definitive 3-percent and 6-percent protein foam liquid concentrates employed in the United States are not in common use on a world-wide basis.

Fluoroprotein Foam Agents -

A. Type 6-Percent Fluoroprotein Agents - The fluoroprotein foam liquid concentrates were developed by the Department of the Navy and industry specifically to achieve an acceptable degree of compatibility between a protein-type foam conforming to the requirements of federal specification (Reference 6) and Purple-K powder (PKP) (Reference 11). This effort, therefore, recognized the basic incompatibility between the current 6-percent protein foam and PKP. As a result of this effort a protein-type agent was developed which demonstrated a greatly improved compatibility with PKP (Reference 8).

At present there are three manufacturers of fluoroprotein liquids in the United States and one in Canada. The 6-percent agents demonstrate complete conformance with the requirements of federal specification (Reference 6) and, in addition, display a high order of compatibility with PKP when evaluated in accordance with tests developed by NASL in Reference 8.

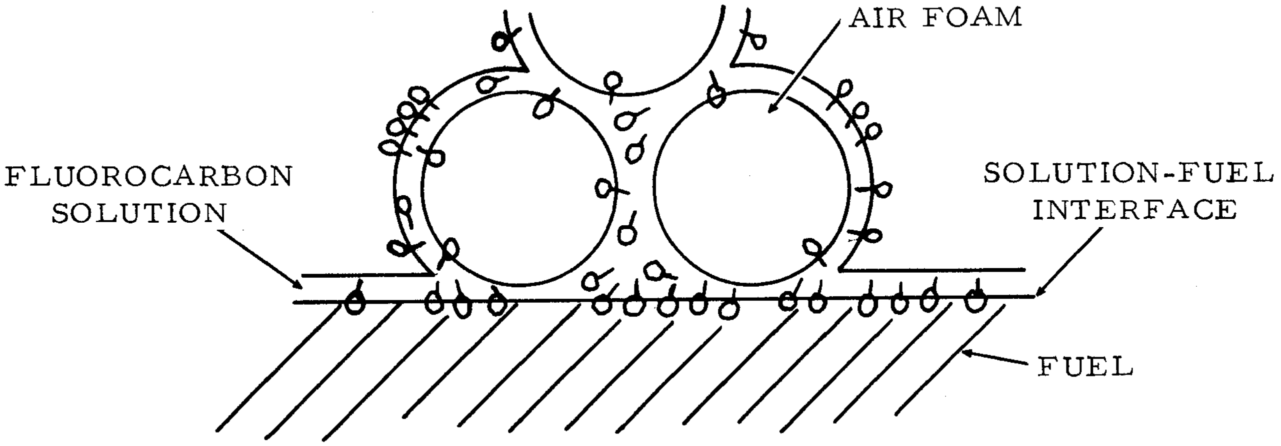
However, only marginal compatibility with PKP was demonstrated when some of these agents were evaluated in accordance with fire test requirements of the UL (Reference 12). One interpretation for this lack of correlation between the two test methods is attributed to different methods of foam application which was substantiated by the results of this investigation.

From the standpoint of chemical composition, the only difference between the fluoroprotein agents and those approved under the federal specification (Reference 6) is the presence of a relatively small quantity, generally less than 1-percent by weight, of a perfluorinated surfactant(s). The fluorocarbons convey powder compatibility to the protein foam through a physical rather than a chemical property. The fluorocarbon molecule is functionally double ended (bifunctional), i.e., one end is hydrophilic (water loving) and the other is hydrophobic and oleophobic (water and oil hating). The empirical formula for an effective fluorocarbon compound which may be employed to fortify regular protein base foam is represented by $(X)[(CF_2)_7CF_3]$ where the (X) moiety is hydrophilic but with limited or controlled solubility, while the fluorocarbon moiety $(CF_2)_7CF_3$ is both water and oil repelling with very low aqueous solubility.

The manner in which the fluorocarbons protect the protein foam from destruction by dry chemical powder is presented in Figure 1, and may be visualized by considering the way in which a drop of hydrocarbon fuel, such as JP-4 or gasoline, spontaneously spreads when placed on the surface of water. This same spreading phenomenon may be considered to occur when an aqueous protein-base foam is placed on the surface of a hydrocarbon fuel. That is, a very thin film of fuel, probably monomolecular in thickness, "climbs" or spreads up and across the foam surface. This hydrocarbon film in itself is not destructive to the foam; however, when PKP (or stearated powders) are present in the system, a synergistic foam-destructive mechanism is established between the powder and the fuel which causes a very rapid and progressive destruction of the foam body. When a fluorocarbon is present in the foamed solution, the surface tension of the aqueous phase is lowered from approximately 45 dynes per cm to approximately 34 dynes per cm, in some formulations, and the fluorocarbon molecules are oriented in the foam wall in such a way that the fluorocarbon end is extended outward and forms an oleophobic or oil-repelling barrier at the interface between the foam and fuel. This interpretation of the phenomena implies that the hydrocarbon film is no longer able to spread over the surface, and therefore, the fuel parameter is excluded from the foam-destructive mechanism involving PKP, fuel, and foam. This system is dynamic, however, and only a few seconds are required to establish the optimum foam-fuel interfacial equilibrium condition.

From these considerations it is evident why foam-powder compatibility shows a different order of magnitude depending upon the test method employed. When foam-powder compatibility is determined in accordance with the UL method, a very turbulent condition is developed by the plunging foam stream, so that it is physically impossible for the protective fluorocarbon film to be fully established and to reach equilibrium conditions at the foam-fuel interface, which may result in obtaining only marginal compatibility.

Therefore, it is evident from a consideration of the fluorocarbon function in these new protein-base agents that gentle application is necessary when they are employed with PKP. Every precaution should be exercised to reduce turbulence to an absolute minimum to allow maximum time for the protective film to be fully developed at the foam-fuel interface



FLUOROCARBON MOLECULES ORIENTATING AT THE SOLUTION-FUEL INTERFACE

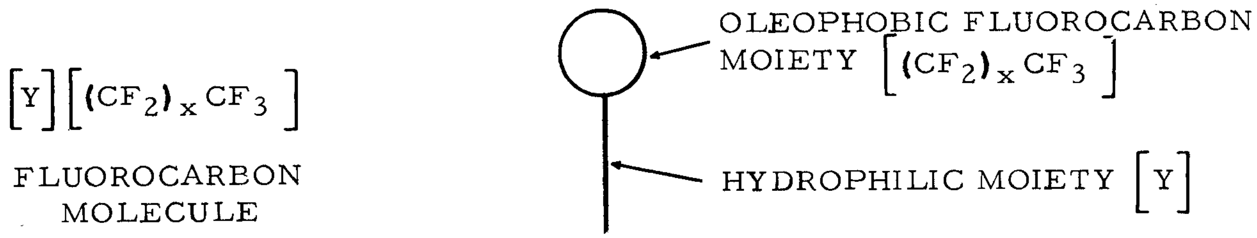


FIGURE 1 - HYPOTHETICAL ACTIVITY OF CERTAIN FLUOROCARBON MOLECULES USED IN COMBINATION WITH PROTEIN HYDROLYZATES

The work performed by the NASL which led to the development of a protein foam compatible with PKP did not result in a government specification. However, in recognition of the fact that some minimum degree of protein foam and PKP compatibility was necessary, a test was developed and included in the federal specification (Reference 13) which was representative of the average foam-powder compatibility demonstrated by the protein foams then current on the QPL.

Although this test defines a degree of compatibility between protein foams conforming to the federal specification and PKP, it has been demonstrated that these two agents are not compatible in aircraft ground firefighting (Reference 3).

B. Type 3-Percent Fluoroprotein Agents - There were only two 3-percent fluoroprotein-type agents available during the time the agent selection survey was being conducted. The basic chemical composition of the protein portion of the 3-percent agent is essentially identical with that of the 6-percent type, and the fluorocarbon surfactants employed as fortifying agents are either identical with or similar to those employed with the 6-percent type. Therefore, the theoretical aspects concerning their compatibility with PKP are similar.

The recent advances made in the protection of large fuel storage tanks by means of the subsurface application of protein-base foam were made practicable through the use of the fluoroprotein agents.

Synthetic Foam Agents - The syndet foam agents are sometimes referred to as high-expansion foams, because expansion ratios of the order of 15:1 to 20:1 are readily obtainable with the ordinary air-aspirating equipment employed with the low-expansion protein agents. These mechanical foams were among the first firefighting agents to be developed for the control and extinguishment of hydrocarbon fires (Reference 1). However, their use was limited after the development of the protein agents because of poor radiant heat stability and relatively short 25-percent solution drainage time. Syndet foams have good fluidity and are capable of very rapid flame knockdown, and gain rapid control of hydrocarbon fires at low to moderate solution application densities. The chemical composition of the syndet foam liquids is very similar, and in some cases, identical with those employed in the recently developed high expansion foam-making equipment.

High-Expansion Synthetic Foam Agents - High-expansion synthetic foam, sometimes referred to as ultra-high expansion foam, is produced in specialized equipment by driving a high volume airstream, by means of a fan, through a metal or cloth grid which is continually sprayed with a syndet foam solution at a predetermined rate and concentration. Two types of units are recognized, depending upon the method employed to drive the fan, namely, the electrical and the hydraulically powered units. The hydraulic units may be further classified with regard to the type of hydraulic power employed; i.e., the reaction motor and the turbine-powered types. The systems are equally efficient, and they eliminate the hazards which may be associated with the electrical units. Other mechanical means employing different techniques are also being developed commercially for the production of high expansion foams. Some current hand-portable units have no moving mechanical parts and produce foams with expansion ratios from 100:1 to 200:1.

Recent large-scale fire tests, conducted with high-expansion foam, have shown that the optimum expansion ratios for this type of foam may vary from 500:1 to 800:1 for the large units, depending upon the type and chemical composition of the syndet and foam stablizer system employed in its manufacture. The firefighting effectiveness of high-expansion foam is dependent upon achieving the optimum balance between the foam expansion ratio, foam stability and fluidity. A detailed discussion of these interrelated properties is contained in Reference 14.

High-expansion foam was not evaluated in high-capacity equipment as a primary firefighting agent for use in aircraft accidents involving fire during this program. Previous large-scale tests performed with high-expansion foam at NAFEC are reported in Reference 3. In these experiments, foam was dispensed at variable solution discharge rates from 100 to 500 gpm on 60-ft-diameter JP-4 fuel fires. The results of these experiments indicated that high-expansion foam is capable of obtaining progressive and effective control and extinguishment of JP-4 fuel fires at solution application rates from 0.04 to 0.10 gpm per sq ft. However, the vulnerability of this type of foam to disruption by wind in exposed outdoor conditions, and its limited vapor securing characteristics restrict its use as a primary firefighting agent.

One hand-portable high-expansion generator demonstrated at NAFEC was capable of producing foam with a variable expansion ratio of 5:1 to 100:1 and a corresponding foam discharge range from 60 to 15 ft.

The equipment was a composite unit comprising a variable water-fog nozzle which was mounted, by means of an adapter, into the high-expansion foammaker. The foammaker was constructed of two concentric sheet metal cylinders with an overall length of 38 in. and an overall width of 19 in.. A conical cloth grid with a hole in its apex was mounted over the inner cylinder. The completely assembled unit weighed 20.5 lbs and had a solution discharge rate of 100 gpm at 100 psi.

Foam was produced by discharging a proportioned foam solution from the water spray nozzle through the cloth grid. The functioning of the unit was novel in that foam with an expansion ratio of 5:1 could be discharged for 60 ft, when the straight stream was projected through the hole in the conical grid. As the solution spray angle was increased from straight stream to 30°, the range was reduced to 15 ft and the foam expansion ratio increased to 100:1. These variations could be accomplished by manually changing the solution spray angle during discharge.

Two experiments were performed with this unit; the first employed a hydrocarbon-syndet foam agent, and the second an AFFF agent. The foam solutions were made by proportioning the foam liquid concentrate into a 1.5-in.-diameter hose line, by means of a by-pass eductor, before delivery to the nozzle. The hydrocarbon-syndet was proportioned to yield a solution concentration of 2 percent by volume, in accordance with the manufacturer's recommendation, and the AFFF agent was proportioned at a concentration of 6 percent by volume.

The demonstrations were performed by charging a 30-ft-diameter pit with 250 gal of JP-4 fuel and applying foam at a solution rate of 0.142 gpm per sq ft. During the fire extinguishing process, the manufacturer's operator adjusted the foam discharge range and expansion ratio as required to obtain the most rapid fire control and extinguishment times.

The fire control time for the first experiment using the hydrocarbon-syndet at an estimated foam expansion ratio of 100:1 was 70 sec, and for the second experiment employing AFFF, with an estimated foam expansion ratio of 80:1, it was 50 sec.

The results of these demonstrations indicate that AFFF was more rapid than the hydrocarbon-syndet foam in obtaining fire control, but it was estimated to have only one third the burnback resistance of the hydrocarbon-syndet foam. The rapid burnback of the AFFF when compared with the hydrocarbon-syndet foam was attributed, in part, to its apparent shorter 25-percent-solution drainage time at an expansion ratio of 80:1. The demonstration employing AFFF was of particular interest in that it was the first time AFFF had been employed in a high-expansion-foam generator on a large outdoor JP-4 pool fire. The fact that AFFF can be dispensed with high-expansion type equipment and used successfully in the control and extinguishment of a large pool fire, suggests its use as a 3-dimensional auxiliary-type foam agent for aircraft cabin fires when AFFF is carried on board foam-water trucks equipped with water dispensing handlines.

High-expansion foam has displayed spectacular fire-extinguishing performance under certain fire test conditions (Reference 3), but its general outdoor use under adverse climatic conditions will require further study before reliable recommendations for its use can be established.

Aqueous Film Forming Foam - The development of the AFFF agents which are currently being employed in fire-fighting technology stems indirectly from the academic and technical advances in the field of organic fluorine chemistry made by J. H. Simons (Reference 15), R. A. Guenther, and M. L. Vietor (Reference 16), and others. The unique physical and chemical properties of the perfluorocarboxylic and perfluorosulfonic acid derivatives in suppressing the vaporization of hydrocarbon liquids were known and investigated. However, little was accomplished in the field of firefighting with the aqueous foams produced by these agents prior to the NRL effort (Reference 7). Based upon the results of the NRL work, a U.S. Patent claim was filed September 4, 1963, and a patent granted on June 28, 1966, which was assigned to the United States of America (Reference 17). Shortly after the U.S. Patent application was filed, teaching the use of perfluorinated hydrocarbons in 1963, several military specifications were issued defining the performance of different formulations of AFFF (References 18, 19, and 20).

Prior to November 21, 1969, the term "Light Water" was used in the title of the military specifications defining the requirements of the perfluorinated surfactant agents. However, since "Light Water" had become associated with a particular brand of surfactant firefighting agent, a proposal was made to devise a generic term for this class of agents at an NFPA subcommittee meeting. The term aqueous-film-forming-foam was proposed and later accepted.

The following theoretical discussion of the probable functioning of the AFFF agents is presented so that a more meaningful interpretation of the fire extinguishing mechanism can be made from the results of the practical fire tests. It was noted in the discussion of the fluoroprotein agents that certain bifunctional fluorocarbon molecules were capable of protecting a protein-base foam from destruction by PKP through the development of an oleophobic film at the interface between the hydrocarbon fuel and the foam structure which nullified the effect of the fuel parameter in the system. It was also indicated that the surface tension of the 6-percent fluoroprotein foam solution was reduced approximately 10 dynes per cm. Although this is significant and critical, it is considerably less than that required to enable an aqueous solution to spread spontaneously on a hydrocarbon fuel. However, some solutions which drain from an AFFF may actually have a surface tension lower than that of the fuel, and therefore be capable of spontaneously spreading and floating upon the hydrocarbon fuel surface, thereby suppressing the vaporization rate of the hydrocarbon below its combustible limit in air. The term "Light Water" which appeared in the title of some of the earlier military specifications was coined in recognition of this phenomenon, in which a more dense liquid is capable of floating on a less dense liquid as a result of its oleophobic property and low surface tension.

According to theory (Reference 21) concerning the spontaneous spreading of insoluble films on liquids, the following equation maintains:

$$\text{S. C.} = \gamma_o - (\gamma_w + \gamma_i)$$

where

S. C. = spreading coefficient of the aqueous fluorocarbon solution

γ_o = surface tension of the fuel

γ_w = surface tension of the aqueous fluorocarbon solution

γ_i = interfacial tension between fuel and the aqueous fluorocarbon solution

If the spreading coefficient has a value greater than zero (i.e., positive), the aqueous phase can spread spontaneously upon or "wet" the fuel. A coefficient below zero (i.e., negative) indicates that it cannot spread spontaneously. When the spreading coefficient is zero, the liquids are miscible.

Several qualitative experiments were performed to estimate the effect of environmental changes, such as temperature on a system comprising an aqueous fluorocarbon film floating on JP-4 fuel. In general the effect of heat on a liquid solution is to cause a reduction in the surface tension. The rate at which the surface tension is lowered over a given temperature range is a physical function of that particular liquid or solution. Hydrocarbon fuels show a somewhat more rapid reduction in the surface tension with increasing temperature than do aqueous solutions. This implies that an aqueous film which has a sufficiently low surface tension to float upon a hydrocarbon liquid at one particular temperature, may be completely dissipated as the temperature of the system is raised. This inversion in the surface tension values, if they did occur, could result in gross lensing of the aqueous phase and its subsequent removal from the hydrocarbon surface by gravity. A system in which the vapor sealing barrier was lost due to a rise in the temperature of the system was found to reestablish an effective vapor seal upon returning to its original temperature. Although laboratory experiments of this type were useful and informative in exploring certain unique physical characteristics of some of the perfluorinated surfactants, no examples of a loss in vapor sealability have ever been observed during extensive large scale fire tests which could be attributed directly to this phenomenon.

Another method employed for studying the vapor suppressing effect of the different perfluorinated surfactants was to dissolve small known quantities of the pure fluorocarbon in the fuel and pass a lighted torch over the surface. When these systems were at ambient room temperatures, the fuel could not be ignited; but as the temperature was slowly raised, a temperature was reached at which ignition did occur. This temperature was found to be a rough measure of the vapor-suppressing effect of the particular fluorocarbon or combination of fluorocarbons being investigated.

As a result of the unique property of AFFF to produce an aqueous film on the surface of hydrocarbon liquids, a phenomenon known as secondary foam development may occur with certain of the more volatile hydrocarbon fuels. The secondary foam is composed of a multitude of fuel-vapor filled bubbles caused by the normal vaporization of the fuel under the aqueous film.

The mechanism whereby this secondary foam is produced is diagramatically shown in Figure 2. The actual development of secondary foam in the laboratory is shown pictorially in Figure 3 using aviation gasoline as the fuel.

In Figure 2(a), the initial phase of secondary foam development is depicted. This sketch corresponds in general with Figure 3(a) in which the aqueous film has just spread across the fuel surface.

Figure 2(b) shows the fuel vapor starting to lift the aqueous film from the surface of the fuel. This phase of foam development is presented in Figure 3(b).

Figure 2(c) shows the fuel vapor filled bubbles continuing to grow in size. This phase of foam development roughly approximates that shown in Figure 3(c).

Figure 2(d) shows a fully developed fuel-vapor filled bubble with additional bubbles forming. This phase of foam growth is presented in Figure 3(d).

This phenomenon was recognized and reported in a Military Specification dated March 1965 (Reference 17). In this document, the fuel vapor sealability is tested after 30 minutes by probing the vapor-filled bubbles on the fuel surface with a lighted torch which is required to show only a flash ignition. In this test, the fuel is cyclohexane (practical, B.P. 172° to 178°F).

Secondary foam development was observed to occur on all tests performed with JP-4 aviation fuel. The actual rate of growth was dependent upon the formulation of the AFFF and the test conditions. Photographs showing typical "trails" left by the burned fuel-vapor-filled foam are shown in Figure 4(a), (b), and (c). In these tests, where the AFFF completely covered the surface of the fuel, no permanent ignition of the fuel substrate has ever occurred. However, under moderate ambient wind conditions, the foam blanket may be blown from the fuel together with the aqueous film; this

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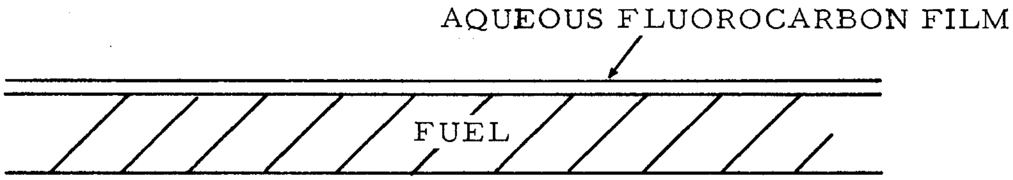
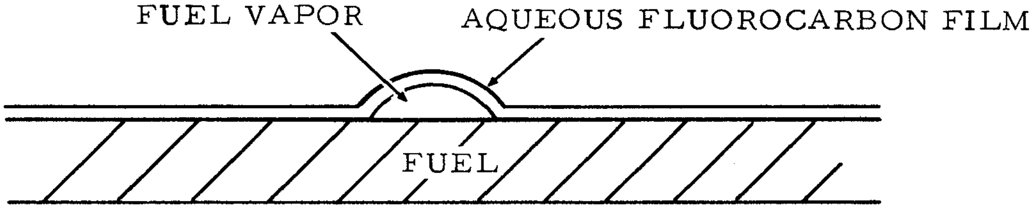
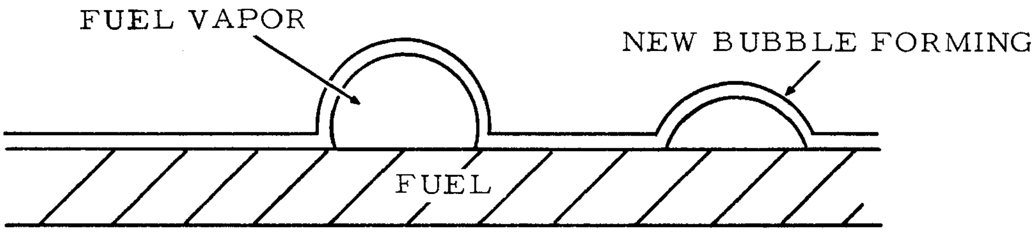
Secondary foam development was observed to occur on all tests performed with JP-4 aviation fuel. The actual rate of growth was dependent upon the formulation of the AFFF and the test conditions. Photographs showing typical "trails" left by the burned fuel-vapor-filled foam are shown in Figure 4(a), (b), and (c). In these tests, where the AFFF completely covered the surface of the fuel, no permanent ignition of the fuel substrate has ever occurred. However, under moderate ambient wind conditions, the foam blanket may be blown from the fuel together with the aqueous film; this



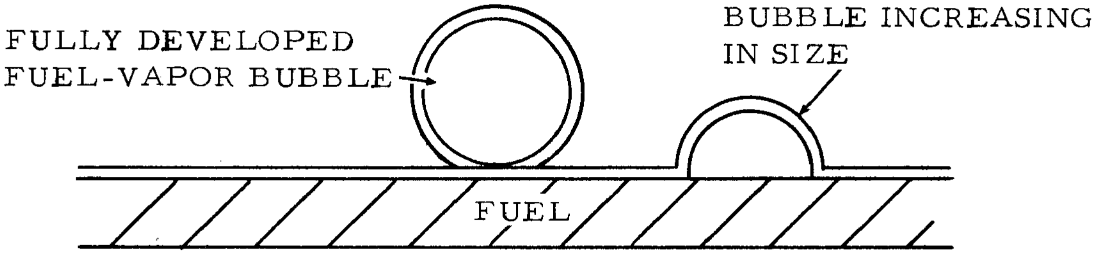
(a) AQUEOUS FLUOROCARBON FILM FLOATING ON A HYDROCARBON FUEL



(b) INCIPIENT STAGE OF FUEL VAPOR BUBBLE FORMATION

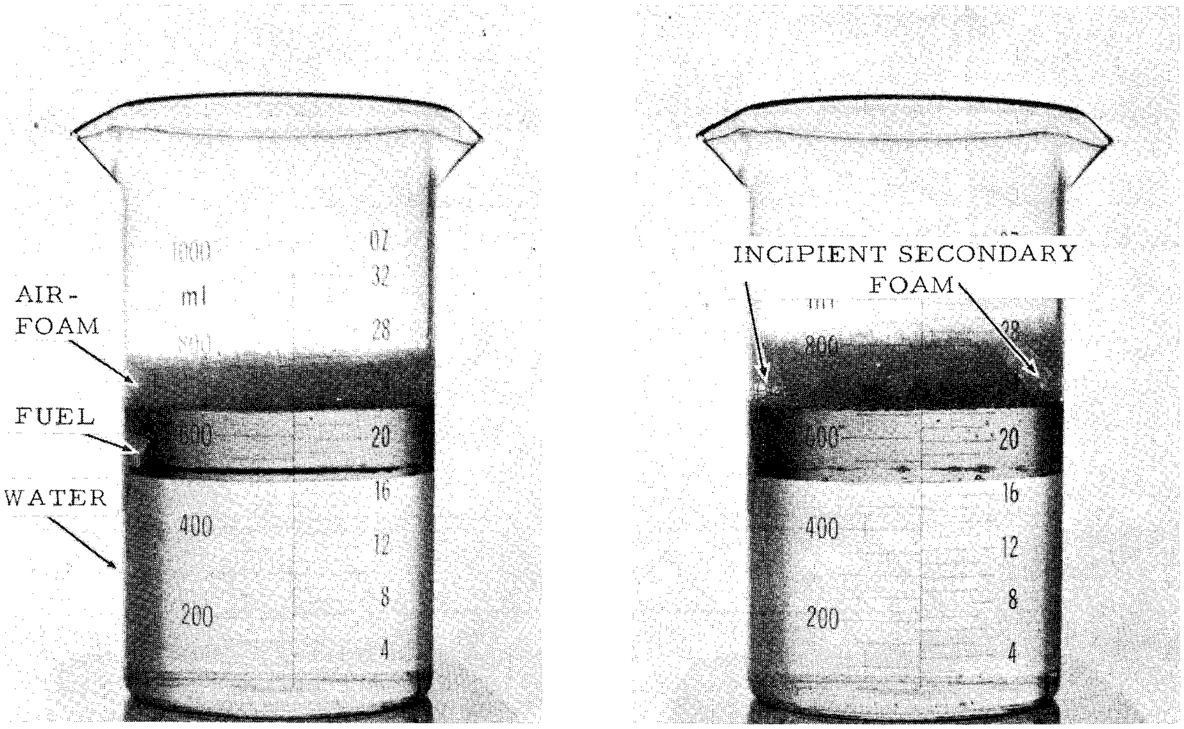


(c) FUEL VAPOR FILLED BUBBLE CONTINUES TO GROW WHILE NEW BUBBLE IS FORMING

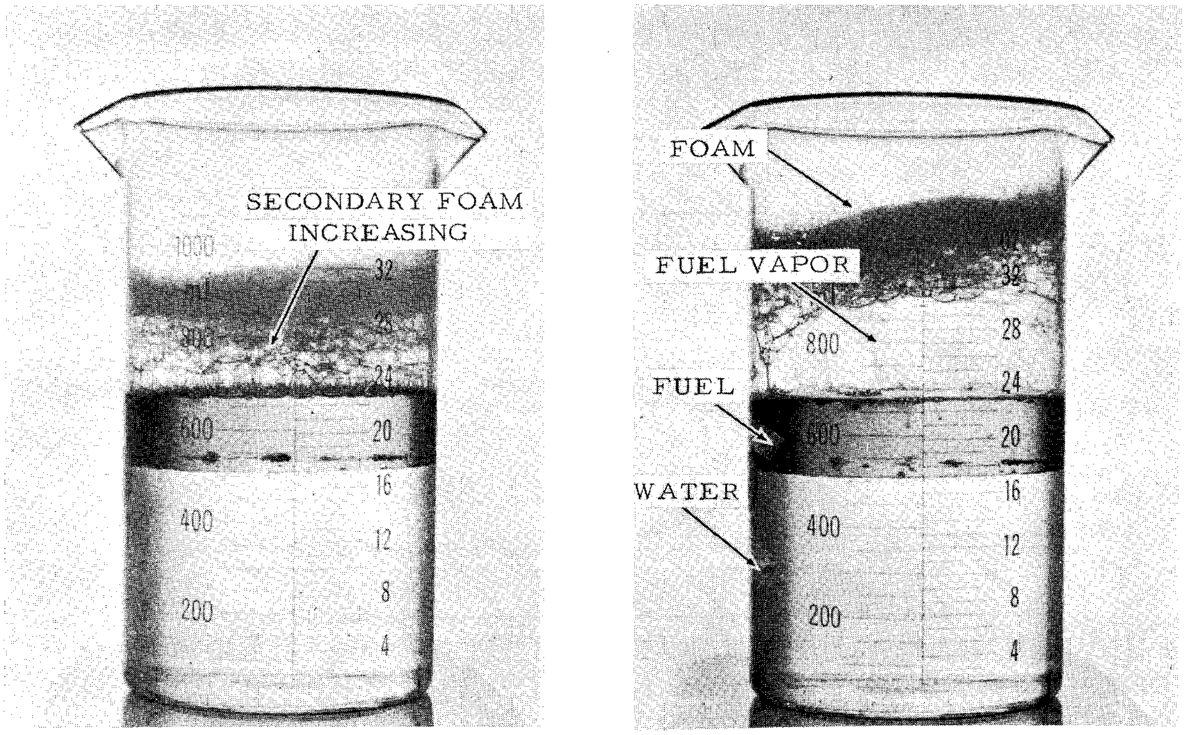


(d) FULLY DEVELOPED FUEL VAPOR FILLED BUBBLE ABOUT TO BE DETACHED FROM THE FUEL SURFACE WHILE NEW BUBBLE CONTINUES TO GROW

FIGURE 2 - MECHANISM OF SECONDARY FOAM DEVELOPMENT



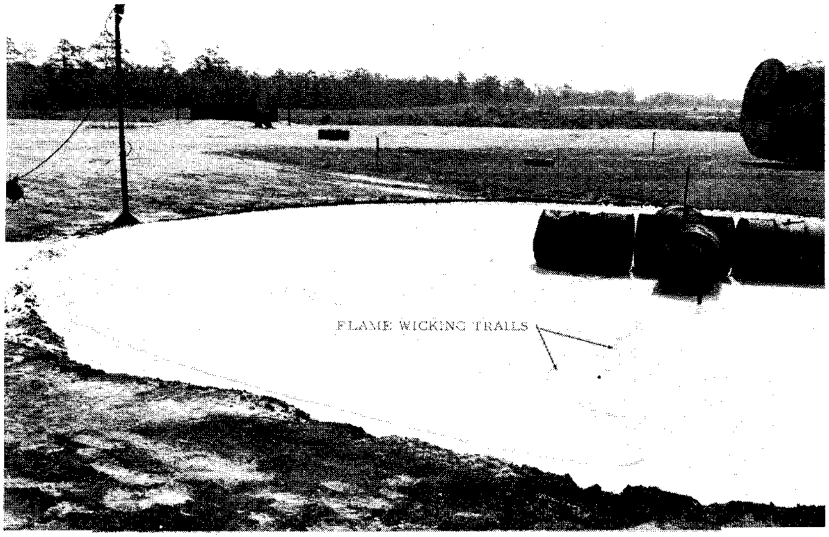
(a) AFFF FLOATING ON FUEL SURFACE (b) SECONDARY FOAM STARTING TO FORM



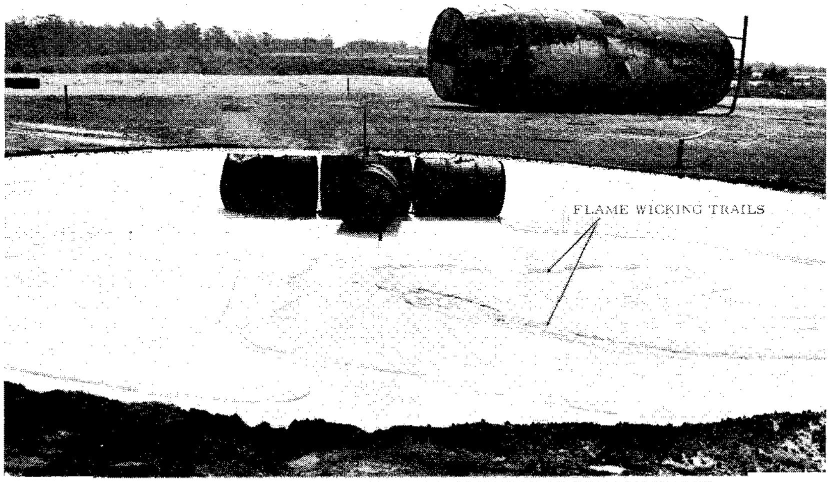
(c) SECONDARY FOAM INCREASING IN VOLUME

(d) VAPOR FILLED SPACE BENEATH FOAM

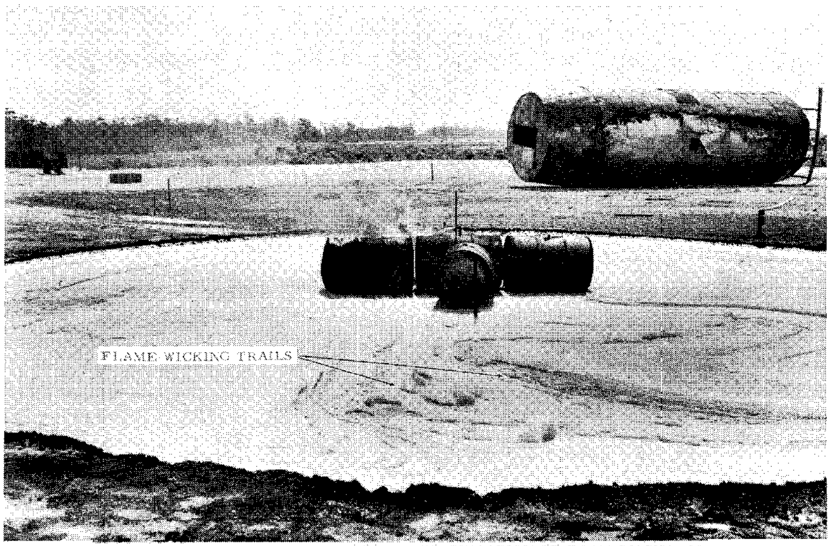
FIGURE 3 - A LABORATORY EXPERIMENT SHOWING THE DEVELOPMENT AND GROWTH OF A SECONDARY FUEL-VAPOR FOAM



(a) TRAILS FORMED 3 MINUTES AFTER THE CESSATION OF FOAM DISCHARGE



(b) TRAILS FORMED 5 MINUTES AFTER THE CESSATION OF FOAM DISCHARGE



(c) TRAILS FORMED 7 MINUTES AFTER THE CESSATION OF FOAM DISCHARGE

FIGURE 4 - TYPICAL "TRAILS" LEFT BY THE BURNED SECONDARY FUEL-VAPOR FILLED FOAM CAUSED BY FLAME WICKING

then exposes the unprotected fuel to ignition by the wicking action of the fuel-vapor-filled foam. The secondary foam which develops on the surface of AFFF blankets is not, in itself, a serious problem if its formation and possible side effects are understood, but it should not be ignored as a possible source of reflash in the presence of ignition sources.

Mechanical Foam Devices - Mechanical or airfoam can be produced in a number of different ways, but the principal methods in common use are (1) by air-aspirating nozzles, (2) the in-line foam pump system, and (3) the in-line compressed air or blown-foam system.

The air-aspirating nozzles produce foam by mixing a proportioned solution of water and foam liquid concentrate under high pressure with air at atmospheric pressure. This system is capable of achieving the maximum foam range with the straight stream discharge, and various mechanical devices are generally used to shape the issuing foam to produce different ground patterns and a more gentle foam application on the surface of burning fuels. Commercial devices of this kind are classified as the low-expansion type and produce foam with expansion ratios from 8:1 to 10:1 and drainage times from 4 to 5 minutes at solution discharge rates from 2 to 1500 gpm or higher.

The in-line foam pump system employs a special type of reciprocating vane rotary pump with screened intake open to the atmosphere. Metered quantities of water and foam liquid concentrate are fed into the solution intake manifold and air is drawn in to make up the difference in the compartment volume. The liquid and air are then churned in the pump and homogenized in a stabilizing chamber before passing through a series of foam refining screens in the piping to the turret nozzle, which serves only to distribute the foam in different patterns. This system is flexible in terms of foam quality expressed as the drainage time and expansion ratio. Typical foam quality characteristics for a unit with a solution discharge rate of 500 gpm would be a solution drainage time of 20 to 30 min. and an expansion ratio of 12:1 to 15:1. The range of the solid foam stream from this type of unit is approximately 200 to 205 ft. in still air.

The in-line compressed air system employs an air compressor to inject air into a proportioned solution of water and foam liquid concentrate which is mixed within the system piping to produce foam. The nozzles serve only to distribute the foam in various patterns.

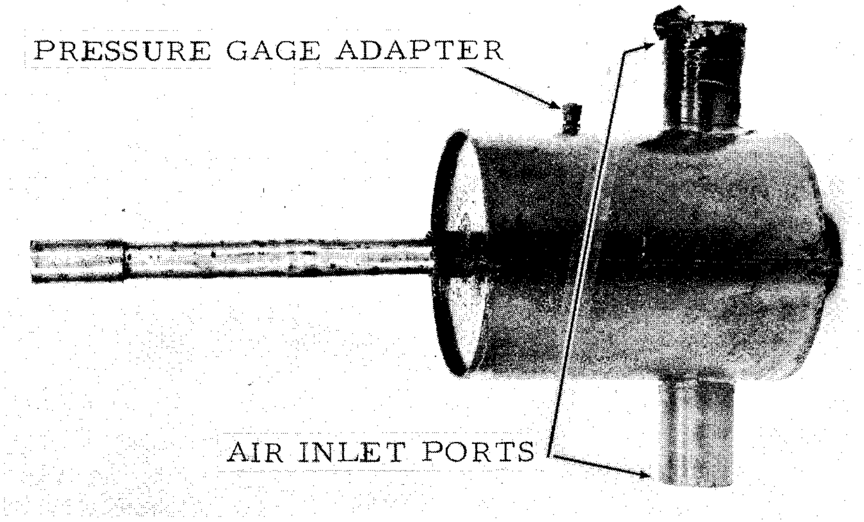
Numerous modifications to these basic methods for producing foam have been made to achieve specific objectives. However, it is evident that the major difference in the various systems is the way in which air is incorporated into the foam solution. In aspirating systems air is mixed with the foam solution at atmospheric pressure, while in all other systems air is incorporated into the foam solution at pressures above atmospheric.

The basic experimental unit employed in the laboratory evaluation was the 6-gpm foam nozzle required to perform the fire test in the federal specification for protein foam. This unit was selected because of its well established performance characteristics with mechanical-type foam agents. The initial modification to this nozzle consisted of a manifold hermetically sealed over the air intake ports and connected to an air compressor. The purpose of the manifold was to control the pressure of the air which would be available for aspirating into the nozzle during foam production. By varying the air pressure within the manifold, the foam expansion ratio could be varied from approximately 5.5:1 to 10.0:1 and the 25-percent drainage time from 3 to 10 minutes. Experiments were also performed in which a series of screens and perforated metal cones were inserted at various positions within the nozzle barrel. Photographs of the small-scale air-aspirating mechanical foam nozzle with the special air manifold are shown in Figure 5. In Figure 6 the foam nozzle with the air manifold is shown mounted on the monitor stand with auxiliary equipment.

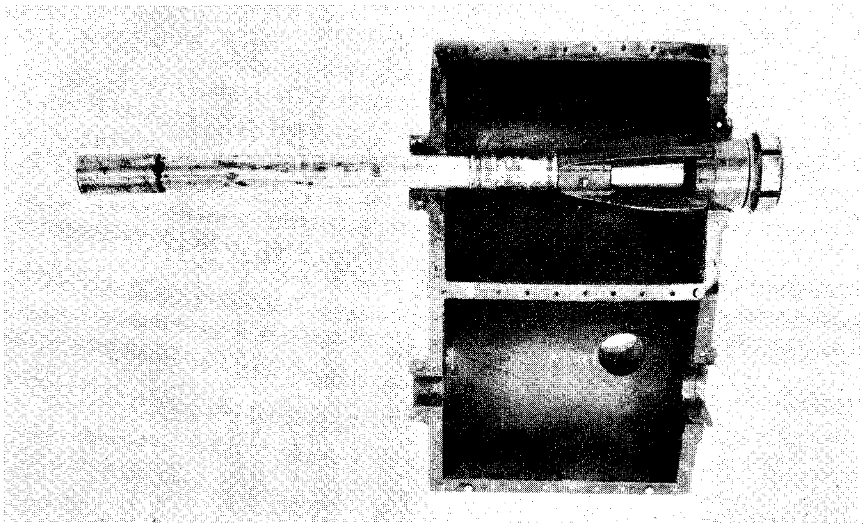
In another series of experiments, the effects of nozzle barrel length and shape were studied and one modification is shown in Figure 7. As a result of all of these experiments, it was apparent that full-scale air-aspirating foam nozzles could be developed which would be capable of producing protein foam with expansion ratios from 9:1 to 12:1 and any 25-percent drainage time between 5 and 12 minutes without sacrificing foam patterns or discharge range.

Low-Expansion Mechanical Foams -

A. Physical Properties of the Protein Foam Liquid Concentrates - The physical properties and firefighting effectiveness of both the 3- and 6-percent foam liquid concentrates were evaluated in accordance with the requirements of the federal specification (Reference 6). The results obtained with the four 6-percent type agents currently listed on the QPL are presented in Table I. The results of similar tests performed with the 3-percent protein liquids are presented in Table II. In Tables I and II, a range of values is given for most liquid properties and any variation from these values would indicate that a change in composition had taken place which would warrant further investigation.



(a) MANIFOLD CLOSED SHOWING THE TWO AIR INLET PORTS AND PRESSURE GAUGE ADAPTER.



(b) MANIFOLD OPEN SHOWING THE INTERNAL CONFIGURATION

FIGURE 5 - SMALL-SCALE (6 GPM) STANDARD MECHANICAL FOAM NOZZLE AND AIR MANIFOLD

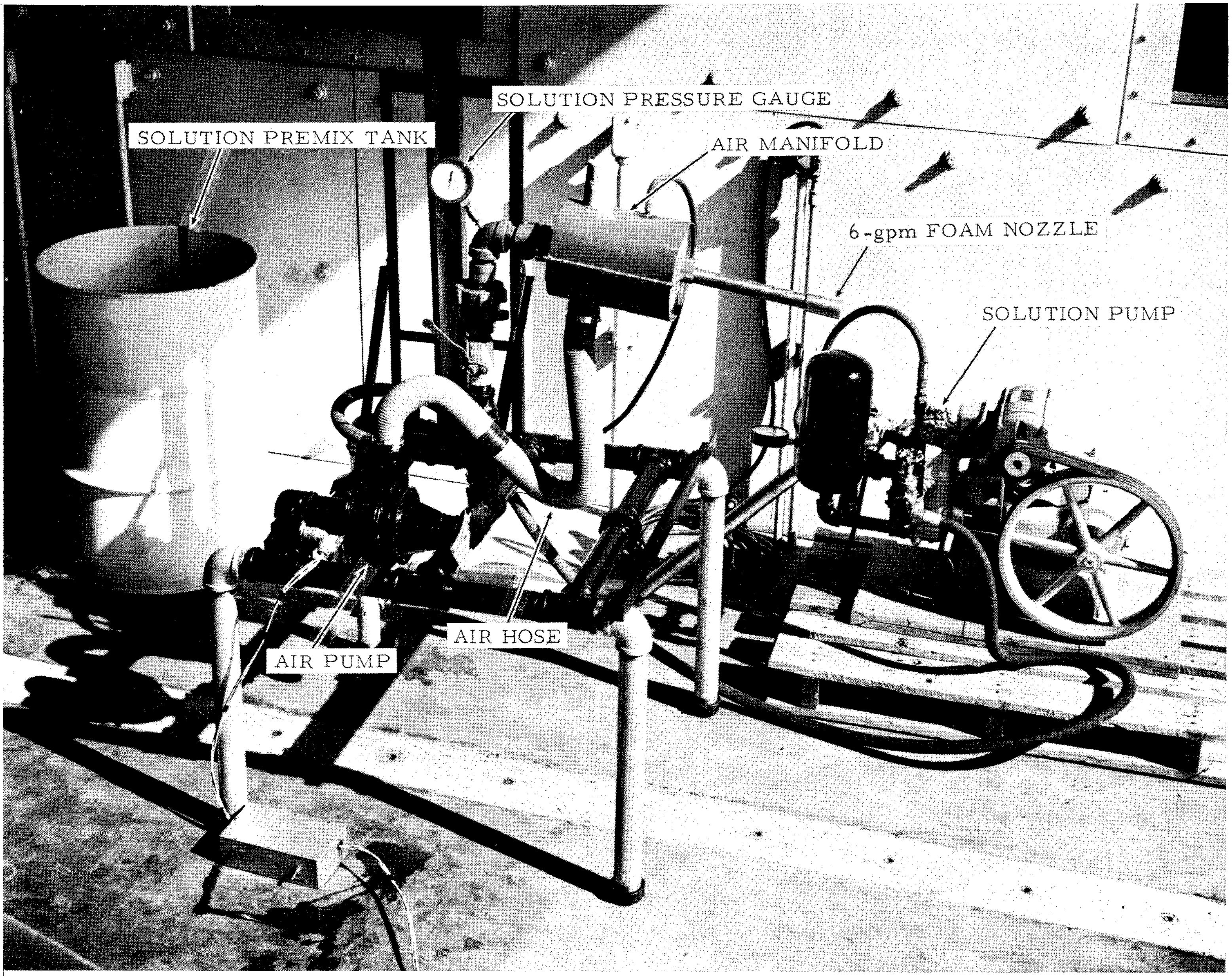
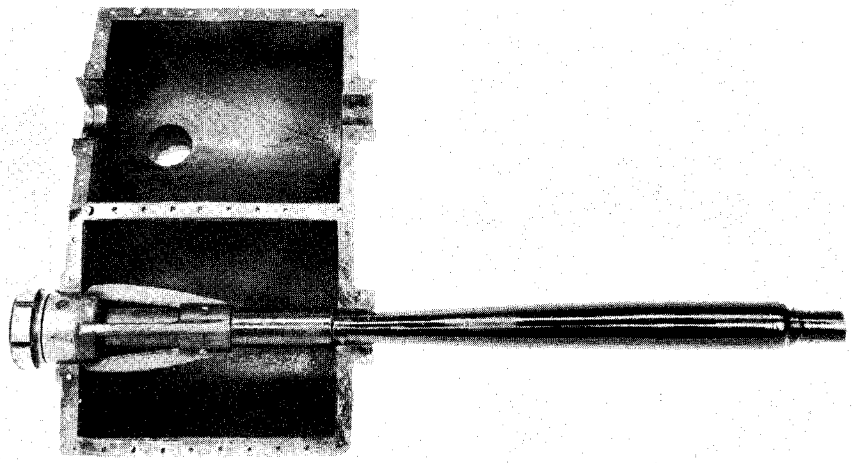


FIGURE 6 - SMALL-SCALE (6 GPM) FOAM NOZZLE SETUP

(a) MECHANICAL FOAM NOZZLE
WITH A MODIFIED BARREL



(b) MODIFIED FOAM NOZZLE WITH
THE AIR MANIFOLD OPEN

FIGURE 7 - SMALL-SCALE (6 GPM) MECHANICAL FOAM NOZZLE WITH
A MODIFIED BARREL AND AIR MANIFOLD

TABLE I

PHYSICAL PROPERTIES OF 6-PERCENT PROTEIN TYPE FOAM LIQUID CONCENTRATES

PROPERTIES OF THE FOAM LIQUID CONCENTRATE	PROTEIN BASE FOAM AGENTS 6-PERCENT TYPE			
	MANUFACTURER A	MANUFACTURER B	MANUFACTURER C	MANUFACTURER D
Specific Gravity 60°/60°F	1.140-1.147	1.14-1.16	1.150-1.170	1.158-1.164
Kinematic Viscosity (Centistokes)				
68°F	22.31-27.05	15-25	16.5-19.0	19-23
32°F	66.25-83.53	25.7-65.7	----	50-65
PH Value @ 70°F	7.4	6.8-7.5	6.5-7.5	6.8-7.0
Sedimentation % by volume	Trace 0.03	0.1 Max.	(1)	(1)
Precipation % by Volume				
Sea Water	Trace-0.05	Trace	(1)	0.05
Distilled Water	Trace-0.01	Trace	(1)	0.05
Low Temperature Stability -85°F	(1)	0.2 Max.	(1)	(1)
High Temperature Stability 149°F	Trace-0.05	0.2 Max.	(1)	0.05-0.20

(1) Meets Requirements

TABLE II

PHYSICAL PROPERTIES OF 3-PERCENT PROTEIN FOAM LIQUID CONCENTRATES

PROPERTIES OF THE FOAM LIQUID CONCENTRATE	PROTEIN BASE FOAM AGENTS 3-PERCENT TYPE			
	MANUFACTURER A	MANUFACTURER B	MANUFACTURER C	MANUFACTURER D
Specific Gravity 60°/60°F	1.159-1.166	1.16-1.18	1.17-1.19	1.155-1.165
Kinematic Viscosity (Centistokes)				
68°F	49.30	40-75	20-35	40
32°F	171.69	----	----	50
PH Value @ 70°F	7.3-7.4	6.5-7.5	6.5-7.5	6.8-7.0
Pour Point °F	-6, +10	10	Max. -15	10-15
Sedimentation % by Volume	Trace-0.01	0.1 Max.	(1)	0.05
Precipation % by Volume				
Sea Water	Trace-0.01	----	(1)	0.05
Distilled Water	Trace-0.01	----	(1)	0.05
Low Temperature Stability -85°F	(1)	(1)	(1)	(1)
High Temperature Stability 149°F	Trace-0.08	0.2 Max.	(1)	0.05-0.2

(1) Meets Requirements

A summary of the results of the fire tests conducted in accordance with the requirements of the federal specification (Reference 6), for both the 6- and 3-percent foam agents, is presented in Table III. These data show that both concentrations of protein foam agents were capable of extinguishing the 100-sq-ft standard fire within a 5-minute period, but that the residual foam blankets developed by the 3-percent agents were not capable of developing the required vapor seal nor of preventing the spread of fire beyond an area 20-in. square, required by the burnback test.

B. Corrosive Effects of Protein and AFFF Liquids on Metals and Ancillary Materials - Effective firefighting is dependent upon the ability of the equipment to reach the fire site in the shortest possible time and to dispense the extinguishing agents in an efficient manner. To perform adequately, a foam-water dispensing system must be free from the effects of corrosion. To design an acceptably corrosion resistant foam dispensing system, the effect of the foam liquids on the various metallic components, greases, and elastomeric materials must be known. Therefore, a series of experiments was performed to determine the corrosive effects of AFFF and protein-foam liquids on some critical components of a typical foam-dispensing system. The data presented were derived from experiments and a literature survey, as well as from unpublished manufacturers' data.

Two types of AFFF were available from Manufacturer E for the corrosion studies during the time this phase of the project was being conducted. Composition 1, by Manufacturer E (Manufacturer E-1), was limited in use to fresh water, while Composition 2, by Manufacturer E (Manufacturer E-2), was suitable for use in either fresh or sea water. One type of AFFF agent was available from Manufacturer F which was not claimed to be compatible with sea water, and another from Manufacturer A-1 which was claimed to be compatible with sea water.

The protein foam liquid concentrates tested for corrosiveness were all of those currently listed on the QPL.

The resistance of four common construction metals to corrosion by the foam liquid concentrates and their 6-percent solutions was determined in accordance with the requirements of the federal specification (Reference 6). A summary of the results of these tests is presented in Table IV for the four protein foam liquid concentrates, and in Tables V, VI, and VII for the AFFF liquids. The corrosive effects

TABLE III

RESULTS OF SMALL-SCALE FIRE TESTS USING PROTEIN FOAM

	6-PERCENT TYPE				3-PERCENT TYPE			
	MANUFACTURER				MANUFACTURER			
	A	B	C	D	A	B	C	D
Ambient Air °F Temperature	75-80	75	74-76	82	75-76	73	80	79
Wind Velocity mi/h	10	10	10	10	10	10	10	10
Premixed Solution temperature °F	65-70	68-70	65-68	70-72	72	68-70	70-72	66-68
25% Drainage Time min:s	3:20	3:15	4:20	2:35	3:54	0:49	1:45	1:58
Foam Expansion Ratio	8.2:1	8.4:1	8.9:1	8.1:1	8:2	5.4:1	6:1	5.2:1
Type of Fuel	JP-4	JP-4	JP-4	JP-4	JP-4	JP-4	JP-4	JP-4
Fire Preburn Time S	60	60	60	60	60	60	60	60
Fire Control Time min:s	1:43	2:52	1:48	2:04	2:10	3:10	2:10	1:40
Fire Extinguishing Time min:s	3:15	4:29	2:48	3:40	4:30	3:55	3:50	5:00
Sealability Test	Passed	Passed	Passed	Passed	Failed	Failed	Failed	Failed
Burnback Test	Passed	Passed	Passed	Passed	Failed	Failed	Failed	Failed

TABLE IV

SUMMARY OF CORROSION TEST RESULTS OBTAINED WITH PROTEIN FOAM LIQUID CONCENTRATES

Manufactures	Loss in Weight (milligrams per square decimeter per day)		
	Cold Rolled Steel	Brass ASTM B-16	Aluminum 6061
Manufacture A	8.39	17.00	3.20
Manufacture B	7.53	2.24	1.02
Manufacture C	6.09	13.46	1.46
Manufacture D	7.07	6.68	22.66

Conditions of test - 100° ± 2°F for 21 days.

TABLE V

SUMMARY OF CORROSION TEST RESULTS OBTAINED WITH AFFF (MANUFACTURER E-1)

Test Liquids	Loss of Weight (milligrams per square decimeter per day)			
	Steel Cold Rolled	Brass Astm B-16	Aluminum 6061	Stainless Steel 302
Foam Liquid Concentrate	4-8	1-5	4	0
6% Tap Water Solution	2-12	5	1-3	0
Sea Water (alone)	9-11	1.7	1.4	0
Tap Water (alone)	7-9	1.6	0.5	0

Conditions 100° ± 2°F for 21 days.

TABLE VI

SUMMARY OF CORROSION TEST RESULTS OBTAINED WITH AFFF (MANUFACTURER E-2)

Test Liquids	Loss of Weight (milligrams per square decimeter per day)			
	Aluminum 6061	Brass 70/30	Carbon Steel 1020	Stainless Steel 304L
Foam Liquid Concentrate	0.2 - 3.0	1 - 10	8 - 19	0
6% Tap-Water Solution	0.3	2.4	2	0
6% Sea-Water Solution	0.8	3	2 - 19	0

TABLE VII

SUMMARY OF CORROSION TEST RESULTS OBTAINED WITH AFFF (MANUFACTURER A-1*)

Test Liquids	Loss of Weight (milligrams per square decimeter per day)			
	Mild Steel	Monel	Brass (Yellow)	Stainless Steel 304L
Foam Liquid Concentrate	7.2	1.1	25.1	0
6% Sea-Water Solution	12.3	0.45	4.5	0.07

* Manufacturer's Data

of sea water and tap water alone on four different test metals are included in Table V for comparison with the corrosion results obtained with the 6-percent solutions of the foam agents made with these liquids.

Table IV shows that the average loss in weight of the steel coupons, which were exposed to the four different foam liquids, was approximately 25 percent of the maximum allowable limit of 30 miligrams per square decimeter per day (mdd). However, the corrosive effect of these liquids upon the brass and aluminum varied widely, and there is apparently no direct correlation between the corrosivity of protein liquids produced by different manufacturers. In fact, the loss in weight of the aluminum coupons was lowest for Manufacturer B, but the effect was considered severe because the corrosion caused deep pitting of the surface which could cause rapid perforation of the metal.

The data presented in Tables V, VI, and VII show the average weight loss for aluminum, brass, carbon steel, and stainless steel. The results of these corrosion experiments indicate that the metal lost by the coupons expressed as mdd is relatively low. However, carbon steel without a protective coating is not recommended for the storage of any of the AFFF agents in either the concentrated form or as a premixed solution because of the rust which may develop. Carbon steel is the least resistant metal to all of the liquid environments. Additional data concerning the corrosion resistance of some common metals in contact with AFFF and protein foam are contained in Reference 22.

In addition to the loss in weight through corrosion of copper-base alloys in contact with AFFF liquids, there was visual evidence of complex ion formation during the process, but the effect of these complex ions upon foam quality was not investigated. However, the effect of complex ion formation on the firefighting effectiveness of the AFFF should be determined, since it constitutes a significant change in the original chemical composition of the concentrate. The overall effect, if any, of complex ion formation on foam quality should be determined for solution concentrations which are representative of those which may develop under actual storage conditions.

Another very serious form of metallic corrosion may occur in foam-dispensing systems when dissimilar metals are employed in its fabrication. The electrolytic corrosion of some dissimilar metal couples in contact with protein foams is treated in detail in Reference 23. These data show the severe damage which may occur when unprotected iron is in metallic contact with brass or bronze.

The effects of protein foam and AFFF on current elastomeric materials which are useful for the fabrication of gaskets and other purposes in foam-dispensing systems were evaluated by methods presented in References 24 and 25. The experimental materials included Neoprene, Nitrile, ethylene propylene terpolymer (EPT), Butyl, and natural rubber. Tests were performed to determine some of the critical physical properties of these elastomers including volume change, permanent set, tensile strength, percent elongation, hardness, and absorption on one AFFF sample. The results of these experiments are summarized in Table VIII. These data indicate that EPT would be the most stable material for use with Manufacturers' E-1 concentrate and the 6-percent solution. However, the results obtained for Nitrile and Neoprene, when immersed in Manufacturers' E-1 product, do not preclude their use with this agent, but they are not recommended. Nitrile and Neoprene were less affected by protein-foam liquid than the AFFF agent.

The absorption change shown in Table VIII for Neoprene and Nitrile correlate with the volume swell. The change in tensile strength is considered insignificant, but the change in elongation and hardness, as well as the percent swell and permanent set, could limit the use of these materials for some applications, such as the O-ring seal in ball valves.

The effects of AFFF and protein foam on two common types of rotary shaft packing materials, designated as Asbestos Style 5810 and Metallic Style 100-M, were determined by exposing segments of each to the liquid concentrates and to 6-percent solutions at ambient room temperature, (68° to 70°F) for 35 days. The effect of exposure to the fluids was determined by measuring any change in weight of the sample and by visual observation. The results of these experiments are summarized in Table IX. These packing materials are currently employed in the A/S32P-2 and MB-2 firefighting vehicles and they should show adequate stability toward AFFF and protein foam liquids.

The effect of AFFF (Manufacturer E-1) and protein foam was determined for the concentrate and 6-percent solution on a commonly employed water pump grease (Lithium HD2). The qualitative test procedure is outlined in Appendix B. A summary of the visual results of the experiments is presented in Table X, from which it is evident that there is no tendency for the fluids to emulsify the grease.

TABLE VIII

EFFECT OF PROTEIN FOAM AND AFFF (MANUFACTURER E-1) ON ELASTOMERS*

Agent and Test Coupons	Volume Change % Swell 72 h	Volume Change % Swell 400 h	Permanent Set % of Original	Tensile Strength % of Original	Elongation % of Original	Hardness % of Original	Absorption % of Original
Manufacturer E-1							
Concentrate							
Nitrile	7.6	22	10	-11	-11	- 7	+ 9.5
Neoprene	7.6	15	7	+ 5	+25	-15	+11
EPT	0	0	2	-	-	-	
Butyl	-	-	-	+12	+18	- 7	+ 1
Natural Rubber	-	-	-	-12	+20	- 4	+ 3
Teflon	-	-	-	-10	0	+ 4	- 0.1
Manufacturer E-1							
6% Solution							
Nitrile	3.0	1.5	5				
Neoprene	7.6	3.0	10				
EPT	0	0	2				
Protein Foam							
Nitrile	0.5	1.5	3				
Neoprene	3.0	10	3				
EPT	0	0	2				
Protein Foam							
6% Solution							
Nitrile	0.5	1.5	2				
Neoprene	3.0	10	4				
EPT	0	0	2				

---

* Private Communication

TABLE IX

EFFECT OF PROTEIN FOAM AND AFFF (MANUFACTURER E-1) FOAM ON ROTARY SHAFT PACKING*

Test Liquids	Packing Materials Change in Weight - Percent of Original	
	Asbestos	Metallic
AFFF Foam Liquid Concentrate	No significant change.	No significant change.
AFFF 6% Tap-Water Solution	No significant change.	No significant change.
Protein Foam Concentrate	No significant change.	No significant change.

* Private communication.

TABLE X

EVALUATION OF WATER PUMP GREASE WITH AFFF (MANUFACTURE E-1) (LITHIUM HD2 BEARING GREASE)

Test Liquid	Physical Effect on Liquid and Grease
Tap Water	No visible change in liquid or grease.
AFFF Foam Liquid Concentrate	No visible change in liquid or grease.
AFFF 6-Percent Solution	No visible change in liquid or grease.
Protein Foam Concentrate	No effect on liquid (grease intact).
Protein Foam 6-Percent Solution	Solution turbid due to protein precipitation (grease unaffected).

C. Effect of Water Hardness on the Firefighting of AFFF and Protein Foams - At the outset of the laboratory investigation, the current formulation for the AFFF was designated by Manufacturer E as a fresh water formulation (Reference 18). Therefore, it was evident that the liquid was potentially sensitive to the calcium and magnesium cations and to the chloride, sulfate, carbonate, and bicarbonate anions. Since it is known that various combinations of these and other moities are responsible for the hardness of potable ground waters, it was apparent that the quality of foam produced would be reduced, and consequently the firefighting effectiveness, if hard water was employed for foam production. At approximately this same time, the first sea water compatible AFFF agent was made available, and it was stated that the fresh-water formulation would be systematically phased out of production. Therefore, this sea-water formulation was used in subsequent tests until it was superseded by another sea-water formulation (Manufacturer E-3), which had been approved under a pertinent military specification (Reference 20).

With respect to hardness, waters may be roughly classified as soft, less than 50 parts per million (ppm); moderately hard, 50 to 100 ppm; and hard, above 100 ppm.

A determination of the water hardness at a number of Air Force installations throughout the United States indicated that the hardness varied from approximately 3 ppm to 410 ppm. As a result of this survey, it was decided to conduct the agent evaluation at 18 ppm, which is the approximate hardness of water at NAFEC, and at 470 ppm, which is roughly equivalent to one-half the hardness of coastal sea water.

A series of four fire tests was performed in accordance with the requirements of the federal specification (Reference 6), using one AFFF sample (Manufacturer E-3), and protein foam, each agent premixed to a concentration of 6 percent by volume with water of the required hardness. The results of these experiments are summarized in Table XI, from which it is apparent that AFFF and protein foam can be employed effectively in either soft or hard water. However, when a 6-percent premixed solution is made with AFFF in water with a hardness of 470 ppm, there is a significant reduction in the foam expansion ratio and 25-percent-solution drainage time, which caused an increase in the fire control and extinguishing times.

TABLE XI

EFFECT OF WATER HARDNESS ON FIRE PERFORMANCE EMPLOYING PROTEIN FOAM AND AFFF (MANUFACTURER E-3)

	Water Hardness			
	18 PPM		470 PPM	
	Protein Foam	AFFF	Protein Foam	AFFF
Foam Expansion Ratio	8.1:1	10.2:1	8.0:1	8.6:1
25-% Solution Drainage Time Min:Sec	3:45	3:30	3:30	1.30
Wind Velocity MPH	2-4	4-6	2-4	2-4
Air Temperatures °F	79	78	79	76
Fire Control Time Min:Sec	1:55	0:32	1:50	1:10
Fire Extinguishment Time Min:Sec	3:55	1:15	3:50	3:15
Foam Burnback Area Sy In.	400	Self-Extinguishing	400	Self-Extinguishing

D. Effect of Temperature on Foam Quality and Foam-Dispensing Systems - The effect of the ambient air temperature upon foam production, under simulated crash-fire conditions, was not extensively investigated because of the logistics problems inherent in conducting full-scale fire tests under extremely low-temperature conditions. However, it was evident in one series of experiments conducted at temperatures from 18° to 20°F, that the ambient air temperature was of minor importance in determining the fire control time, probably in part because of the temperature moderating influence produced by the intense thermal radiation on the environment during foam application.

In general, the temperature of the water and foam solution was determined to be more influential than the ambient air temperature in establishing the foam quality produced by any particular foam-dispensing system. Laboratory tests were performed which showed that the quality of foam produced by the four different protein foam agents listed on the QPL varied among themselves, but that in general, the effect of reducing the foam solution temperature was to cause a reduction in the expansion ratio, an increase in the 25-percent drainage time, and a small decrease in the foam viscosity.

The results of experiments conducted with one particular air-aspirating foam nozzle dispensing protein foam showed an average reduction in the foam expansion ratio of 0.032 unit for each 3°F decrease in solution temperature from 125° to 35°F with a corresponding increase in the 25-percent drainage time of 0.132 min and a reduction of approximately 4-percent in foam viscosity. These results are considered significant only in the trends they establish with regard to the variation in foam quality as a function of the solution temperature. Other foam generating equipment capable of achieving different energy input levels during foam production would be expected to yield different results.

Identical tests conducted with AFFF (Manufacturer E-2), which was claimed to conform nominally with the military specification (Reference 19), indicated that foam quality was of the same order of magnitude for most low-expansion air-aspirating foam-dispensing equipment and consequently less critical than when protein foam was employed. Experiments performed with this AFFF agent produced an average reduction of 0.032 unit for each 3°F decrease in solution temperature from 125° to 35°F with a corresponding increase in the 25-percent-solution drainage time of 0.125 min with no significant change in the foam viscosity.

The results of these tests indicated that the effects of low-solution temperatures on foam quality were somewhat greater for protein foam than they were for AFFF.

Recent work directed toward developing a better understanding of the effect of very low temperatures on firefighting operations employing foam was contained in an Alaskan Air Command report dated March 19, 1970. This report summarizes the results of a series of 21 demonstrations which was conducted at Eileson AFB, Alaska, during 1969-1970, to determine the effectiveness of AFFF when employed in standard Air Force equipment in extremely low-ambient air temperatures. According to the report, two different lots of AFFF were employed in these experiments; namely, Lot 128-A-3-69 and Lot 129-A-4-69. These lots were identified verbally by the Manufacturer E to be suitable for use only in fresh water. Experiments employing these liquids at subzero temperatures in an A/S32P-2 Firefighting Vehicle indicated that solutions of AFFF froze almost as rapidly as potable water, which resulted in the freezing of the linkage on the turret nozzle. Therefore, it was found advisable to adjust the foam pattern prior to discharging the foam, which would restrict or limit the flexibility built into the foam nozzle for changing the foam pattern.

It is evident that the actual difficulties encountered in operating foam equipment at subzero temperatures are, in fact, those directly associated with the freezing of water. This same condition would also be encountered using protein foam. The effect of subfreezing temperatures (i.e., 18° to 20°F) upon an established foam blanket was observed during tests conducted on large JP-4 fuel fires as well as in laboratory experiments using protein foam. During the large-scale tests it was noted that after fire extinguishment, the foam blanket slowly froze from the surface downward. During the actual freezing process, which required from 8 to 10 minutes, the foam solution continued to drain from the unfrozen foam below the surface. This process resulted in the formation of a surface film of ice supported by a poorly defined cellular structure beneath. The frozen foam lost its original sealing property and became permeable to fuel vapor penetration in varying degrees over its entire surface. Therefore, protein foam and AFFF foam blankets, which have been exposed to subfreezing temperatures, may be assumed to be permeable to fuel vapor regardless of their physical appearance.

E. A Determination of the Thermal Stability of Foam Blankets - The relative thermal stability of mechanical foam blankets was determined for AFFF, protein and syndet foams by modifying the fire test procedure required in Reference 6, to include a source of thermal radiation and flame impingement on the established foam blankets. A description of the equipment and test method is presented in Appendix C.

In these experiments, 6-percent protein foam conforming to the federal specification was chosen as a frame of reference for comparing the foam blanket stability with that obtained for the other agents.

The results of the fire tests are presented in Table XII. From these data it is evident that the two AFFF demonstrate equivalent firefighting performance. A comparison of the fire control and extinguishing times obtained with AFFF and protein foam illustrates the very rapid fire control times that are characteristic of the AFFF agents. It was observed, during these tests, that fire control, and particularly the fire-extinguishment time, was a function of foam fluidity. The drum obstruction in the center of the tank required the foam to flow around the back of the obstacle, and the more viscous foams produced a V-shaped opening in this area which required a massive buildup of foam to close. This condition was most evident with protein foam. However, these data also show that foam fluidity, per se, is not a substitute for foam quality in the fire control and extinguishing mechanism as evidenced by the test employing syndet foam submitted by Manufacturer F. In this test, it was evident that, although fire control was obtained within 70 sec, the fire extinguishment time was excessively long because of the rapid thermal decomposition of the foam.

From the results of these experiments, it is apparent that the stability of the foam blanket produced by the AFFF agents is adequate to maintain a fuel vapor seal under the high-thermal radiation established by the test conditions.

It is also evident from a comparison of the reignition times obtained for AFFF and protein foam that protein foam is more resistant to thermal disintegration than AFFF.

The results of the experiments performed with the syndet-foam agents show a rather wide variation in fire performance. This is probably because they are not currently manufactured in accordance with any particular specification or requirement. The fire test results obtained for the

TABLE XII

THERMAL STABILITY OF MECHANICAL FOAM BLANKETS

	Protein Foam	Aqueous Forming Film-Foam		Syndet Foam Agents		
		Manufac-turer E-1	Manufac-turer F	Manufac-turer F 6% Type	Manufac-turer A 6% Type	Manufac-turer B 3% Type
Wind Velocity - knots	2	3	0-1	2-4	6	2
Ambient Temp °F	88	88	90	95	85	93
Fire Control Time - sec	160	90	70	70	358	210
Fire Ext. Time - sec	570	160	110	550	434	Failed
Reignition Time - sec	760	490	520	10	412	---
Foam Depth - in.	8.25	12.5	6.8	6.5	1.5	0.70
25-% Drainage Time - sec	170	190	88	10	28	Very rapid
Foam Expansion Ratio	8.2:1	7.5:1	7.9:1	5:1	6.5:1	Very low

two 6-percent type agents submitted by Manufacturers A and F varied widely, except in the fire extinguishment times, while the 3-percent agent submitted by Manufacturer B did not extinguish the fire within the 10-minute foam discharge period because of the very rapid destruction of the foam blanket under the influence of fuel vapor and the high-radiant energy from the heat sink. Therefore, the syndet foams were not considered as candidate agents for further evaluation in the full-scale fire test program.

F. The Effect of Terrain on the Control and Extinguishment of JP-4 Fuel Fires - Previous tests conducted at NAFEC comparing the fire control and extinguishment times for different foam agents were performed on large water-base pool fires. In these experiments, a water substrate was used under the fuel to adjust the level of the liquid surface and prevent the intrusion of islands through the surface. Although this procedure led to the establishment of uniform fire test conditions, it was not necessarily representative of aircraft crash-fire conditions. Therefore, to establish a more valid basis for the estimation of foam blanket stability, a series of eight small-scale experiments was performed on three different types of terrain using protein foam and AFFF. A description of the fire test procedure and the equipment employed in these experiments is contained in Appendix D. The types of terrain employed to evaluate foam stability included sand, traprock, simulated tree-studded sod, and a standard water-base pool fire for comparison of the fire control and extinguishment times. In these tests, the primary objectives were to evaluate the stability of the foam in contact with the burning fuel-soaked surfaces and to estimate the rate of flow of foam across the various simulated terrains. A steel backboard requiring foam stream impingement, before draining into the fire pit, was used to expose the foams to the most severe environmental conditions possible. Foam was dispensed at a solution rate of 0.06 gpm per sq ft for all tests, which approximates the threshold value for protein foam. The effect of these different terrains upon the fire control and extinguishment times for JP-4 fuel fires employing AFFF is presented in Table XIII, and for protein foam, in Table XIV.

The results of the water-base pool fire tests show that protein foam controlled the fire in 2 min and 10 sec, while AFFF required only 1 min and 10 sec. This confirms the results of previous experiments that demonstrated AFFF to be approximately twice as rapid at equal solution rates. However the fire extinguishment time obtained using AFFF is approximately twice as long as that required for protein foam under equivalent conditions.

TABLE XIII

EFFECT OF TERRAIN ON EXTINGUISHMENT AND CONTROL OF JP-4 FUEL FIRE WITH AFFF (MANUFACTURER E-1)

Foam Quality - Expansion Ratio 8.4:1
Drainage Time (25%) 3:15 (min:sec)

	TERRAIN			
	Sand(1)	Trap-rock(2)	Grass and Wood Covered Soil(3)	Pool Fire (Water Base) (4)
Total Foam Application Time(min:sec)	---	15:55	14:20	---
Control Time (min:sec)	9:00	Failed	Failed	1:10
Extinguishing Time(min:sec)	13:25	Failed	Failed	12:55
Temperature(°F)	95	95	96	96
Wind Velocity (knots)	4-8	4-8	3-5	0-2
Preburn Time (min:sec)	1	2:00	1:00	1:00

(1) Variable wind caused some shifting of the foam stream. The thermal stability of the foam appeared to be low and the dike areas continued to burn behind the foam front.

(2) The foam could not penetrate and control the fire area behind the upwind dike.

(3) The flow of foam was very slow, and the solution was exhausted before 25 percent of the pit was covered. The established foam blanket rapidly decomposed after termination of application.

(4) The flow of foam across the fuel surface was very rapid, but the fuel burned vigorously on the dikes behind the foam front which required a large buildup of foam to obtain extinguishment. The foam demonstrated a strong tendency to push the fuel and flames before it over the dikes.

TABLE XIV

EFFECT OF TERRAIN ON EXTINGUISHMENT AND CONTROL OF JP-4 FUEL FIRE WITH PROTEIN FOAM

Foam Quality - Expansion Ratio 8.2:1
Drainage Time (25%) 4:50 (min:sec)

	TERRAIN			
	Sand(1)	Trap-rock(2)	Grass and Wood Covered Soil(3)	Pool Fire (Water Base) (4)
Total Foam Application Time(min:sec)	---	14:10	14:20	---
Control Time (min:sec)	9:20	Failed	Failed	2:10
Extinguishing Time(min:sec)	14:10	Failed	Failed	5:55
Temperature(°F)	84	78	88	84
Wind Velocity (knots)	6-7	4-5	2-4	4-5
Preburn Time (min:sec)	1:00	4:00	1:00	1:00

(1) Foam flowed slowly as it built up and extinguished both pool area and dike fires as it progressed. Variable wind caused minor shifting of foam stream.

(2) Approximately 80 percent of the pool fire was extinguished, but a large buildup of foam was required at the base of the backboard before it would flow across the pit. Foam progressively extinguished all dike fire in its path. The thermal stability of the blanket appeared to be somewhat greater than for AFFF. The long preburn time was required for this fire to reach maximum intensity.

(3) There was insufficient foam solution to achieve extinguishment of the fire. However, fire control was uniform and progressive, but the wooden stakes were a serious hindrance to the flow of foam.

(4) Overall fire test performance closely approximated that specified in the federal specification (Reference 6).

All other types of terrain showed that prolonged fire control and extinguishment times were required when compared with the conventional pool fire environment. This evidence indicated that in situations where mechanical foam could not be readily skimmed across a level fuel surface, the mechanical distribution and placement of the foam blanket might (or could) become the controlling factor in determining fire control and extinguishment times.

The results of these tests also suggest that fire control and extinguishment times obtained under simple pool fire conditions may not be adequate to accurately define the actual requirements with regard to the solution application density necessary and the time required to achieve fire control and extinguishment when different natural surface structures are involved. These facts were confirmed by subsequent full-scale fire tests using B-47 aircraft, which emphasized the fact that other parameters are involved in aircraft firefighting than those encountered in simple pool fire experiments. The aircraft configuration and its position relative to the wind direction and the type of terrain are among the factors which may affect the fire control time.

G. The Toxicity of Protein Foam and AFFF - Protein foam forming concentrates consist basically of a hydrolyzed protein containing iron salts as foam stabilizers with suitable freezing point depressants and preservatives. During World War II, the U.S. Government standardized the use of mechanical protein-base foam for fighting gasoline and oil fires. At this time, the basic composition and performance requirements for these agents were finalized in a U.S. Joint Army-Navy Specification JAN-C-266 (Dec. 4, 1945). Since the issuance of this specification, there have been numerous minor changes in the fire performance requirements of the protein agents. However, the basic chemical composition has remained unchanged to the present time, and no toxicological problems related to its use have been observed during this period.

The scope of this project precluded a clinical determination of the toxicity of the AFFF liquids. However, the results of toxicity studies reported by one manufacturers' medical department showed that AFFF (Manufacturers E-1 and E-2) have oral LD 50 (50-percent lethal dose) in rats greater than 23 grams per kilogram (g per kg) of body weight and are minimally irritating to both skin and eyes of albino rabbits. AFFF (Manufacturer E-3) has an LD 50 of approximately 13.9 g per kg of body weight and would be classified as being practically nontoxic orally. It was also found to be nonirritating to the eyes of albino rabbits.

The results of controlled toxicity experiments employing AFFF and aquarium-type fish were reported recently. The fish (goldfish, Blackmoors, and Calicos) ranged in weight from 1.5 g to 3 g and from 2 to 2.5 in. long. The survival times for the fish were determined when exposed to concentrations of AFFF from 2 to 0.002 percent by volume. The behavioral patterns and survival times of the fish were observed for periods in excess of 7 days. The results of these experiments, as reported by the investigators, showed that at the highest concentrations death occurred within 3 to 10 min, but that at all concentrations down to 0.002 percent, the fish were in distress, which was evidenced by their loss of equilibrium, erratic spinning motion, and headlong plunging into the sides and bottom of the tank. The lethal threshold concentration to these fish was estimated to be 0.006 percent by volume, at which death occurred within 2 to 7 days.

A survey of the pertinent military specifications concerning the toxicity requirements of AFFF liquids during the development stages, from November 1, 1963, through April 25, 1967, contained a statement indicating that the concentrate should be composed of nontoxic fluorocarbon surfactants and appropriate foam stabilizers. However, the degree of toxicity of the compounds was not defined, and is of only academic interest, since all of these specifications have been superseded by the development of another fresh and sea water compatible agent. The AFFF military specification dated November 21, 1969 (Reference 20), contains the following statement concerning toxicity, "The material shall have no adverse effect on the health of personnel when used for its intended purpose."

H. A Determination of the Compatibility Between Protein Foam Agents Listed on the QPL - The current specification applicable for the procurement of protein mechanical foam-liquid concentrates by the U.S. Government is federal specification (Reference 13). This specification and the preceding specification (Reference 6) contain a requirement for complete compatibility between all protein foam agents listed on the QPL. This requirement is mandatory because there are four different products currently available through the Federal Government supply system, and no effort can be justified by supply centers to segregate stocks by source or manufacturer. Therefore, the liquid storage tanks on aircraft rescue and firefighting vehicles may contain a mixture of all qualified agents in any proportion.

The potential incompatibility of the protein foam-liquid concentrates listed on the QPL was apparent from field reports indicating that excessive amounts of sludge had been found in liquid bulk-storage compartments. An investigation into the causes of the imcompatibility was accordingly undertaken by the NASL with the participation of the foam liquid manufacturers. The results of this joint effort were published in a report (Reference 26) which proposed a theoretical explanation for the incompatibility. Although these data showed that protein foam-liquid concentrates could be made mutually compatible for storage periods up to 18 months, the effort was abandoned.

As a result of continuing unfavorable reports from the field concerning the presence of objectionable quantities of sediment in foam-liquid storage tanks, a series of high-temperature stability experiments was performed to determine the amount of sediment produced when the liquids are mixed in different proportions by volume. Tests were performed in accordance with federal specification (Reference 6) under paragraph 3, REQUIREMENTS, 3.3 Compatibility. Only the procedure under paragraph 4.7.7.2, High-Temperature Stability, was applicable because the sediment was found to be so heavy with certain foam-liquid combinations that it was impossible to transfer a representative sample from the larger containers to the centrifuge tubes for processing.

The agents tested varied in age from 12 to 16 months, and included all of those currently listed on the QPL.

The quantity of sediment obtained with samples taken from previously unopened cans of liquid from each of the four manufacturers is summarized in Table XV. In this regard, it is considered noteworthy that all liquid concentrates tested in the as-received condition showed an acceptable degree of sediment when determined in accordance with the federal specification.

The results of these accelerated aging experiments are summarized in Tables XVI through XVI E which show a wide variation in the degree of compatibility between the protein agents when tested in accordance with the federal specification. The actual quantity of sediment formed when two different liquids are mixed is a function of their chemical composition and the zeta potential established on each colloidal protein particle during manufacture. The data show that the liquids supplied by Manufacturer A and Manufacturer D produced sediment within the acceptable range of 0 to 0.25 percent by volume when tested in accordance with the federal specification. All other combinations of agents yielded sediment in excess of the maximum limit.

TABLE XV

SEDIMENT CONTAINED IN PREVIOUSLY UNOPENED PAILS OF PROTEIN FOAM LIQUIDS

Liquid Manufacturer	Sediment Percent by Volume
Manufacturer A	0.025
Manufacturer B	0.10
Manufacturer C	0.025
Manufacturer D	0.05

The data obtained from the high-temperature stability experiments for mixtures of two protein type agents at three different concentrations are presented in Tables XVI through XVIE.

TABLE XVI

SEDIMENT OBTAINED IN HIGH TEMPERATURE STABILITY TESTS FOR MIXTURES OF PROTEIN FOAM LIQUIDS

Foam Liquid Concentrate Mixtures Percent by Volume		Sedimentation
Manufacturer A	Manufacturer B	Percent by Volume
100	0	0.025
75	25	0.025
50	50	1.0
25	75	0.75
0	100	1.80

TABLE XVI A

Foam Liquid Concentrate Mixtures Percent by Volume		Sedimentation
Manufacturer A	Manufacturer D	Percent by Volume
75	25	0.025
50	50	0.10
25	75	0.20
0	100	0.20

TABLE XVI B

Foam Liquid Concentrate Mixtures Percent by Volume		Sedimentation
Manufacturer A	Manufacturer C	Percent by Volume
75	25	0.10
50	50	1.30
25	75	1.50
0	100	1.00

TABLE XVI C

Foam Liquid Concentrate Mixtures Percent by Volume		Sedimentation
Manufacturer B	Manufacturer D	Percent by Volume
75	25	1.10
50	50	1.20
25	75	0.70

TABLE XVI D

Foam Liquid Concentrate Mixtures Percent by Volume		Sedimentation
Manufacturer B	Manufacturer C	Percent by Volume
75	25	3.10
50	50	2.50
25	75	3.00

TABLE XVI E

Foam Liquid Concentrate Mixtures Percent by Volume		Sedimentation
Manufacturer D	Manufacturer C	Percent by Volume
75	25	0.50
50	50	0.75
25	75	1.17

The experiments performed in this study were exploratory and not an exhaustive study of the high-temperature stability of protein foam liquids, and the quantity of sediment found in these experiments should not be considered representative of that which may be developed when liquids from different manufacturers are randomly mixed in firefighting equipment under ambient temperature conditions.

Another recent investigation into the mutual compatibility of protein liquids listed on the QPL was performed at ambient room conditions by the NRL (Reference 27). The test procedure was to store the mixed samples in 100 ml glass-stoppered graduated cyclinders at ambient room temperature (75° to 80°F) for periods of up to 131 days. The results of these experiments indicated that as much as 20 percent by volume of sediment formed within 12 days for certain combinations of liquids.

In recognition of the serious problems associated with the bulk storage of firefighting liquids on board naval vessels, a test kit was assembled which is useful for determining the physical condition of protein liquids, including sediment and the quality of foam it is capable of producing (Reference 28).

I. Extinguishing Polar Solvent Fires - The primary hazard associated with aircraft firefighting is the large quantity of hydrocarbon fuel and oil carried. These petroleum products are insoluble in water and are sometimes referred to as nonpolar compounds, to differentiate them from the polar compounds or polar solvents which are either completely soluble or partially soluble in water. All other flammable liquids associated with the operation of the aircraft are extremely small by comparison, but were considered worthy of investigation and discussion.

Regular AFFF and protein foams are satisfactory for extinguishing large JP-4 fuel fires at nominal application rates from 0.10 to 0.20 gpm per sq ft depending upon the fire condition. However, neither AFFF (from literature published by Manufacturer E-1) or protein foam is capable of extinguishing large quantities of polar solvents at these rates. To effectively fight polar solvent fires, a special class of extinguishing agents has been developed which are variously referred to as being of the "alcohol-type," "polar-solvent type," or "all-purpose type."

An example of the solution application rates recommended to extinguish several different typical polar-solvent fires using one commercially available all-purpose agent is presented in Table XVII. From these data, it is apparent that the solution application rates required to extinguish different polar solvent fires are determined by the particular fuel involved.

The data presented in Table XVIII show that regular protein foam may be employed to extinguish certain polar-solvent fires, from which it may be deduced that the foam destructiveness demonstrated by the polar solvents is one of degree. Therefore, foam application rates must be experimentally determined for each class of foam compound.

The solution application rates shown in Tables XVII and XVIII were determined for very gentle, Type I foam discharge (Reference 10). Experience has shown that the foam solution application rates, necessary to control and extinguish deep polar solvent fires, must be increased significantly when the foam stream is plunged over those required when gentle application is employed.

Since there are no significant amounts of pure polar-solvent compounds employed in the operation of an aircraft, the experimental fire testing was limited to hydraulic fluid conforming to MIL-H-5606B and jet engine oil conforming to MIL-0-6081.

Exploratory experiments were performed to determine the relative stability of protein foam on burning hydraulic fluid and engine oil for comparison with JP-4 fuel. The tests were performed in a 4-sq-ft earthen pit filled to a depth of 1 in. with the test fluid. Protein foam, with an expansion ratio of 8.1:1 and a 25-percent drainage time of 4.8 min, was dispensed from the 6-gpm nozzle (Reference 6) into the center of a steel backboard positioned on the downwind side of the pit from which the foam drained onto the surface of the burning fluid. The foam was applied for 48 sec, after which the blanket was probed with a lighted torch for a period of 5 min in an effort to ignite any escaping fuel vapors.

After 15 min, a 6-in.-sq hole was cut in the center of the foam blanket and the fluid ignited and permitted to burn for 5 min. During this burnback period, the fire area increased to approximately 6.4 in. sq which indicated that an acceptable degree of compatibility maintained between the protein foam and burning fluid, when compared with the permissible increase in fire area from 6 in. sq to 20 in. sq established in Reference 6.

TABLE XVII

SOLUTION APPLICATION RATES FOR THE EXTINGUISHMENT OF POLAR SOLVENT FIRES *

	Solution Application Rates (gpm/10 sq ft)
Polar Solvent Fuel	All Purpose Foam
Methyl Alcohol	1.0
Isopropyl Alcohol	1.5
Methyl Isobutyl Ketone	2.0
Methyl Ethyl Ketone	2.5

* Manufacturer's Data

TABLE XVIII

EXAMPLES OF POLAR SOLVENT FIRES ON WHICH EITHER ALL-PURPOSE OR PROTEIN FOAM MAY BE USED*

	Solution Application Rates (gpm per sq ft)	
Polar-Solvent Fuel	All-Purpose Foam	Protein Foam
Cyclohexanol	1.5	1.5
Ethyl Acrylate	1.5	1.5
Methyl Methacrylate	1.5	1.5

* Manufacturer's Data

J. The Burnback Resistance of Established Blankets of Protein Foam and AFFF - The resistance of a foam blanket to thermal destruction from the burning fuel it is covering is known as the "burnback" resistance, and is commonly measured in terms of the increase in size of a known fire area after a given period of time. Foam burnback time is considered significant because it is a measure of the fuel-vapor securing property of the foam blanket and may be closely related to the time available for the firefighting crew to effect passenger rescue and evacuation from an aircraft fuselage exposed to fire.

In a previous effort, a series of 37 fire tests was performed using AFFF and protein foam on 40-ft-diameter JP-4 fuel fires to determine the relative foam burnback time for each agent after initial fire control had been obtained. The results of these tests were not reproducible and consequently inconclusive, principally because of the effect produced by variable wind conditions and because of the different techniques required in successive fires to achieve the shortest possible fire control time. The difficulties inherent in making a quantitative determination of the burnback resistance of an established foam blanket were also noted in the full-scale fire modeling tests performed at the Naval Air Station, Miramar, California (Reference 29).

Based upon previous experience, a new test procedure was developed which would tend to average the effect of the known variables insofar as possible. This was accomplished by monitoring the fire control burnback times through consecutive "burn cycles" over a period of 30 min. For the purpose of this test, one complete burn cycle was established as the sum of the fire control time and the burnback time. Fire control time is defined as the elapsed time between the initiation of the extinguishing operation to that time when the heat flux, as measured by the radiometers, is reduced to 0.20 Btu per sq ft per sec after which the agent application was terminated. The burnback time was established as the elapsed time from the instant foam application was terminated to that time when the thermal radiation had increased in intensity from 0.20 to 0.50 Btu per sq ft per sec.

The fire test environment is schematically presented in Figure 8. Fires were confined in a circular diked area, 40 ft in diameter, containing sufficient water to present a smooth surface and prevent islands from intruding through the fuel surface. The charge was 1,000 gal of JP-4 fuel. The fixed

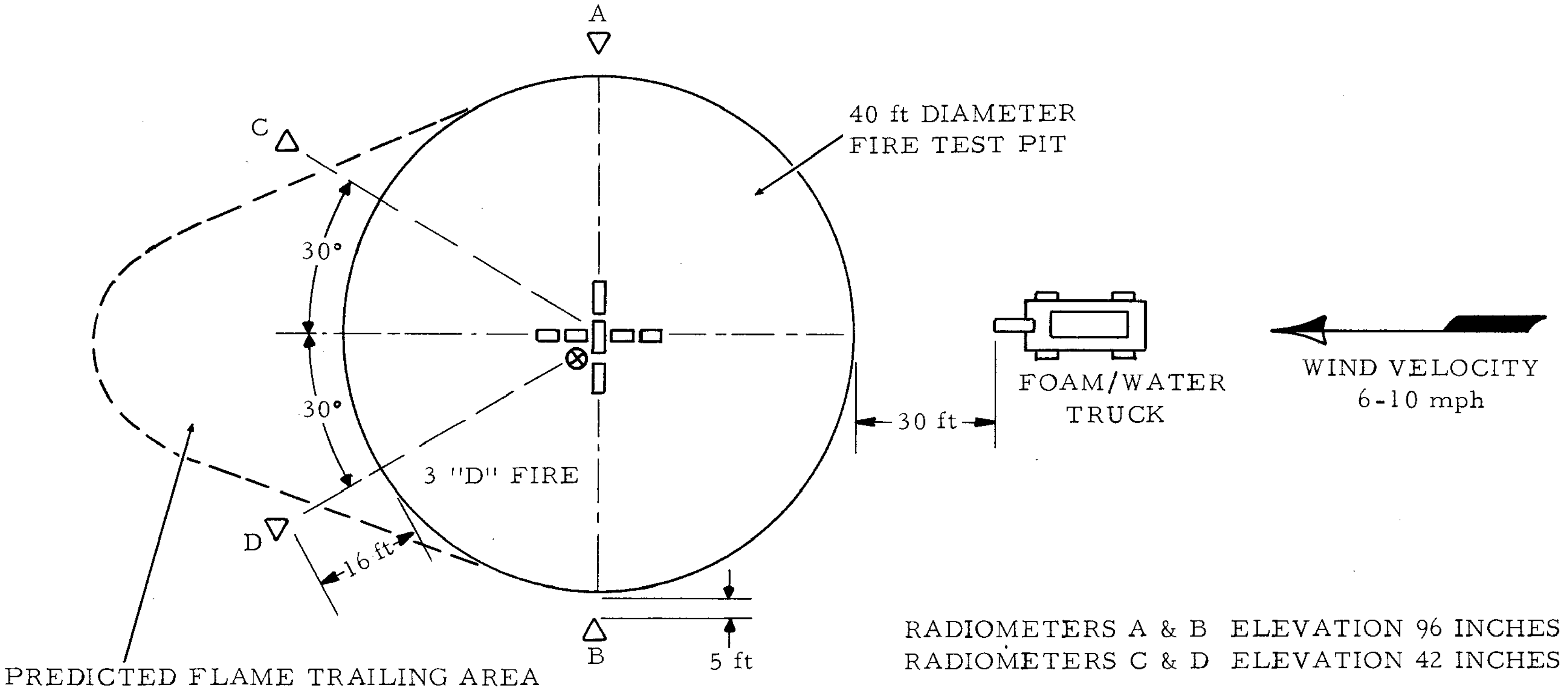


FIGURE 8 - PLAN VIEW OF THE FIRE TEST BED USED FOR MEASURING THE BURNBACK RESISTANCE OF PROTEIN FOAM AND AFFF OVER A 30-MINUTE PERIOD (NOT TO SCALE)

fire conditions incorporated a cruciform cluster of seven 55-gal steel drums as an obstacle in the center of the pool, which acted as a heat sink in support of a 3-dimensional fire that was sustained by a spray of fuel from a 4-ft-high, 0.25-in.-diameter stainless steel tube.

The instrumentation employed in monitoring the tests comprised a configuration of four radiometers positioned around the pool perimeter. Two of the radiometers were supported on steel poles 8 ft above the ground at the pool perimeter on the diameter at right angles to the wind direction. The other two radiometers were elevated 42 in. above the ground on the downwind side of the fire as shown in Figure 8. These units were placed in position only after initial fire control had been obtained to prevent their being destroyed during the 30-sec preburn period. The elevation of the four radiometers above ground level and their positions around the fire pit were determined by experiment to be capable of effectively scanning the area for fire.

The experiments were performed by discharging a 6-percent premixed solution of the agent through the air-aspirating nozzle of a foam-water truck at the rate of 400 gpm onto the 40-ft diameter fire. Foam application was started 30 sec after fuel ignition and continued until the radiant energy on the two sides was reduced to 0.20 Btu per sq ft per sec. The two downwind radiometers were then placed in position and the fire allowed to burn until any one of the four radiometers indicated a heat flux of 0.50 Btu per sq ft per sec. At this time, foam was applied until the fire was again brought under control. This sequence of events was continued for a period of 30 min.

The results obtained by this fire test procedure are summarized in the data presented in Figure 9. These profiles show the foam solution discharge period and the fire control period as a function of time. The duration of foam discharge is indicated by the length of the horizontal bar opposite the Foam Discharge Period. After fire control was obtained, the length of the lower horizontal bar opposite the Fire Control Period indicates the elapsed time before the fire burned out of control during each burn cycle.

A comparison of the fire control performance for protein and AFFF shows that protein foam allowed four burn cycles to develop during the 30-min test period, which required the application of 1,040 gal of foam solution on the fire intermittently for a total of 2.60 min, while during a similar 30-min

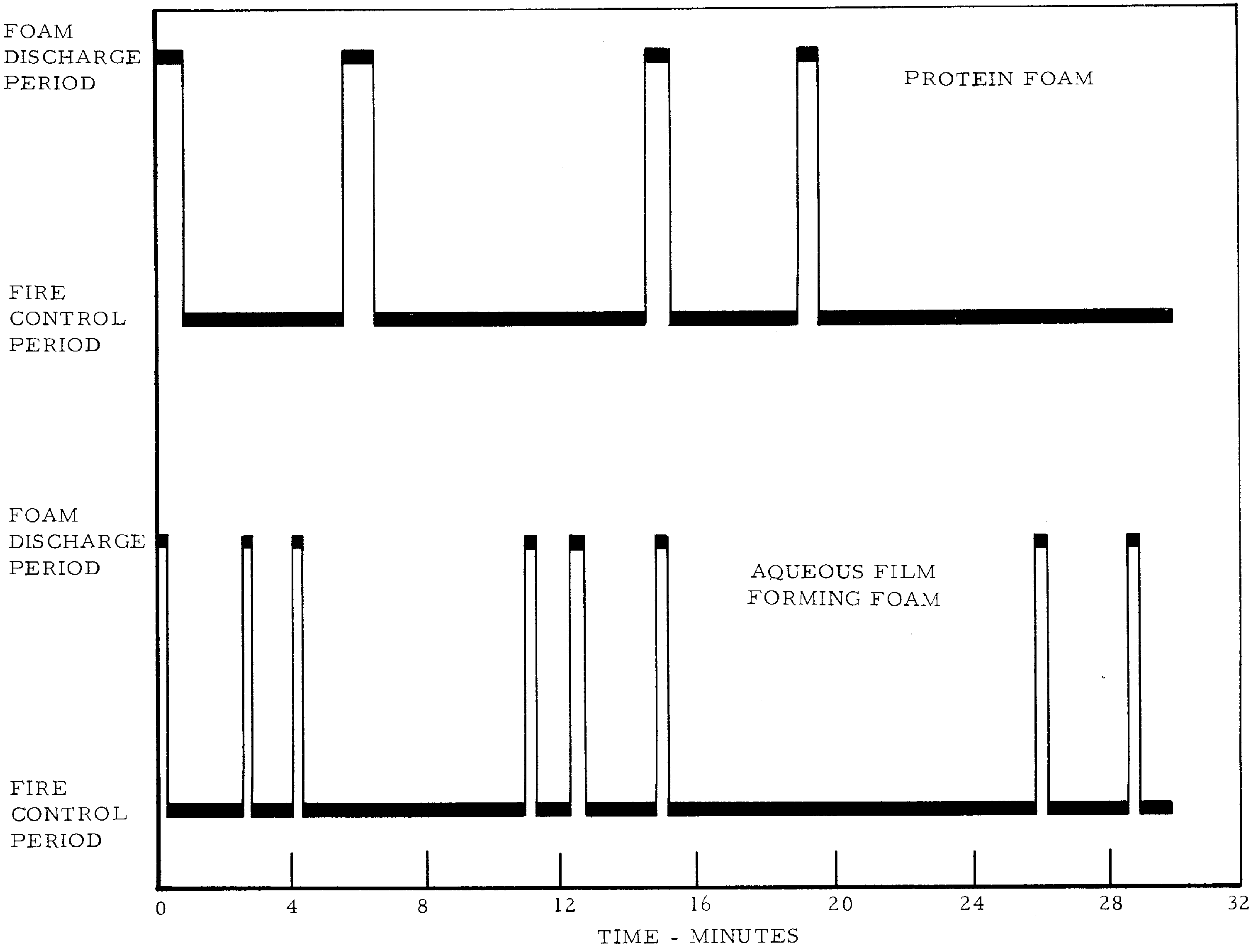


FIGURE 9 - THIRTY-MINUTE FIRE CONTROL PERIOD USING PROTEIN FOAM AND AFFF ON A 40-FOOT DIAMETER JP-4 FUEL FIRE

fire control period using AFFF, there was a total of eight burn cycles which required the application of 664 gal of foam solution discharged intermittently for a total of 1.66 min.

These performance data cannot be directly related in a practical way to actual firefighting conditions or procedures because, in each event where the fire was brought under control, the 3-dimensional fire could have been readily extinguished by the use of an auxiliary agent. However, the profiles clearly show the difference in firefighting techniques that were required to maintain control of a 40-ft-diameter JP-4 fuel fire for a prolonged period of time employing each agent. These data also indicated that it is unnecessary and uneconomical to attempt to build up a thick foam blanket, this is particularly applicable when AFFF is used. It is also noteworthy that these experiments were performed with one common type of air-aspirating foam nozzle, and the results obtained may not necessarily be representative of the performance obtained when other types of foam-dispensing equipment are employed.

K. Effect of Solution Concentration on Fire Control Time Employing Protein Foam - The effect of solution concentration on fire control time using protein foam was determined experimentally with full-scale foam-dispensing equipment because of the complex problems associated with the extrapolation of the results from the laboratory-type experiments. Individual tests were performed using six different solution concentrations on a 40-ft-diameter circular pool charged with 450 gal of fresh JP-4 fuel prior to conducting each experiment. Foam was produced by a common commercial form of air-aspirating foam nozzle at a solution rate of 400 gpm and 225 psi. The truck was positioned 30 ft upwind from the pool perimeter, and the fully dispersed foam pattern was employed exclusively. All tests were performed with the same equipment and personnel. During the time the tests were in progress, the ambient air temperature varied from 74° to 77°F and the wind velocity from 10 to 12 mph.

The quality of foam produced at each concentration in terms of expansion ratio and 25-percent-drainage time is summarized in Table XIX. From these data, it is evident that the foam-expansion ratio and 25-percent-drainage time was very low for solution concentrations from 2 to 4 percent, but as the concentration was increased from 4 to 6 percent, there were a sharp increase in these values.

TABLE XIX

VARIATION IN THE QUALITY OF PROTEIN FOAM WITH SOLUTION CONCENTRATION

Foam Solution Concentration Percent	Foam Expansion Ratio	25-Percent-Solution Drainage Time Sec
2	(estimated) 2 to 4:1	30
4	4.4:1	60
6	7.8:1	210
8	8.1:1	268
10	8.4:1	270
12	8.6:1	295

Therefore, the critical solution concentration range for this particular nozzle lies between 4 and 6 percent, as evidenced by the sharp increase in the 25-percent-drainage time and foam expansion ratio. These data also show there was little to be gained in terms of foam quality by increasing the solution concentration above 8 percent when using this foam dispensing system.

The results of the fire tests performed with foam solutions of different concentrations are summarized in Figure 10, in which solution concentration is plotted as a function of fire control time.

The curve shows that at solution concentrations below 4 percent, the fire control times increased rapidly, but between 4 and 6 percent, there was a reduction in the fire control time of approximately 10 percent, while a decrease of only 1 percent was obtained when the concentration was increased from 6 to 8 percent and a similar reduction was obtained for an increase from 8 to 10 percent. Therefore, the most effective concentration of agent, in terms of the fire control time, lies between 6 and 8 percent. These data show an interdependence of the fire control time on foam quality.

The actual fire control times obtained in these experiments are considered valid only for this particular foam dispensing unit.

L. The Effect of Water Spray on Established Blankets of Protein Foam and AFFF - A study of the relative effect of water spray on established blankets of AFFF and protein foam was considered necessary to provide information which would be useful in estimating the disruptive effect that could be caused by heavy rain or by the water discharge from firefighting equipment.

A small-scale laboratory-type water-spray test procedure was developed based upon the fire test tank and small-scale 6-gpm foam nozzle required in the federal specification. An overhead water-spray device was erected which consisted of a system of pipes supporting a water-sprinkler head over each corner of the tank. The water-sprinkler heads were adjusted to discharge a uniform spray pattern within the tank of 0.01 gpm per sq ft.

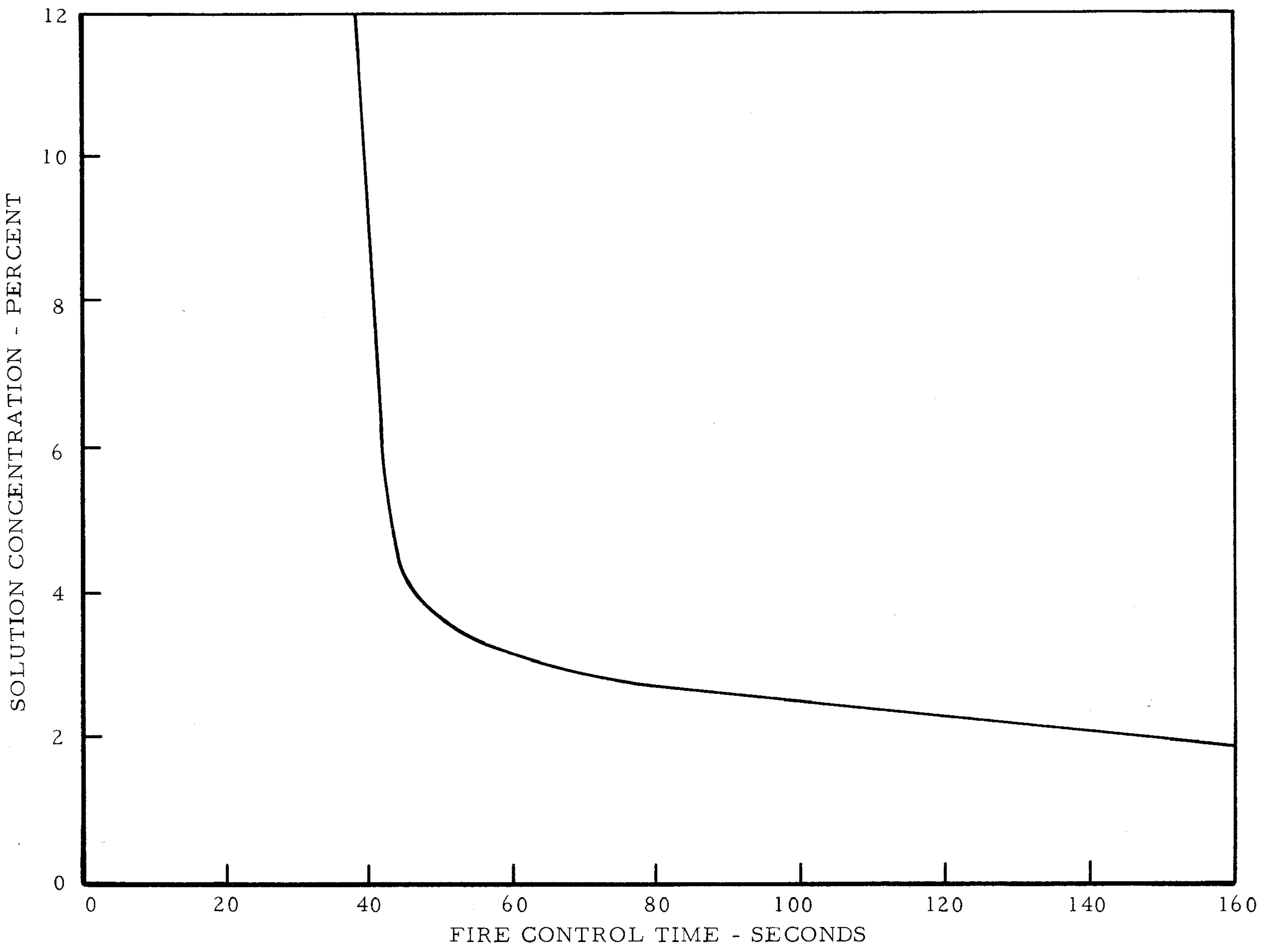


FIGURE 10 - THE EFFECT OF SOLUTION CONCENTRATION ON FIRE CONTROL TIME USING PROTEIN FOAM AND AFFF

The procedure required that the 100-sq-ft test tank be filled to a depth of 12 in. with water upon which 100 gal of JP-4 fuel was floated. The fuel was then ignited and allowed to burn for 60 sec, after which foam was discharged onto the fire for a period of 5 min and the times required to obtain control and extinguishment were recorded. In these experiments, the fire control time was judged to be the time required for 90 percent of the fuel surface to be covered by foam, and the fire extinguishment time was recorded as the total elapsed time until all flames were extinguished within the tank. The foam blanket sealability was evaluated for a period of 1 min by continually passing a lighted torch held one-half inch above the surface in accordance with the requirement of the federal specification. At the conclusion of the 1-min torching period the water-sprinkler system was activated and allowed to discharge for 30 sec, after which the system was deactivated and the torch passed over the remaining foam blanket for 1 min in an attempt to ignite any escaping fuel vapors. This entire process was repeated until permanent ignition of the fuel occurred. The number of successful water-spray cycles completed was considered a measure of the foam blanket stability.

The results of the water-spray tests using AFFF are presented in Table XX and for protein-type foam in Tables XXI through XXIV.

A bar chart relating the foam blanket stability of each agent tested is presented in Figure 11 where the number of spray cycles obtained, before blanket failure occurred, is plotted on the ordinate.

A comparison of the test results shows that the average number of spray cycles completed using AFFF was 4.2, while the average value for all protein agents was 4.6. However, if the anomolous performance demonstrated by Manufacturer B is omitted, the overall average of the remaining protein agents rises to 5.4 spray cycles. The most stable protein foam (Manufacturer A) shows an increase of 2.4 in the number of spray cycles over AFFF. However, a comparison of individual foam blanket stability within the protein class shows a variation of 4.6 spray cycles. Therefore, it is evident that a direct comparison of AFFF with an average value for protein foam would be unrealistic, and any comparison must be made with the particular protein agent under consideration.

TABLE XX

EFFECT OF WATER SPRAY ON AFFF

FOAM AGENT, AQUEOUS FILM-FORMING FOAM MANUFACTURER E-1

FOAM QUALITY: Expansion Ratio 7.5:1, Drainage Time (25%) 3:10
WIND CONDITIONS: Velocity 8 Knots, Direction 220°

Test	Fire Times		Number of Spray Cycles Completed															
			1		2		3		4		5		6		7		8	
No.	Control	Extinguish	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water
1	1:26	1:56	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-	-	-	-	-	-	-
2	1.27	1:55	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-
3	1:28	2:09	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-	-	-	-	-	-	-
4	1:35	2:07	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-	-	-
Av.	1:29	2:02								4.2								

NOTE: Foam blanket fuel vapor sealability without water-spray showed one self-extinguishing flash at 5 minutes after foam discharge. Permanent ignition occurred 7 minutes after foam discharge.

TABLE XXI

EFFECT OF WATER SPRAY ON PROTEIN FOAM (MANUFACTURER A)

FOAM AGENT, PROTEIN FOAM MANUFACTURER A

FOAM QUALITY: Expansion Ratio 8.2:1, Drainage Time (25%) 2:50
WIND CONDITIONS: Velocity 4 Knots, Direction 140°

Test No.	Fire Times		Number of Spray Cycles Completed															
			1		2		3		4		5		6		7		8	
	Control	Extinguish	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water
1	1:50	3:25	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	-
2	1:30	3:00	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	-
3	1:50	3:20	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	-	-	-
Av.	1:43	3:15							6.6									

NOTE: Foam blanket fuel vapor sealability without water-spray produced one self-extinguishing flash at 11 minutes after foam discharge. Permanent fuel ignition occurred 13 minutes after foam discharge.

TABLE XXII

EFFECT OF WATER SPRAY ON PROTEIN FOAM (MANUFACTURER B)

FOAM AGENT, PROTEIN FOAM MANUFACTURER B

FOAM QUALITY: Expansion Ratio 8:4:1, Drainage Time (25%) 3:15
WIND CONDITIONS: Velocity 7 Knots, Direction 170°

Test	Fire Times		Number of Spray Cycles Completed															
			1		2		3		4		5		6		7		8	
No.	Control	Extinguish	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water
1	2:40	4:20	1:00	0:30	1:00	0:30	1:00	FAIL										
2	2:50	5:00	1:00	0:30	1:00	0:30	1:00	FAIL										
3	3:00	4:15	1:00	0:30	1:00	0:30	1:00	FAIL										
4	3:00	FAIL	-	-	-	-	-	-										
5	3:00	4:20	1:00	0:30	1:00	0:30	1:00	FAIL										
6	3:05	FAIL	-	-	-	-	-	-										
Av.	2:52	4:29								2								

TABLE XXIII

EFFECT OF WATER SPRAY ON PROTEIN FOAM (MANUFACTURER C)

FOAM AGENT, PROTEIN FOAM MANUFACTURER C

FOAM QUALITY: Expansion Ratio 8.9:1, Drainage Time 4:20
WIND CONDITIONS: Velocity 3 Knots, Direction 100^{o}

Test	Fire Times		Number of Spray Cycles Completed															
			1		2		3		4		5		6		7		8	
No.	Control	Extinguish	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water
1	1:40	2:40	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-	-	-
2	1:55	3:00	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-
3	1:50	2:45	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-	-	-	-	-
Av.	1:48	2:48									5.0							

TABLE XXIII

EFFECT OF WATER SPRAY ON PROTEIN FOAM (MANUFACTURER C)

FOAM AGENT, PROTEIN FOAM MANUFACTURER C

FOAM QUALITY: Expansion Ratio 8.9:1, Drainage Time 4:20
WIND CONDITIONS: Velocity 3 Knots, Direction 100°

Test	Fire Times		Number of Spray Cycles Completed															
			1		2		3		4		5		6		7		8	
No.	Control	Extinguish	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water
1	1:40	2:40	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-	-	-
2	1:55	3:00	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-
3	1:50	2:45	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-	-	-	-	-
Av.	1:48	2:48								5.0								

TABLE XXIV

EFFECT OF WATER SPRAY ON PROTEIN FOAM (MANUFACTURER D)

FOAM AGENT, PROTEIN FOAM MANUFACTURER D

FOAM QUALITY: Expansion Ratio 8:1, Drainage Time (25%) 2:35
WIND CONDITIONS: Velocity 8 Knots, Direction 100°

Test	Fire Times		Number of Spray Cycles Completed															
			1		2		3		4		5		6		7		8	
No.	Control	Extinguish	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water	Torch	Water
1	1:53	3:35	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-	-	-	-	-
2	2:05	3:45	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-	-	-	-	-
3	2:15	3:40	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	0:30	1:00	FAIL	-	-
Av.	2:04	3:40									4.6							

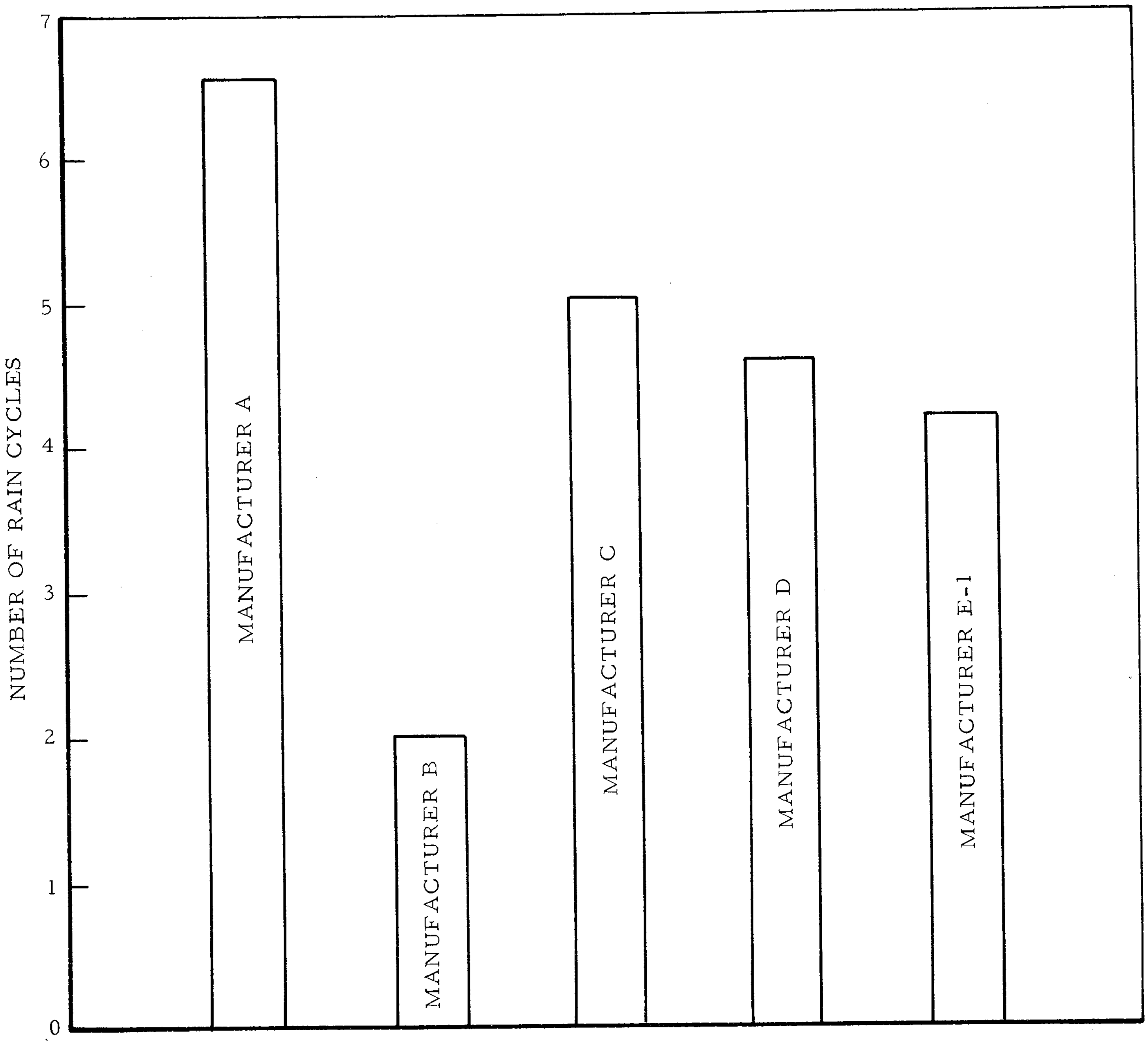


FIGURE 11 - THE STABILITY OF PROTEIN FOAMS AND AFFF IN TERMS OF WATER SPRAY CYCLES

This test was of value in the preliminary screening of candidate agents to be used in the full-scale fire tests and in detecting variations in foam quality which could be of significance in a practical firefighting situation. This is especially true in consideration of the fact that all protein agents were procured under the federal specification (Reference 6) which does not contain a water spray stability test.

The results of the experiments also indicate that the average resistance of established foam blankets of AFFF and protein foam, when considered as different classes of agents, are of the same order of magnitude.

Visual observations of foam blanket stability under moderate wind (3 to 8 mph) and water-spray conditions indicate that AFFF was more vulnerable to disruption than protein foam, excluding that supplied by Manufacturer B. This was apparently caused by the destruction of a portion of the AFFF foam blanket by the water-spray discharge, which then allowed the wind to push the foam back and widen the exposed fuel surface. From these tests it was also evident that the AFFF was more stable on the fuel than on the water surface.

The effect of water-spray discharge in combination with protein and fluoroprotein foam is reported in Reference 30.

M. <u>A Determination of the Compatibility Between AFFF and Protein Foam</u> - The primary firefighting agent employed at airports on a world wide basis is protein foam. Therefore, a very considerable effort has been directed toward the development of auxiliary or complementary agents which demonstrate an acceptable degree of compatibility with protein foam. An acceptable degree of compatibility between a primary foam agent and an auxiliary agent is considered to maintain when the use of the auxiliary agent causes no increase in the fire control and extinguishment time and the residual foam blanket has the same stability characteristics that are developed in the absence of the auxiliary agent under the same or equivalent fire conditions. This requirement is valid whether or not the complementary agent is another foam or some other type of agent. Since the two most likely foams to be employed during the same fire-rescue mission are protein foam and AFFF, the compatibility between these agents must be known.

The objective of the compatibility experiments was to determine if the sequential application of protein foam and AFFF would reveal any sign of incompatibility where they impinged on a burning JP-4 fuel surface. The first experiment was performed by discharging AFFF in accordance with the standard fire test procedure (Reference 6) until approximately 60 percent of the fuel surface was covered by foam. Then without interrupting the solution discharge, the valves were adjusted to deliver protein foam until the fire was extinguished. In the second experiment, the sequence of foam discharge was reversed.

The results of the experiments are summarized in Table XXV.

TABLE XXV

FIRE CONTROL AND EXTINGUISHMENT TIME FOR THE SEQUENTIAL APPLICATION OF AFFF AND PROTEIN FOAM

Test No. 1		Test No. 2	
AFFF 60% Foam Coverage Time min:sec	Protein Foam Fire Extinguishing Time min:sec	Protein Foam 60% Foam Coverage Time min:sec	AFFF Fire Extinguishing Time min:sec
1:35	4:35	1:55	4:30

These data indicate that there was no significant reaction between the foams when they were dispensed sequentially under the conditions established in the experiments.

A second series of tests was performed with AFFF and protein foam on 40-ft-diameter JP-4 fuel (400 gal) fires to determine the compatibility between the two foams. The AFFF formulation (Manufacturer E-3) was the most recent, and alleged by the manufacturer to conform with the military requirements for AFFF (Reference 19).

The firefighting equipment consisted of two handline nozzles with adjustable foam patterns, each capable of a solution rate of 60 gpm at 100 psi pressure. The solution application rate for all tests was 0.096 gpm per sq ft. Each experiment was monitored by two radiometers and two instrumentation-type cameras. Documentary motion pictures and still photographs were also taken of each test.

In the first test, protein foam was discharged simultaneously from both handline nozzles; in the second test, protein foam was discharged from one handline nozzle and AFFF from the second handline nozzle simultaneously; and in the third test, AFFF was discharged from both handlines simultaneously. In the second experiment, during the fire extinguishing process, the two foam streams were made to overlap approximately 15 feet down the centerline of the fire pit.

The fire control times obtained from an analysis of the radiometer data for each of the experiments are presented in Table XXVI.

TABLE XXVI

FIRE CONTROL TIME DATA FOR AFFF AND PROTEIN FOAM SINGLY AND IN COMBINATION

		Fire Control Times (From Radiometer Readings) sec		
Test No.	Foam Agents	R1	R2	Average
1	Protein Foam	28.6	29.4	29.00
2	Protein Foam and AFFF	22.4	23.3	22.85
3	AFFF	23.0	21.2	22.10

The results of these experiments showed no incompatibility to exist between the foams produced by these agents when applied simultaneously on a JP-4 fuel fire at a solution application rate of 0.096 gpm per sq ft.

Wicking started over the AFFF blanket approximately 2 minutes after foam application had ceased and proceeded to spread over a large part of the foam blanket. No permanent ignition of the fuel substrate occurred as a result of the wicking except when the foam and aqueous film had been blown from the fuel by the wind. Photographs showing the effects of wicking which occurred during this experiment are presented in a previous section of this report.

At the conclusion of this series of tests, a new candidate AFFF-type liquid (Manufacturer A-1) was submitted for demonstration. One experiment was performed with this agent on the same test bed that was used in the previous tests. The average fire control time obtained was 27.8 sec, and the residual foam blanket showed the usual wicking action associated with this class of agents when employed on highly volatile fuels, but it was considered less extensive than that observed with some other formulations of AFFF.

During the fire-extinguishing process using Manufacturer's A-1 product, a very rapid reduction in the radiant energy from the fire plume was observed which suggested the possibility that some of the foam solution had been pyrolyzed, which resulted in the release of free radical(s) that were effective in disrupting the chain reaction responsible for flame propagation.

Auxiliary Firefighting Agents

General:

This class of compounds is considered to include dry-chemical powders, magnesium fire-extinguishing agents, and liquid vaporizing agents, which may be employed either singly or in combination with foam to accomplish a particular mission in post-crash aircraft firefighting operations. The following discussion includes a brief description of some of the current and recently developed auxiliary agents.

The mechanism whereby some chemical firefighting agents are capable of greater efficiency in extinguishing Class B fires than would normally be expected from a consideration of either their physical or chemical properties alone was not a major part of this project. However, since the effort did employ both dry-chemical powders and vaporizing liquids as auxiliary agents, a brief description of the chain-breaking mechanism responsible for the functioning of these agents is included.

The chemical agents are generally categorized as heterogeneous or homogeneous depending on whether they are dispensed as solids or liquids (vapor). Their primary function upon entering the fire plume is to combine with the free-radicals which are considered responsible for the propagation of the flame.

The alkylhalides are the most common homogeneous flame inhibitors and they have received intensive study. Their principal function is to provide the active moieties necessary to combine with the chain carriers in the combustion wave. The active moieties produced in the flame which are responsible for the continuation of active combustion are O, H, OH, and other more complex fragments of the fuel molecules. The removal of these species from the flame by combination with the dissociated moieties derived from the pyrolysis of the homogeneous inhibitor is believed responsible for the high-extinguishing efficiency of these agents.

The heterogeneous flame inhibitors comprise a vast number of salts and powders. Of all the salts available, only those of the alkali metals have found general acceptance. The mechanism of combustion suppression by means of powders has been considered from two points of view. The solid particles may provide an absorbing surface where the active species can combine or the salt may pyrolize to provide the active chain-breaking moieties necessary to inhibit the combustion process. A third method by which flames may be inhibited is by reducing the flame temperature by the application of powder. Laboratory experiments have indicated that all chemically inert powders with suitable particle size distribution may act as flame inhibitors. However, their effect is of a lower order of magnitude than that obtained with chemically active powders, such as Purple-K powder, Super K, CDC, and others.

A survey and bibliography of some current theories germane to flame inhibition by chemical means are presented in Reference 31.

Dry-Chemical Powders - Over a period of many years, an extensive body of data, literature, and opinion has been developed around the extinguishing properties of the bicarbonates of first sodium, and then potassium, as well as other salts, such as, monoammonium phosphate and potassium sulfate. During this long development period, the performance characteristics of the various dry-chemical agents on small fires have been assigned to matched combinations of powders and equipment by the UL and others. Therefore, it was concluded that a small-scale laboratory evaluation of these agents would, in fact, contribute little to the goals of the program and experiments were accordingly limited to a determination of the performance of the newer agents on large JP-4 fuel fires. A summary of the fire-extinguishing ability of four different dry-chemical powders is presented in Reference 32.

Recent developments in dry-chemical technology include a composition based upon potassium chloride which was demonstrated to be equal to, or superior to, PKP for the extinguishment of hydrocarbon fires, and to show a high order of compatibility with protein foams (Reference 33).

Typical fire-extinguishing data developed by one manufacturer for a particular brand of dry-chemical powders dispensed from a variety of hand-portable extinguishers are presented in Figure 12. These curves show the relative extinguishing power of the different single salt component systems. One current system used to rate the fire quenching effectiveness of dry-chemical extinguishers on Class B fires requires that the dry-chemical powder and dispensing equipment be evaluated as a unit (Reference 34). This procedure is necessary because the effectiveness of the unit is greatly influenced by the physical characteristics of the powder discharge rate and pattern. Other factors influencing firefighting performance are powder density, particle size and distribution, flow characteristics, and the chemical effectiveness of the agent. While these parameters are all critical individually, their combined effect on large outdoor pool fires is less apparent than they are on small indoor pan-fires.

In general, the dry-chemical powders have contained a single salt in a more or less pure form, to which small quantities of other compounds have been added to improve the storage and flow characteristics. A recent departure from this single salt formulation concept was made in a recent commercial development (MONNEX) (Reference 35). This powder composition was divulged to comprise a new composition of matter and its manufacture is contained in two British Patents (References 36 and 37).

According to Reference 36, the general composition of the powder is claimed to contain urea in combination with at least one active fire-extinguishing agent selected from salts and hydroxides of alkali metals. Specific alkali metal

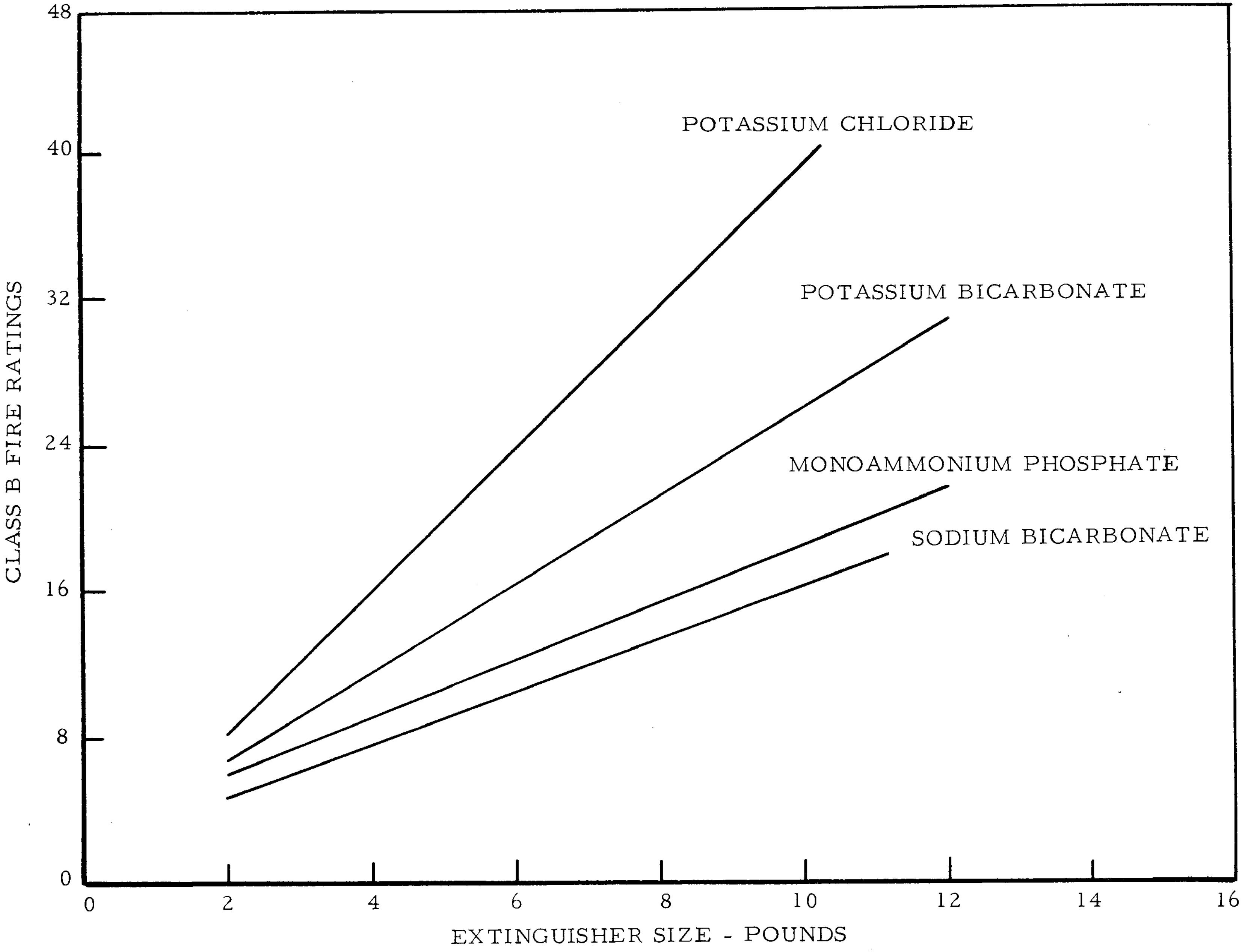


FIGURE 12 - RELATIVE EFFECTIVENESS OF FOUR DIFFERENT SALTS COMMONLY EMPLOYED IN DRY-CHEMICAL POWDER COMPOSITONS

salts, such as potassium bicarbonate, may vary from 10 to 70 percent by weight of total compound. In Reference 37, a composition of matter is claimed comprising the reaction product of urea and at least one alkali selected from bicarbonates, carbonates, sesquicarbonates, and hydroxides of sodium and potassium with the empirical molecular formula $MC_2N_2H_3O_3$ where M represents an atom of potassium or sodium. These novel compounds may well establish a new concept for the future development of dry-chemical powders.

The firefighting characteristics of all dry-chemical powders may be regarded to be of the "go" or "no-go" type. That is, the fire is either completely extinguished and the environment allowed to cool below the flash point of the fuel, or the fire will reflash. No significant blanketing or fuel vapor suppression effect is produced by any of these agents in their present state of development. Therefore their use as the primary agent in aircraft crash firefighting must take into account any ignition source which could initiate flashback. It is for this reason that current powder development trends are directed toward high-capacity dispensing systems capable of discharging powder at rates of several tons per min for periods in excess of 2 min with an effective range of 150 feet.

In an effort to reduce this enormous powder requirement, the combined application of foam and powder has been the subject of intensive investigation. To be successful, the combined system required the development of a fuel vapor-sealing foam blanket which was stable in the presence of large quantities of dry-chemical powder. Therefore, a considerable portion of the current research effort, by both the Federal Government and industry, has been directed toward achieving this goal. The results of large-scale fire tests performed at NAFEC (Reference 3), with incompatible powder-foam combinations, resulted in an almost complete cancellation of the firefighting effectiveness of both agents, and fire control was never obtained. Therefore, the importance of using mutually compatible agents in all aircraft firefighting operations cannot be overemphasized. The results of large-scale foam-powder compatibility tests which are representative of aircraft crash-fire situations are summarized in the schematic drawing in Figure 13.

In this sketch, the dashed lines are drawn connecting the foam agents with the dry-chemical powders which demonstrated an acceptable degree of compatibility when dispensed from representative airport equipment on large aircraft-fuel fires (Reference 3). In these experiments, an acceptable

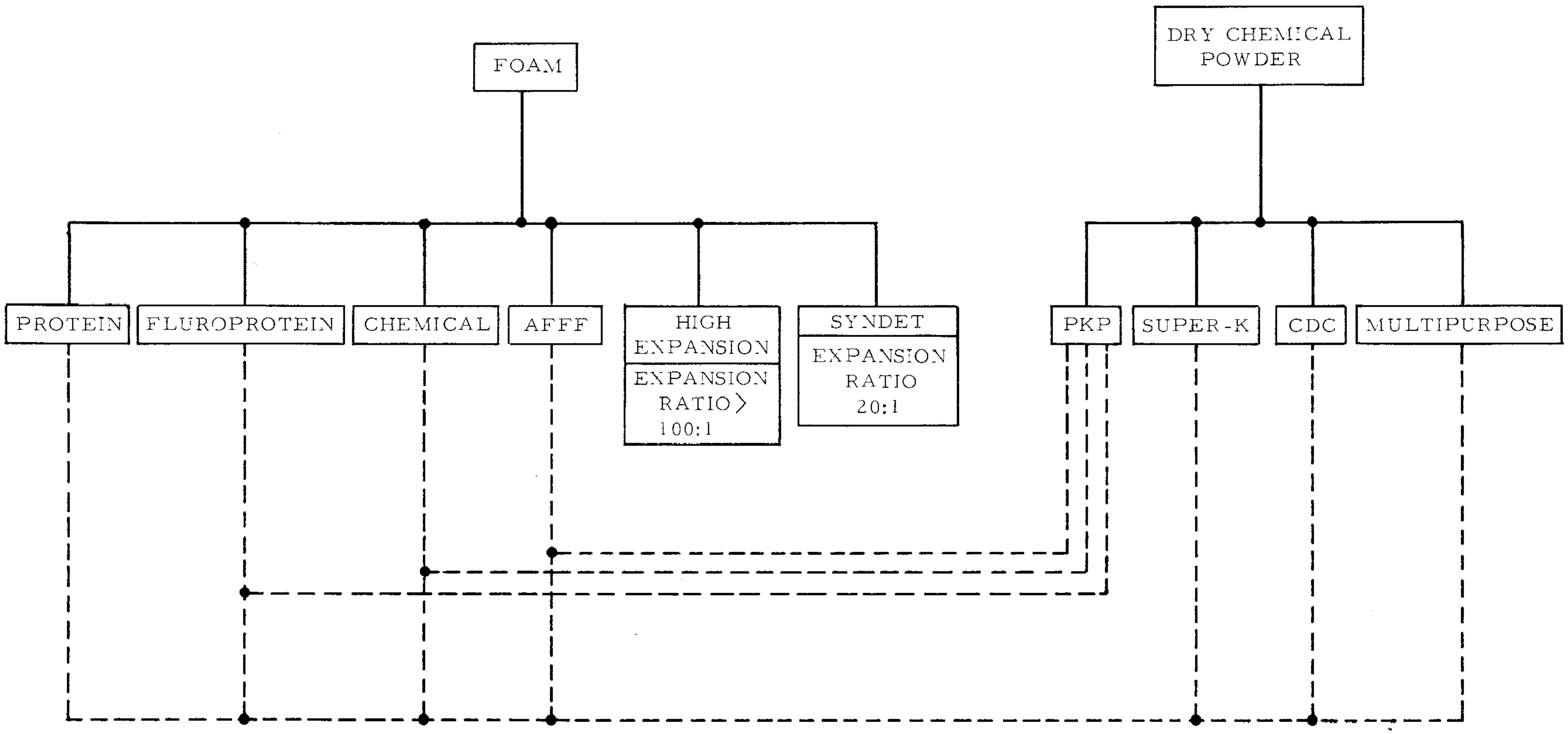


FIGURE 13 - SCHEMATIC DIAGRAM SHOWING VARIOUS COMBINATIONS OF FOAMS AND DRY-CHEMICAL POWDERS FOUND TO BE SUITABLE FOR COMBINED APPLICATION ON LARGE AIRCRAFT-FUEL FIRES

degree of compatibility was considered to maintain when no reduction in the fire control time was realized by the combined agent discharge over that obtained by foam alone.

Although the scope of this project precluded the evaluation of dry-chemical powders as a primary firefighting agent in crash fire situations, a series of five demonstrations was performed with PKP and an agent which had not previously been evaluated in experiments conducted at NAFEC. These demonstrations were performed by the equipment manufacturer and the powder manufacturer under test conditions established in a previous project effort.

The fire test bed employed a 40-ft-diameter JP-4 pool fire containing a cruciform configuration of five 55-gal vented steel drums in the center of the pit. A 3-dimensional fire was established in the approximate center of the pool by discharging JP-4 fuel from a 0.25-in.-diameter stainless steel tube at the rate of approximately 2 gpm into a 9.5- by 6.5- by 4.25-in. steel pan on the downwind side of the drums.

The powder unit employed in the demonstrations was capable of discharging dry chemical at a nominal rate of 16 lb per sec through two 150-ft lengths of 1-in. (inside diameter) hose simultaneously. At the end of the 30-sec preburn time, two expert firefighters attacked the fire simultaneously and dispensed the powder at their own discretion to achieve maximum effectiveness.

To conserve the agent employed in each test, a maximum discharge time of 45 sec was established. This procedure was acceptable to all concerned, since previous experience had shown that if the fire could not be extinguished progressively within 45 sec, continued discharge was ineffective.

The results of the five experiments are summarized in Table XXVII.

Observations made during the demonstrations and from an analysis of the photographic coverage indicated that the powder discharge rate was at or near the threshold value for both agents. Therefore, the wind velocity had a pronounced effect upon the extinguishing potential of the dry chemicals. The reflash potential of fuel vapors during powder discharge appeared to be greater at wind velocities over 10 miles per hour, while the optimum velocity appeared to be below 5 miles per hour. The overall effect produced by the lower wind velocities was to minimize flame turbulence and to permit a longer residence time for the powder in the flame environment.

TABLE XXVII

FIRE EXTINGUISHING CHARACTERISTICS OF PURPLE-K POWDER AND A NEW CANDIDATE DRY-CHEMICAL POWDER (MONNEX)

Test No.	Agent	Fire Area sq ft	JP-4 Fuel gal	Fire Preburn Time sec	Extinguishing Time sec	Powder Discharge Rate lb per sec	Wind Velocity mph
FPB-1	PKP	1256	400	30	Not Extinguished	16.7	5-8
FBP-2	PKP	1256	400	30	Not Extinguished	---	2-4
FBM-1	MONNEX	1256	400	30	Not Extinguished	17.5	12-15
FBM-2*	MONNEX	1256	400	30	25.8	25	2-5
FBM-3*	MONNEX	1256	400	30	Not Extinguished	---	2

* During experiments FBM-2 and FBM-3, trouble was experienced with the equipment's pressure regulator valve.

Small unextinguished peripheral fires outside the bunded area may serve as reignition sources and prevent fire extinguishment. In experiment FBM-3, a small fire burning 10 feet on the downwind side of the fire may possibly have served as a reignition source and prevented the extinguishment of this fire. However, the firefighters considered this unlikely, and in general, their opinion was substantiated by photographic analysis.

The relative effectiveness of these two agents in extinguishing a 3-dimensional fire, for which they are particularly suited, was not established. However, the results do tend to indicate that the actual firefighting efficiency of one agent in terms of another may be, in fact, of purely academic significance and that a more realistic approach to achieving greater firefighting efficiency, per se, would be to conduct a systems evaluation including both equipment and agent for each unit developed for airport use.

The following five dry-chemical powders have found acceptance in combatting Class B fires and several are commercially available in either the regular type which is not compatible with protein foam or the protein-foam-compatible type. The regular and foam-compatible-type powders demonstrate equal firefighting effectivenes for each chemical composition, and the main reason both types are being produced is one of cost, with the regular agents having the price advantage.

<u>Sodium Bicarbonate Base Powder (Foam Compatible CDC)</u> - This agent is procured under a military specification (Reference 38), and its compatibility with protein-type foam has been satisfactorily established. It is also listed and rated by the UL for use in extinguishing Class B fires when dispensed by suitably designed equipment.

<u>Potassium Bicarbonate Base Powder (Purple-K Powder, PKP)</u> - Purple-K powder is procured under a military specification (Reference 39), and it is rated by the UL for use in the extinguishment of Class B fires when dispensed from suitable equipment. The results of work performed under this program show that PKP is not compatible with protein foam.

<u>Monoammonium Phosphate Base Powder, Multipurpose Type</u> - This powder composition is intended for use on Classes A, B, and C fires. This material is compatible with protein foam (Reference 40) and was verified by laboratory experiments.

Potassium Chloride Base Powder (Super K) - This powder composition resulted from research directed toward achieving maximum powder compatibility with protein foams while maintaining the high firefighting efficiency of PKP. The results which show compatibility with protein foam are contained in a NASL report (Reference 33) and were verified under this program.

Monnex-Dry Chemical Powder - The chemical composition of Monnex dry-chemical powder is treated in a previous section. The formulations submitted for evaluation under this program were not compatible with protein foam.

Liquid Vaporizing Agents: An extensive body of technical data has been developed for this class of agents with regard to its relative firefighting efficiency on Class B fires. A comprehensive report was published in January 1960 (Reference 41) which presents a summary of the physical and chemical properties and an investigation of the firefighting effectiveness of five liquid vaporizing agents. Although this report is now 11 years old, the data are completely valid today because these agents are employed in a relatively pure state.

Of the five agents considered in Reference 41, only two in addition to bromochloromethane (Halon 1011) (CB) were selected for evaluation. These were bromochlorodifluoromethane (Halon 1211) (BCF) and 1,2-dibromotetrafluoroethane (Halon 2402) (DBTF). The Halon numbering system was initially employed by Engineering Research and Development Laboratories (ERDL), and a description of the method is contained in Reference 42.

A comparative evaluation of the selected halocarbon by research techniques, such as measuring the burning velocity of a premixed flame and determining its reduction by extinguishants, was not within the scope of this effort. The purpose of the tests which were developed, and the experiments performed with Halon 2402 and Halon 1211, were intended to simulate 3-dimensional fire situations which would be representative of the type encountered in aircraft accidents.

One fire condition common to many aircraft accidents is the flow of fuel down an incline. This condition was simulated by constructing a trough on an incline composed of compacted clayey soil 15 ft wide and 20 ft long. The JP-4 fuel was discharged at the rate of 12 gpm through five holes in a horizontal pipe positioned across the top of the incline. Prior to ignition, the fuel was permitted to completely saturate the ground within the boundaries of the trough, and the discharge of fuel was continued for the duration of the test. The fuel, which was not burned during its passage down the trough, was collected in a 5-ft by 10-ft earthen diked area at the bottom of the incline. A schematic drawing of the fire test pit is presented in Figure 14.

A second hazard prevalent in many aircraft accidents is the engine fire or fire associated with a ruptured wing tank. The jet engine fire was simulated by a mockup employing three 55-gal steel drums, with their tops and bottoms removed, welded together endways. Supported concentrically within these drums was a configuration of six 5-gal steel pails welded together endways with their tops and bottoms intact. A fuel line leak was simulated by discharging JP-4 fuel at the rate of 8 gpm from three 0.25-in.-diameter holes drilled in a stainless steel pipe located on the top inside section of the 55-gal drums so as to spray fuel over the surface of the 5-gal pails beneath. A 0.5-in.-diameter hole was drilled in the underside of each drum to allow the excess fuel to drain into a 10-ft by 5-ft diked area beneath the mockup. The entire drum configuration was supported on legs which positioned it horizontally and 32 in. above ground level. A schematic drawing of the simulated jet engine mockup is presented in Figure 15.

All of the fire-extinguishing experiments conducted in this series were performed by the manufacturer's technical experts. The firefighters had no previous experience in the use of Halon 2402 in the extinguishment of fires in these particular test beds; therefore, there was a learning factor inherent under each test condition.

Fire Tests Employing Halon 2402 - The Halon 2402 employed in these tests was a specially refined product that is currently being produced in commercial quantities. The chemical and physical properties of pure Halon 2402 are presented in Appendix E.

The equipment employed to dispense the liquid halocarbon consisted of one commercially available wheeled unit and two portable hand extinguishers. These units were equipped with special hand-activated dispensing nozzles and could be pressurized by gases which were either soluble or insoluble in the halocarbon.

A sketch of the dispensing equipment is presented in Figures 16 through 19. The nozzles, which were adaptable to either type unit, are shown in Figures 17 and 18.

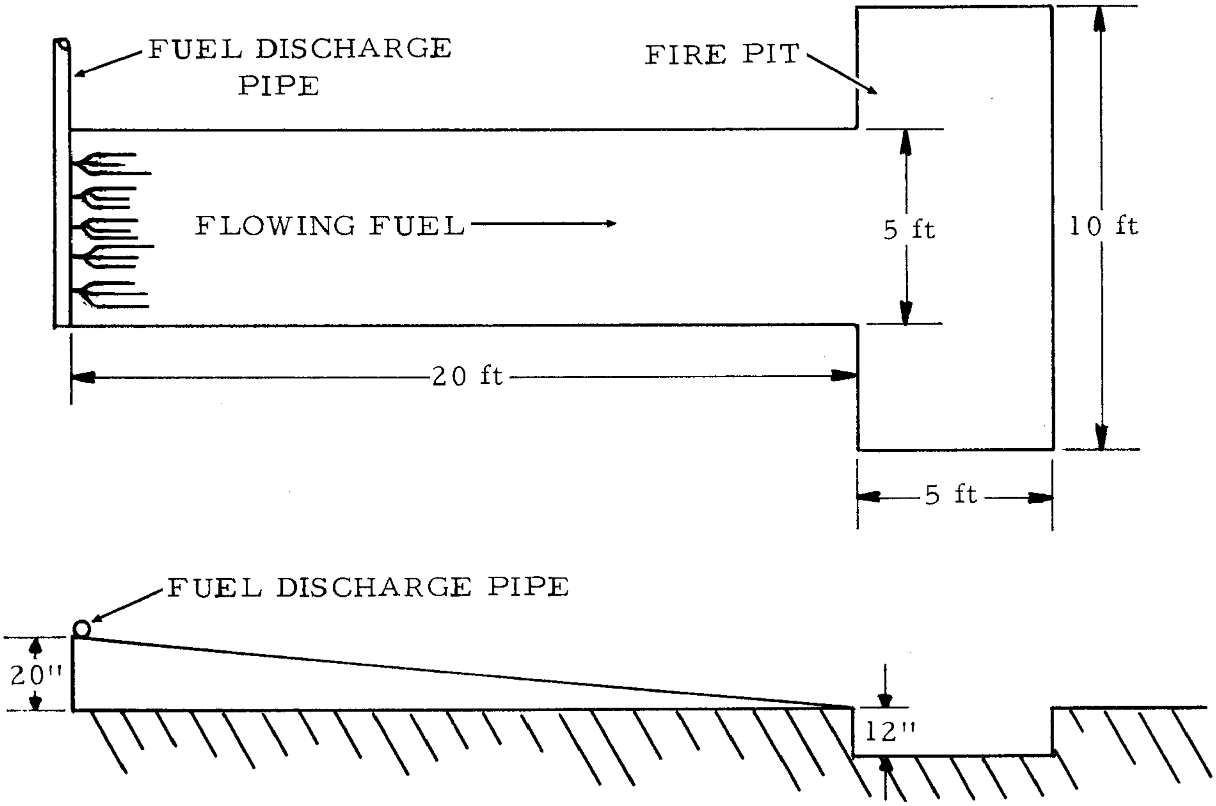


FIGURE 14 - SCHEMATIC DRAWING OF THE FLOWING FUEL FIRE TEST BED

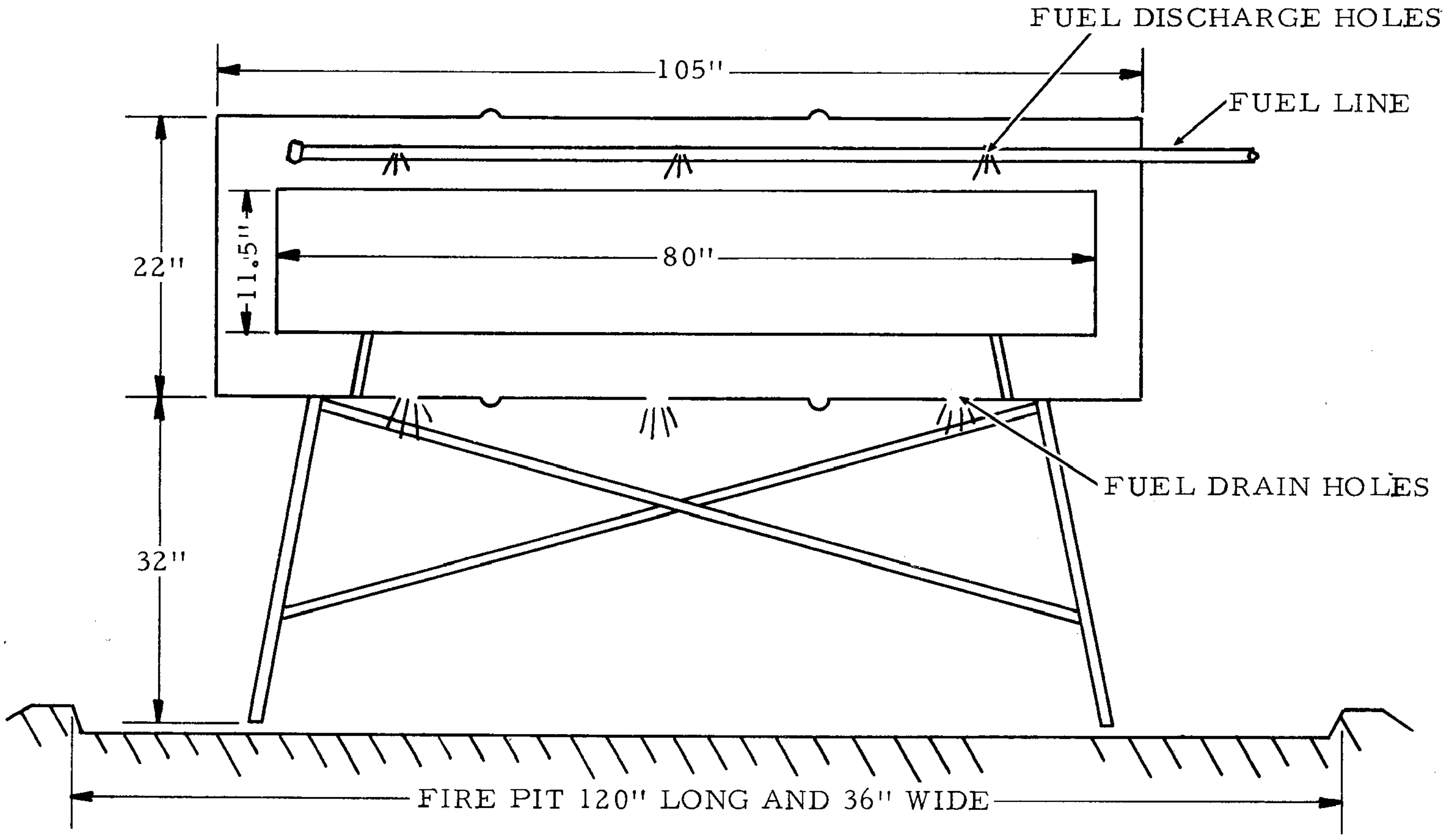


FIGURE 15 - SCHEMATIC DRAWING OF THE SIMULATED JET ENGINE MOCKUP

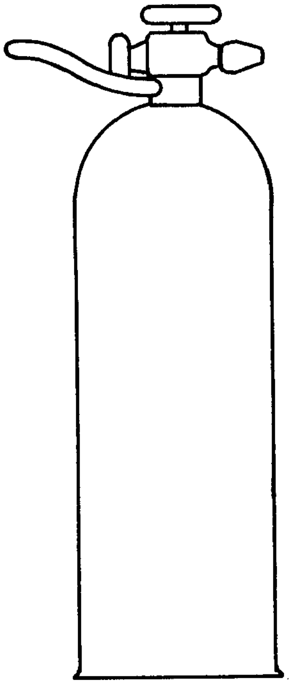


FIGURE 16 - HAND-PORTABLE FIRE EXTINGUISHER

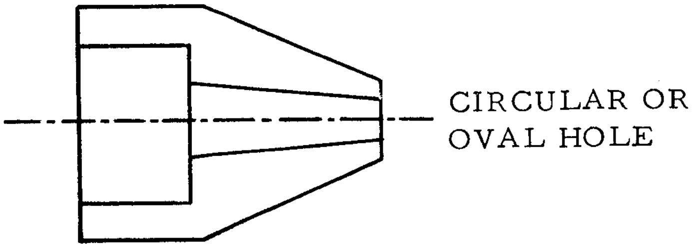


FIGURE 17 - NOZZLE FOR EXTINGUISHERS PRESSURIZED WITH INSOLUBLE GASES

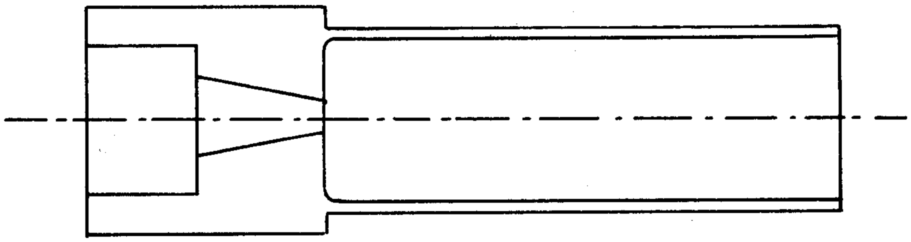


FIGURE 18 - NOZZLE FOR EXTINGUISHERS PRESSURIZED WITH SOLUBLE GASES

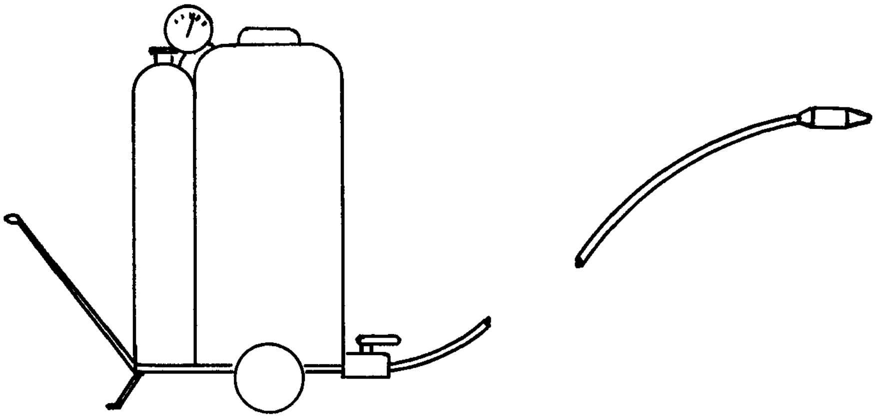


FIGURE 19 - CART-MOUNTED FIRE EXTINGUISHER

The nozzle shown in Figure 17 was designed for use when an insoluble gas, such as nitrogen, is used to pressurize the extinguisher while Figure 18 shows the nozzle, recommended by the manufacturer, when the pressurizing gas is soluble in the halocarbon. All of the experiments conducted in this series employed nitrogen as the pressurizing gas.

The objective of the flowing-fuel fire tests was to extinguish the fire as rapidly as possible with the smallest quantity of agent after a 30-sec preburn period. The method of attack was to apply the agent from the upwind side of the incline at the full discharge rate with a side-to-side swinging motion and as close to the ground as possible.

The results of four fire tests performed with Halon 2402 on the flowing-fuel test bed are presented in Table XXVIII. Tests 1, 2, and 4 employed the cart-mounted unit which discharged the halocarbon at the rate of 5.2 lb per sec; while Test 3 was performed with the hand-portable extinguisher at a discharge rate of 1.2 lb per sec.

The data show that the fire was successfully extinguished in both Tests 1 and 2, but that the time required was twice as long in Test 1 as in Test 2. The lower extinguishment time obtained in Test 2 is attributed to the improvement in operational skill and technique learned by the operator from Test 1. It is considered noteworthy that, in Tests 1 and 2, when the halocarbon was discharged at the top of the incline, it mixed rapidly with the burning fuel which was extinguished and did not reignite during the remainder of its passage down the trough. The data obtained in Test 3, employing the hand-portable unit, indicate that the discharge of the halocarbon was probably below the minimum necessary to extinguish the fire. In Test 4, an effort was made to extinguish the fire with the halocarbon which remained in the wheeled unit after Test 2, but it was found to be insufficient and the attempt was aborted.

The objective of the simulated jet engine fire tests was to extinguish the fire within the drum configuration as rapidly as possible, employing the smallest amount of agent after the 30-sec fire preburn time. The method of attack was to apply the agent from the upwind side of the fire and down the annulus between the drums at the full discharge rate. The stream was then directed rapidly from the center of the drums to the ground, as required, to obtain the most rapid fire extinguishment.

The results of the simulated jet engine fires are presented in Table XXIX. The results of Tests 5 and 6

TABLE XXVIII
FLOWING JP-4 FUEL FIRE TESTS USING HALON 2402
(JP-4 Fuel flow Rate 12 gpm)

Test No.	Liquid Discharge Pressure	Fire Exting. Time	Agent Discharge Time	Wt. of Agent Used	Agent Discharge Rate	Equip. Employed
	psi	sec	sec	lb	lb per sec	
1	165	20	20	104	5.2	1
2	165	10	10	52	5.2	1
3	118	not extng	28	34	1.2	2
4	165	not extng	12	partially filled cylinder	---	1

TABLE XXIX

SIMULATED JET ENGINE FIRE TESTS USING HALON 2402
(JP-4 Fuel Flow Rate 8 gpm)

5	165	23	23	88	3.8	1
6	200	9	9	33	3.7	1
7	165	not extng	19	34	1.8	2
8	165	not extng	23	34	1.5	2

show similar fire-extinguishing performance to that demonstrated in Tests 1 and 2, in that experience gained in Test 5 enabled the operator to apply the discharge more effectively to the fire in Test 6. The increased discharge pressure employed in Test 6 was not considered, by the manufacturer, to be significant in reducing the fire extinguishing time.

The results of Tests 7 and 8 indicate only that the agent application rate was below the minimum necessary to obtain fire extinguishment.

The test procedures developed in this study incorporate two of the basic types of fuel spills encountered in severe aircraft accidents; namely, (1) the flow of fuel down an incline and along the ground, and (2) fuel dripping from above into a pool on the ground. These conditions were demonstrated to be significant in the evaluation of 3-dimensional type agents and the training of personnel in the use of vaporizing liquids under conditions for which they are particularly suited.

The test beds developed in this study were duplicated by one manufacturer, and the results of their experiments are reported in Reference 43.

Fire Tests Employing Halon 1211 - The technical data reported in the literature concerning the relative effectiveness of Halon 2402, Halon 1211, and Halon 1011 in flame extinction experiments precluded the necessity to perform additional laboratory type experiments. For example, the effectiveness of Halon 1211 as a fire-extinguishing agent was investigated (Reference 44) by means of the explosion tube technique in which the concentration of the agent required to prevent the burning of a methane-air mixture was determined. The results of these experiments indicated that for the three agents listed above, the order of decreasing effectiveness on a weight basis was Halon 1211, Halon 1011, and Halon 2402. On the other hand, a series of experiments was performed (Reference 45) in which the flammability peaks were determined, which showed the decreasing order of effectiveness to be Halon 1011, Halon 2402, and Halon 1211. From these data it is apparent that laboratory studies are of value in establishing the relative effectiveness of different agents under a given set of test conditions, but should not be used to establish application rates for practical outdoor fire situations.

In recognition of the difficulties inherent in interpreting the practical fire-quenching efficacy of a homogeneous fire-extinguishing agent from laboratory data, a series of quantitative experiments was performed with Halon 1211 on the same two test beds that were used in the evaluation of Halon 2402. The results of these demonstrations indicated that Halon 1211 was highly effective as a fire-extinguishing agent when it was applied at relatively close range to the seat of the fire. The effective range of the equipment used in combatting these fires was estimated to be from 15 ft to 18 ft, while that for the Halon 2402 was estimated to be 32 ft. The maximum range to which a liquid vaporizing agent can be discharged is primarily a function of its boiling point. Therefore, Halon 2402 (B.P. 47.26°C) and Halon 1011 (B.P. 67°C) are the most suitable agents for long-range outdoor discharge, while Halon 1211 (B.P. 3.4°C) is more advantageous in confined areas or in situations where minimum flooding time is of paramount importance. However, the differences in the boiling points, per se, do not preclude the use of these agents under conditions which may be considered overlapping under actual fire conditions when portable equipment is employed.

Because of its low-boiling point, Halon 1211 must be stored in pressure vessels and transferred from one container to another under closed conditions. Steel drums or metal cans are adequate for the shipment and handling of Halon 1011 and Halon 2402; but a large quantity of these agents may be lost by pouring from one container to another, and it is customary to transfer both agents by means of suitable pumps.

As a result of the study reported in Reference 41, Halon 1211 was determined to be a promising agent for optimum ground-fire protection. In addition, Halon 1211 was reported to be slightly more effective in extinguishing ability and to show an approximate tenfold toxicity improvement over Halon 1011.

Fire Tests Employing Halon 1011 - Halon 1011 is the most widely used liquid vaporizing agent in current use, and its procurement by the Federal Government (Reference 46) is measured in the millions of pounds per year. Therefore, it is understandable why it has been the subject of extensive technical and practical investigations. The results of one major effort in this regard is contained in Reference 41, in which Halon 1011 was used as a standard for the comparison of four other vaporizing halocarbons.

Some of the factors which contribute to the usefulness of Halon 1011 in aircraft incidents are its cleanliness and firefighting effectiveness on Class B fires, the ease of handling, and relatively low cost by comparison with other vaporizing liquids. Among its disadvantages are the high-toxicity rating assigned by the UL method, the corrosiveness to metals, and its high solvency toward many synthetic materials.

The comparative life hazard ratings assigned by the UL method (Reference 5) to the agents considered in this laboratory investigation in the order of increasing toxicity are: Halon 1211 (Group 5), CO_2 (Group 5), Halon 2402 (Group 5 or 4), and Halon 1011 (Group 3). According to a recent report supplied by one manufacturer, the UL rating for a highly purified and commercially available Halon 2402 is 5 (Reference 43). The physical properties of pure Halon 1011 are presented in Appendix E.

Carbon Dioxide Employed as a Fire-Extinguishing Agent: The wealth of literature available on the use of both high- and low-pressure CO_2 precluded the necessity to evaluate this agent in the laboratory study.

Carbon dioxide is effective as a Class B fire-extinguishing agent primarily because it reduces the oxygen content of the air by dilution to a point where it will not support combustion. Under certain conditions of application, low-pressure CO_2 also has some cooling effect on the fire. Because CO_2 functions solely as a diluent of oxygen in the combustion of hydrocarbon fires, an equivalency rating of 2:1, on a weight basis, is suggested by the International Civil Aviation Organization (ICAO) (Reference 47) when compared with dry-chemical powder.

Magnesium-Fire Extinguishing Agents: The quantitative evaluation of magnesium-fire extinguishing agents was beyond the scope of this project. However, a series of qualitative experiments was performed with two dry powders and one solution, which were reported to be useful in the extinguishment of metal fires, including magnesium and magnesium alloys.

The test bed for the experiments was constructed by suspending a magnesium alloy aircraft wheel, weighing approximately 5.5 lb, from a steel pipe supported by two cinder blocks, over two 9- by 8.5- by 2.75-in. steel pans containing

JP-4 fuel (Figure 20). After ignition, the fuel was permitted to burn until the magnesium wheel ignited, which required from 20 to 25 min, before the extinguishing agent was applied.

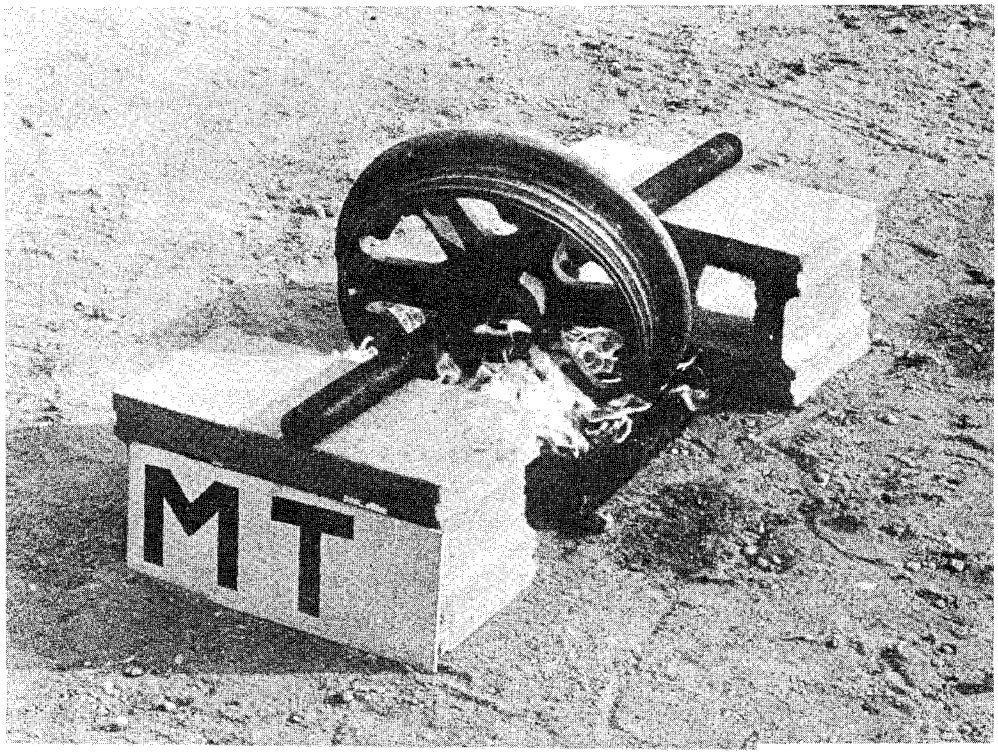
TEC Magnesium-Fire Extinguishant - The experiments were performed by discharging TEC dry powder from a standard hand-portable extinguisher onto the glowing magnesium aircraft wheel, in several short bursts. Within a few seconds, the Class B fire was extinguished and the brilliant white glow of the burning magnesium was replaced by the yellow glow characteristic of molten sodium salts, and the fire was rapidly extinguished. The TEC powder granules were very fine and demonstrated good flow characteristics and blanketing of the burning metal surface. The firefighter expressed a feeling of confidence and a sense of control over the operation during all phases of extinguishment.

The effect of TEC powder on protein foam was evaluated by the method presented in Appendix F, and found to be incompatible. Therefore, in situations where TEC is employed to extinguish magnesium fires within an area protected by protein foam, breakdown must be considered and the powder discharge limited to the burning metal.

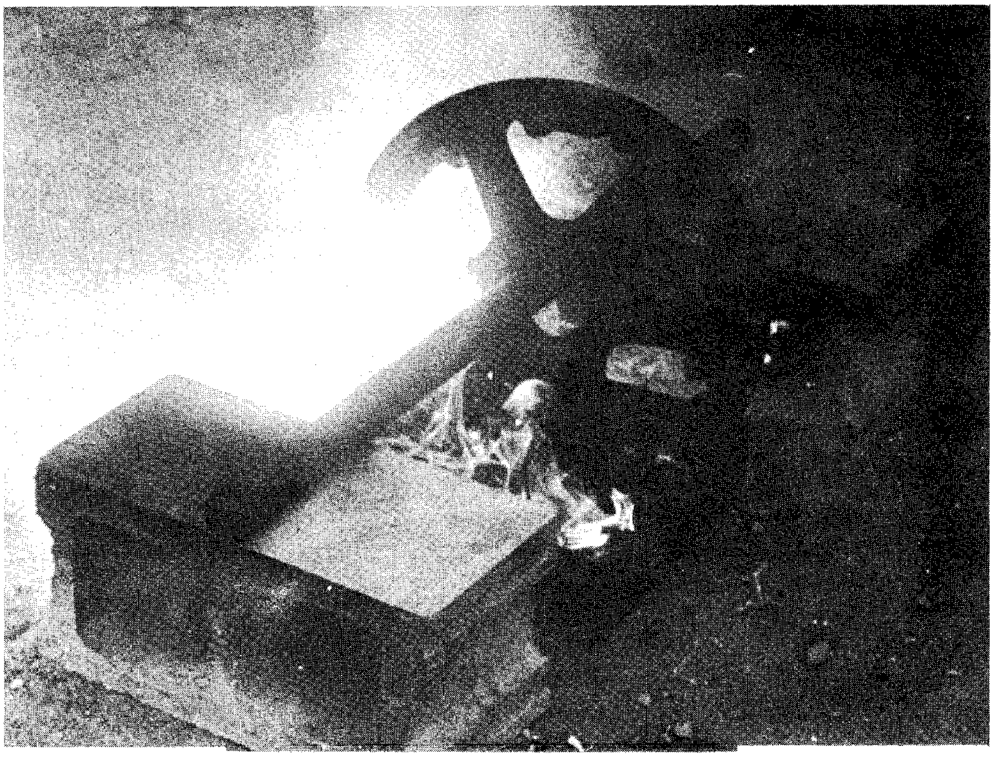
MET-L-X Magnesium-Fire Extinguishant - Magnesium fire-extinguishing experiments were performed using MET-L-X on the same test bed that was employed in the evaluation of TEC. MET-L-X is a sodium chloride-base powder with additives which render it free-flowing and moisture repellent. A thermoplastic material is incorporated in the powder to bind the sodium chloride particles into a solid mass which covers the molten metal under fire conditions. This reaction forms an air-excluding crust which results in the extinguishment of the burning metal.

MET-L-X was a coarser powder than TEC, but both agents rapidly extinguished the burning magnesium wheels through the formatiom of a molten slag-like material on the hot metal surface.

The compatibility between MET-L-X and protein foam was determined by the method presented in Appendix F, and found to be incompatible. However, both TEC and MET-L-X were determined to be compatible with AFFF.



(a) MAGNESIUM FIRE TEST BED (PREIGNITION)



(b) BURNING MAGNESIUM AIRCRAFT WHEEL

FIGURE 20 - CLASS D FIRE EXTINGUISHING AGENT TEST BED USING A MAGNESIUM AIRCRAFT WHEEL

Bromochloromethane and di-2-ethylhexyl phthalate (DOP) Mixture Magnesium-Fire Extinguishant - One experiment was performed with the test bed previously described, in which the extinguishant was a mixture of equal parts by weight of Halon 1011 and DOP, which has been previously shown (Reference 48) to be of value for this purpose.

The test was conducted by discharging the solution from a stored-pressure-type hand-portable extinguisher onto the burning magnesium wheel at the discretion of the operator. The effect produced on the fire by the initial discharge was spectacular in that copious quantities of white vapor interspersed with dense black smoke were immediately liberated. These fumes caused choking and a feeling of nausea when inhaled. The effect upon the fire was nil after 2 gal of the mixture had been discharged, so the fire was extinguished by MET-L-X. No other experiments were performed with this agent, because it was considered too hazardous by all in attendance to be conducted without the assistance of some form of respiratory apparatus.

Summary of Results

The results obtained, from a review of the literature and other knowledgeable sources and from laboratory-type experiments, are:

1. The most effective fuel vapor securing and blanketing agents were determined from the experimental results to be AFFF and 6-percent protein-type foam.

2. The AFFF and protein-foam agents were not found to affect grease, rotary shaft packing, or elastomeric materials seriously either as the concentrate or 6-percent solution. The foams did produce some corrosion of the test metals as indicated in this report.

3. A reduction in firefighting effectiveness was obtained when AFFF (sea water compatible) was mixed with water having a hardness of 470 ppm and tested in accordance with the requirements of Federal Specification O-F-555b. (Determined by tests performed with one manufacturer's product.)

4. The effects of water hardness (470 ppm) on the quality and firefighting effectiveness of protein foam, when tested in accordance with the requirements of Federal Specification O-F-555b, were negligible.

5. The foam solution temperature was determined to have a greater effect upon foam quality, with regard to the foam expansion ratio and 25-percent-solution drainage time, than the ambient air temperature.

6. The effect of different types of terrain on JP-4 fuel spill fires was to increase the fire control and extinguishing time for both protein-type foam and AFFF over that required for water-base pool fires.

7. The mutual compatibility between the protein-foam liquids currently listed on the QPL, in terms of the sediment produced in aging tests, is in excess of the maximum allowable in the federal specification for most binary combinations.

8. The extinguishment of pure polar-solvent spill fires requires that 6-percent-protein foam be employed at higher solution application rates than those required for hydrocarbon fires of equal size. Protein foam was determined to be effective for the control and extinguishing of hydraulic fluid and jet engine oil fires. The foam blanket demonstrated adequate stability in contact with the burning fluids.

9. The burnback resistance of AFFF was approximately 50 percent of that obtained with protein-type foam when measured in terms of the number of burn cycles completed during a 30-min fire control period. During the 30-min fire control period, approximately 35 percent less AFFF solution was consumed than protein-foam solution.

10. The most effective solution concentration for protein foam, in terms of fire control time, was determined to be from 6 to 8 percent by volume for one particular air-aspirating mechanical foam nozzle.

11. The resistance of established blankets of protein foam to disruption by water-spray discharge, in the spray-cycling tests, was found to vary widely between the different products listed on the QPL. However, the average number of spray cycles obtained for all protein-foam agents tested was approximately the same as that obtained for the single AFFF agent.

12. There is no incompatibility between protein foam and AFFF when they are dispensed from separate nozzles, either sequentially or in combination on JP-4 fuel fires.

13. A flame-wicking action was obtained with all AFFF-type agents on JP-4 fuel fires.

14. The syndet and high-expansion foams are capable of obtaining rapid control and extinguishment of JP-4 fuel fires at low-solution application densities, but their vulnerability to wind and limited vapor securing characteristics restrict their use as primary crash firefighting agents.

15. Halon 2402 was effective in extinguishing 3-dimensional JP-4 fuel fires under ambient outdoor conditions.

16. Halon 1211 was effective in extinguishing JP-4 fuel fires in semi-enclosed areas where very rapid vapor flooding was required, but not in combatting large outdoor fires.

17. AFFF demonstrated an acceptable degree of compatibility when paired with Purple-K powder, Compatible Dry Chemical, Super K, All-Purpose dry chemical, and Monnex.

18. The 6-percent protein agents demonstrated an acceptable degree of compatibility when paired with Compatible Dry Chemical, Super K, and All-Purpose dry chemical.

19. Burning magnesium aircraft wheels were extinguished by the application of either TEC or MET-L-X dry chemical discharged from hand-portable extinguishers.

20. MET-L-X and TEC were not compatible with protein foam but were compatible with AFFF.

21. A mixture of equal parts by weight of CB and DOP was not effective in extinguishing a burning magnesium aircraft wheel when discharged from a 2.5-gallon portable fire extinguisher.

Conclusions

Based upon the results of laboratory-type experiments and from a review of the literature and other knowledgeable sources, it is concluded that:

1. The most effective fuel vapor securing and blanketing agents are protein foam and AFFF.

2. Hard water may cause a reduction in the foam expansion ratio and 25-percent drainage time, and an increase in the fire control and extinguishing times when it is employed with some formulations of AFFF type agents.

3. The type of terrain is a factor in determining the control and extinguishing times of spill fires employing either protein foam or AFFF.

4. The bulk storage of mixtures of protein foam liquid procured from different manufacturers listed on the QPL, may result in the development of sufficient sediment to prevent the accurate proportioning of the foam liquid into the water stream during foam production.

5. Established blankets of AFFF and protein foam floating on JP-4 fuel demonstrate equal resistance to disruption by water-spray discharge.

6. Water-spray tests can serve as a means for estimating the stability of mechanical foam blankets produced by protein foams and AFFF.

7. Protein foam and AFFF may be dispensed by their nozzles in any combination of sequences to accomplish a given fire-rescue mission.

III. AN EVALUATION OF THE U.S. AIR FORCE A/S32P-2 FIREFIGHTING TRUCK USING PROTEIN FOAM AND AFFF

Introduction

The purpose of this effort was to obtain the data necessary to evaluate the firefighting effectiveness of the A/S32P-2 foam-water truck dispensing AFFF, and to compare the results obtained with those reported by the U.S. Navy employing the MB-5 truck.

Discussion

A detailed account of the test methods and procedures are presented in Appendix G.

Summary of Results

The results obtained from a determination of the foam quality and fire extinguishing effectiveness of the A/S32P-2 vehicle are:

1. AFFF (Manufacturer E-1) dispensed by the agent system on the U.S. Air Force A/S32P-2 and the U.S. Navy MB-5 vehicles at approximately equal solution application rates resulted in essentially equivalent fire control and extinguishing times as the foam solution application rates approached the threshold value.

2. The quantity of foam solution per sq ft of fire area required to control and extinguish a JP-4 fuel fire with AFFF (Manufacturer E-1) decreased as the fire size increased.

3. The quality of protein foam dispensed by the A/S32P-2 bumper nozzle and the roof turret nozzle was equivalent.

4. AFFF and protein foam liquids may be proportioned accurately by means of the system provided on the A/S32P-2 vehicle.

Conclusions

Based upon the results of foam quality experiments and fire-extinguishing tests conducted with the U.S. Air Force A/S32P-2 vehicle, it is concluded that:

1. The firefighting effectiveness of the AFFF (Manufacturer E-1) dispensed by the U.S. Air Force A/S32P-2 and the U.S. Navy MB-5 vehicles is essentially equal on large JP-4 fuel fires at the threshold value.

2. The application of AFFF at rates in excess of the optimum for a particular fire size is wasteful of the agent.

3. The roof turret nozzle and bumper nozzle on the A/S32P-2 vehicle may be employed interchangeably to provide different solution discharge rates with foam of equal quality.

IV. A COMPARATIVE EVALUATION OF A MODIFIED U.S. AIR FORCE 0-11A FIREFIGHTING TRUCK DISPENSING CHEMICAL FOAM WITH A U.S.. AIR FORCE A/S32P-2 FIREFIGHTING TRUCK DISPENSING MECHANICAL FOAM

Introduction

The objective of this effort was to conduct tests and obtain the data necessary to develop a meaningful comparison between the firefighting efficiency of a U.S. Air Force A/S32P-2 truck using mechanical protein foam and a converted 0-11A truck dispensing chemical foam on water-base pool fires and on traprock base fires, and to determine the degree of compatibility between chemical and mechanical foams and PKP.

Discussion

The test methods and procedures are presented in Appendix H.

Summary of Results

The results obtained from a determination of the foam quality and firefighting effectiveness of the U.S. Air Force A/S32P-2 vehicle and the converted 0-11A chemical foam truck are:

1. A longer foam-discharge time was required to obtain fire control for chemical foam than for protein foam at equal solution application rates.

2. A higher foam-solution application rate and a longer discharge time was required to obtain fire control for both chemical and protein foams when employed on traprock-base fires than on conventional water-base pool fires.

3. From 25 to 30 percent of the chemical foam and all of the protein foam were destroyed during the small-scale foam-powder compatibility tests after the 4-minute burn period.

4. Approximately 29 percent of the protein foam and 38 percent of the chemical foam blankets were destroyed during the heat-resisitance experiments after 4 minutes.

5. A significant quantity of the total volume of chemical foam discharged onto the pool-fires was destroyed by the turbulence resulting from the plunging action of the high-velocity foam stream.

Conclusions

Based upon the results of tests conducted with the U.S. Air Force A/S32P-2 vehicle and the converted 0-11A chemical foam truck, it is concluded that:

1. Protein foam is more effective in controlling JP-4 pool fires than chemical foam at equal solution application rates.

2. Traprock-base JP-4 fuel fires are more difficult to control than water-base pool fires when using either protein or chemical type foams.

3. Protein foam is incompatible with PKP.

4. Chemical foam is compatible with PKP.

5. Protein and chemical foams demonstrate equal burnback resistance.

6. Protein foam is more resistant to the destructive effects caused by stream plunging than chemical foam.

V. AN EVALUATION OF THE U.S. AIR FORCE FIRE SUPPRESSION KIT (FSK) AND THE EFFECT OF HELICOPTER ROTOR WASH ON PILOT RESCUE TIME

Introduction

The purpose of this effort was to determine the firefighting effectiveness of the U.S. Air Force FSK dispensing protein foam and AFFF singly and in combination with CB under conventional pool-fire conditions, and on traprock-base fire surfaces. One experiment was also performed using fluoroprotein foam for comparison with the other two agents. A simulated pilot rescue mission was conducted by opening and maintaining a fire-free path to the cockpit of an F-86 fuselage using the FSK alone and in combination with the helicopter rotor-wash.

Discussion

A detailed account of the test methods and procedures are presented in Appendix I.

Summary of Results

The results obtained from a determination of the foam quality and firefighting effectiveness of the U.S. Air Force FSK using protein foam and AFFF singly and in combination with CB are:

1. The fire control and extinguishing times using protein foam on JP-4 fuel fires were longer when CB was added to the water compartment of the FSK than when protein foam was employed alone.

2. A significant reduction in the quality of protein foam, in terms of the expansion ratio and 25-percent-solution drainage time, resulted when CB was added to the water compartment of the FSK.

3. The fire control and extinguishing times for JP-4 fuel fires using AFFF alone were basically the same as when CB was added to the water compartment of the FSK.

4. No appreciable reduction in the quality of AFFF in terms of the expansion ratio and 25-percent-solution drainage times resulted when CB was added to the water compartment of the FSK.

5. During the initial CB discharge, the visibility through the flames was greatly improved, which afforded the operator a clear view of his objective.

6. The traprock-base fires were more difficult to control than the water-base pool fires using protein foam singly or in combination with CB or with AFFF in combination with CB. Only AFFF employed alone was capable of controlling the traprock-base JP-4 fuel fire.

7. The F-86 aircraft fuselage skin failed (melted) in 40 sec or less when exposed to severe JP-4 fuel fires which emphasizes the necessity for conducting the most rapid rescue mission possible.

8. A very hazardous environmental condition was developed inside the cockpit of the F-86 fuselage, due to the high heat flux, within 10 sec after fuel ignition, even though the air temperature remained relatively low.

9. A comparison of the fire control time data developed under equivalent fire conditions, with and without the use of helicopter rotor-wash, shows that the rotor-wash had a tendency to increase the air temperature and to decrease the heat flux. Since approximately 60 percent of the total destructive thermal energy of a free burning pool fire may be caused by radiation from the plume, considerable advantage may be gained in obtaining rapid fire suppression by the controlled use of rotor-wash.

10. AFFF alone and in combination with CB were both superior to regular protein foam in opening and maintaining a fire-free path to the aircraft cockpit.

11. AFFF and protein foam were both superior to fluoroprotein foam in securing a fire-free path to the aircraft cockpit.

12. The thermal data show that the most effective use of the FSK was obtained using the helicopter rotor-wash when the fire rescue path extended from the fire perimeter to the cockpit of the aircraft and was from 25 to 30 ft in width.

Conclusions

Based upon the results of tests conducted with the U.S. Air Force FSK using protein foam and AFFF, singly and in combination with CB, it is concluded that:

1. CB should not be added to the water compartment of the FSK when dispensing protein foam.

2. CB may be added to the water compartment of the FSK when dispensing AFFF to accelerate flame knockdown and improve visibility.

3. The type of terrain may have a significant effect on the fire control and extinguishment times of JP-4 fuel fires.

4. The survival time for an F-86 fuselage is 40 sec or less under severe fire conditions.

5. All aircraft personnel should be adequately protected from bodily exposure to thermal radiation during evacuation in aircraft accidents involving fire.

6. The controlled use of helicopter rotor-wash is effective in reducing the thermal radiation from the fire plume.

7. The primary objective of the initial attack, using the FSK, should be to establish a rescue path from 25 to 30 ft wide to the cockpit of the aircraft.

VI. A DETERMINATION OF THE QUALITY OF PROTEIN FOAM AND AFFF REQUIRED TO OBTAIN THE MOST RAPID FIRE CONTROL AND EXTINGUISHING TIMES FOR LARGE JP-4 FUEL FIRES

Introduction

Objective: The objective of these experiments was to determine the optimum quality of protein foam and AFFF in terms of the foam expansion ratio, 25-percent-solution drainage time, and foam viscosity required to achieve the most rapid fire control and extinguishing times of large traprock-base JP-4 fuel fires.

Background: The results of the laboratory evaluation indicated that protein foam and AFFF were the most acceptable agents for use in aircraft accidents involving fire. The firefighting effectiveness of these agents was determined in part to be a function of quality of foam produced by the dispensing system.

Therefore, it was evident that the most meaningful contribution to current foam technology would be achieved by determining the optimum foam quality required by each foam agent to achieve the most rapid fire control times.

From the laboratory experiments, it was apparent that there are certain significant differences in the quality of foam produced from the same equipment by the various protein agents listed on the QPL. Since all of these liquids were presumed to have met all of the physical requirements of the federal specification (Reference 6), the differences were partially attributed to variations in the chemical composition of the agents. Therefore, to negate any possible adverse side effects which might accrue through the mixing of the different protein foam liquids, a single agent was selected from those listed on the QPL which had been previously determined to be most representative of the class. This agent was employed in all subsequent fire tests.

Discussion

Foam Fire-Extinguishing Agents

A. AFFF - The AFFF employed in the foam quality evaluation tests was designated as Manufacturer E-3, and it was claimed by the manufacturer to be compatible with sea water. This was a newly developed agent at the time the foam quality experiments were in progress and the supply was limited.

Therefore, to effect the maximum economy in the conduct of the foam pattern determinations, which required relatively large quantities of foam liquid, a hydrocarbon base synthetic detergent (Orvus K) (Reference 52) was substituted for the AFFF liquid. This syndet used at a concentration of 2 percent by volume in the foam pump and air-aspirating systems, produced foam with an expansion ratio and 25-percent-solution drainage time equivalent to the AFFF agent.

B. Protein Foam Agent - The protein-foam liquid concentrate employed in these tests was manufactured to conform with the requirements of the federal specification (Reference 6).

Test Methods

A. Foam Quality Determinations - The quality of protein foam and AFFF was determined, in terms of the expansion ratio and 25-percent-solution drainage time, in accordance with NFPA methods (Reference 9). A third physical property of firefighting foams not included as a requirement in current federal and military specifications is viscosity. Numerous publications are available in the literature which describe suitable methods for determining the viscosity of firefighting foams, and several of these methods are presented in References 53 and 54.

The instrument employed in measuring the foam viscosity in these experiments is shown in Figure 21. Essentially, the instrument consists of a constant speed rotating torsion wire and vane which may be adjusted to shear a sample of foam held in a special container.

The torsion wire and vane are rotated by geared motor in the head of the instrument. The torsion wire is enclosed in a brass tube on the downward facing spindle of the gear box. Attached to the lower end of this tube is an adjustable circular scale which is divided into 100 divisions. The vane is attached to the torsion wire which is also fitted with a steel disk of sufficient size to keep the wire taut. These components are arranged so that they can be moved vertically as a unit, and the sliding head is fitted with adjustable stops which can be preset so that when the head is depressed the vane is fully emersed in the foam to its uppermost edge.

Foam Dispensing Equipment

A. Air-Aspirating Nozzles - Two different air-aspirating foam nozzles were employed in these experiments. One (Nozzle A) was a composite unit comprising two 500-gpm foam dispensing units and two 500-gpm water-discharge nozzles

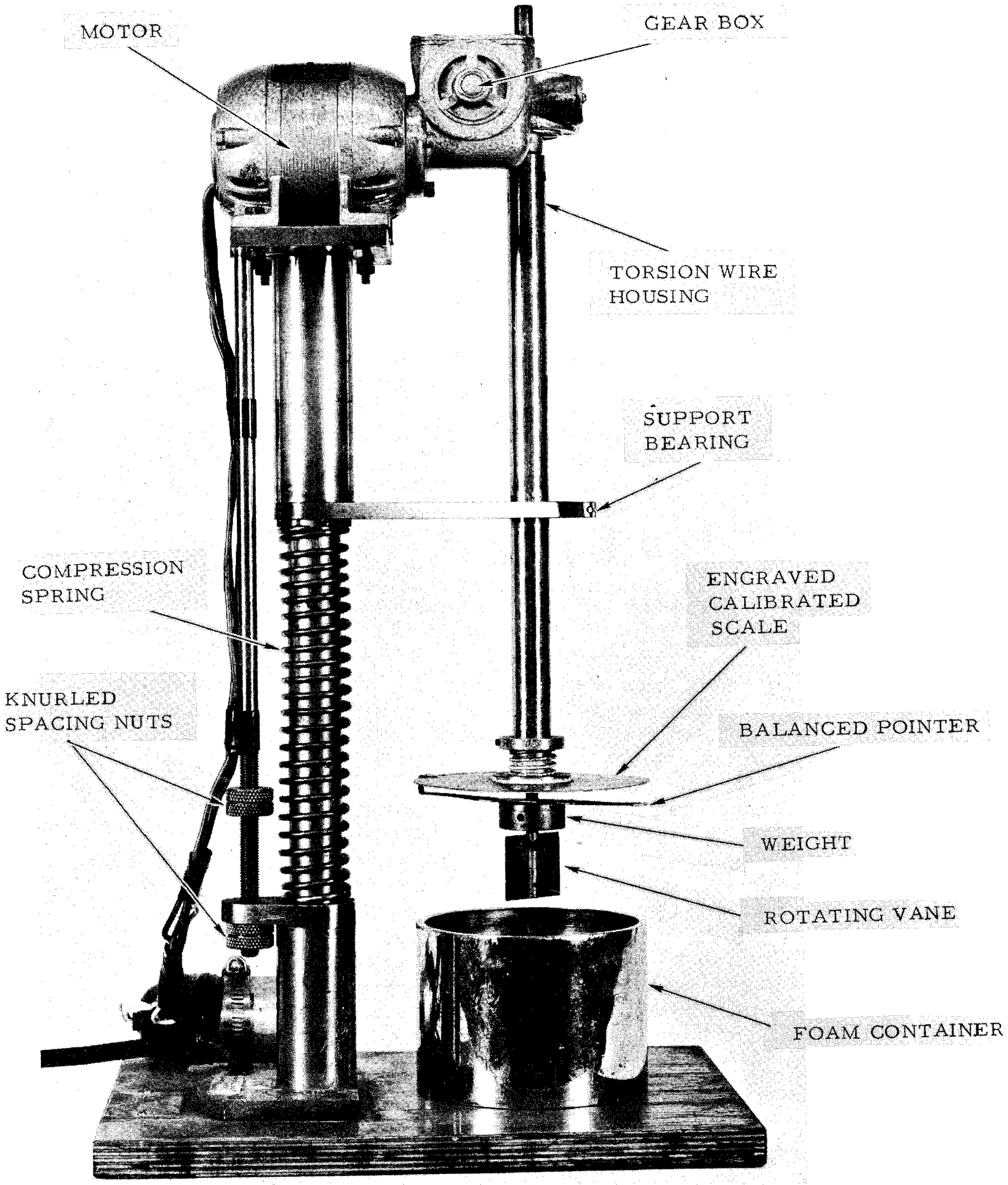


FIGURE 21 - FOAM VISCOMETER

enclosed in a metal housing. The foam and water dispensing systems were arranged so that in both systems the nozzles could be discharged either singly or in combination. A photograph of the configuration of Nozzle A is shown in Figure 22.

The second air-aspirating foam nozzle (Nozzle B) was a specially designed, single-barrel unit with a nominal solution discharge rate of 800 gpm. This nozzle was capable of imparting high energy to the foam stream by creating a condition of high shear and turbulation to the foam during passage through the barrel. A photograph of Nozzle B is shown in Figure 23.

Prior to performing the large-scale fire tests, a series of experiments was conducted to determine some of the more important physical characteristics of each dispensing system. These data were of value in establishing the most effective foam quality for each agent to achieve the shortest fire control time at different solution application rates.

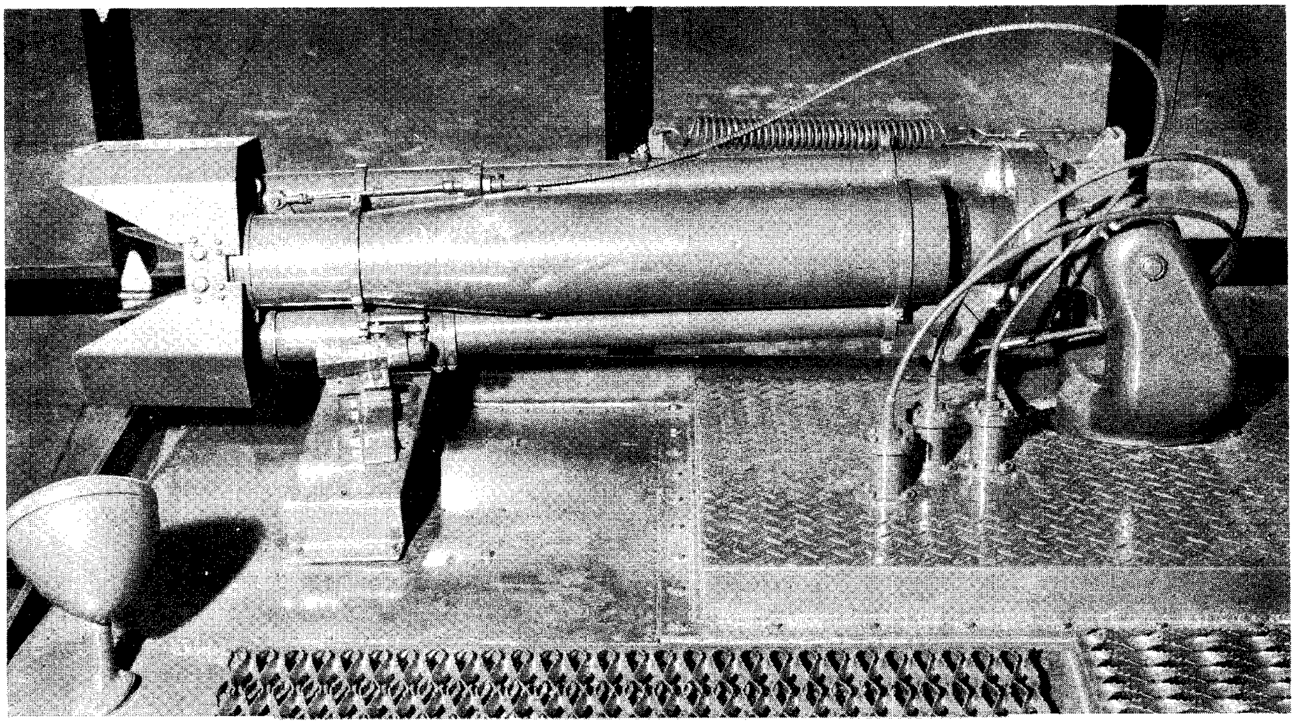
Experiments were performed to determine the effect of changes in the pump pressure on the solution discharge rate of one 500-gpm barrel of Nozzle A. The results of these experiments are shown in Table XXX.

TABLE XXX

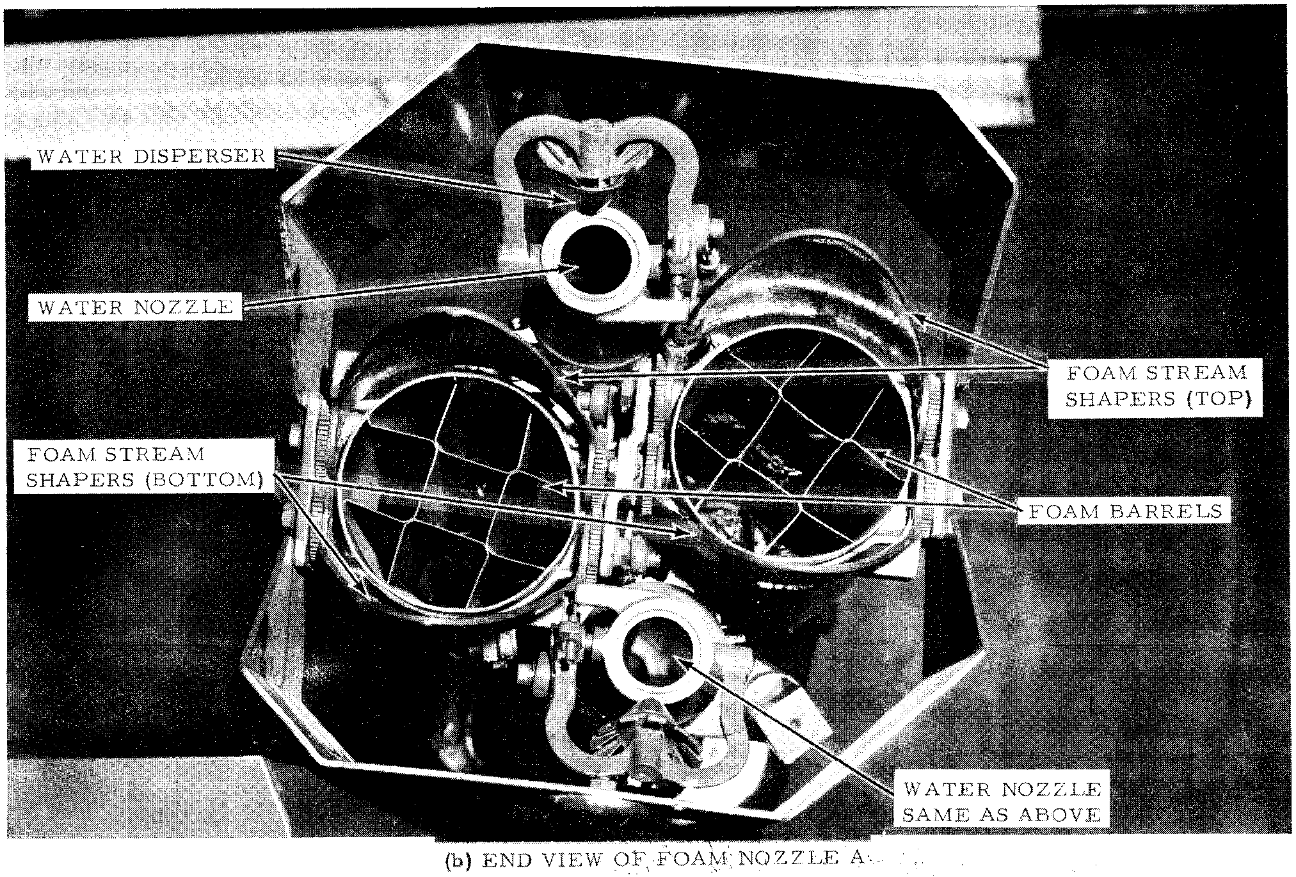
THE EFFECT OF CHANGES IN PUMP PRESSURE ON THE SOLUTION DISCHARGE RATE OF NOZZLE A

Pump Pressure psi	Nozzle Discharge Rate gpm
150	410
200	453
250	496

The effect upon foam quality of an increase in the pump pressure from 150 to 250 psi was to increase the foam expansion ratio by approximately 30 percent and the 25-percent drainage time by approximately 17 percent. All of the experiments in the series which follow were performed with the pump pressure set at 250 psi.

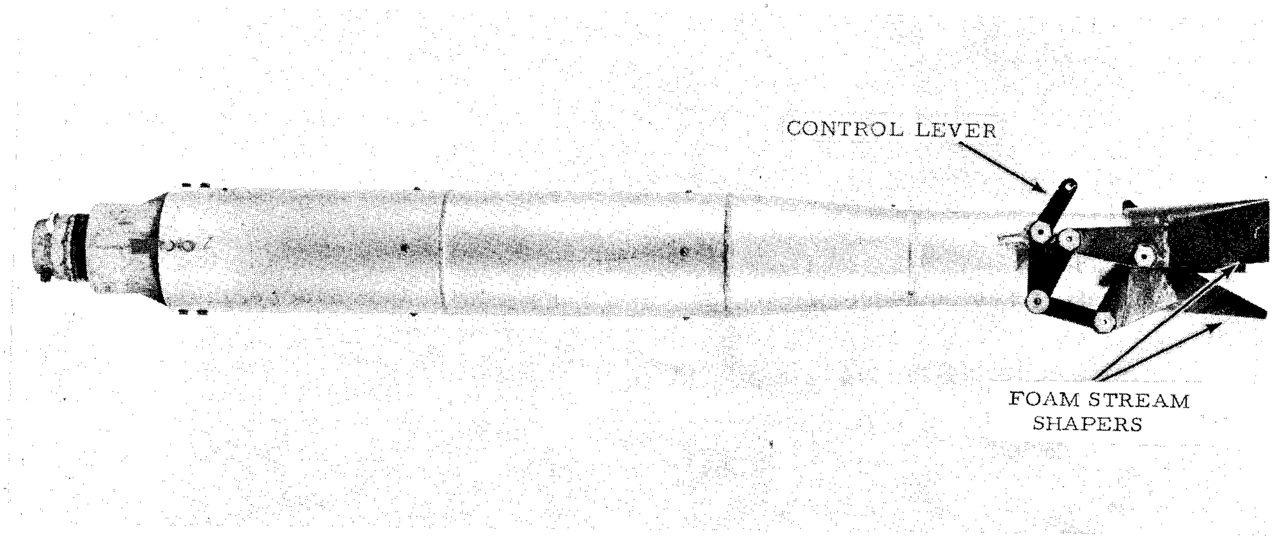


(a) PROFILE VIEW OF FOAM NOZZLE A (TRUCK MOUNTED)

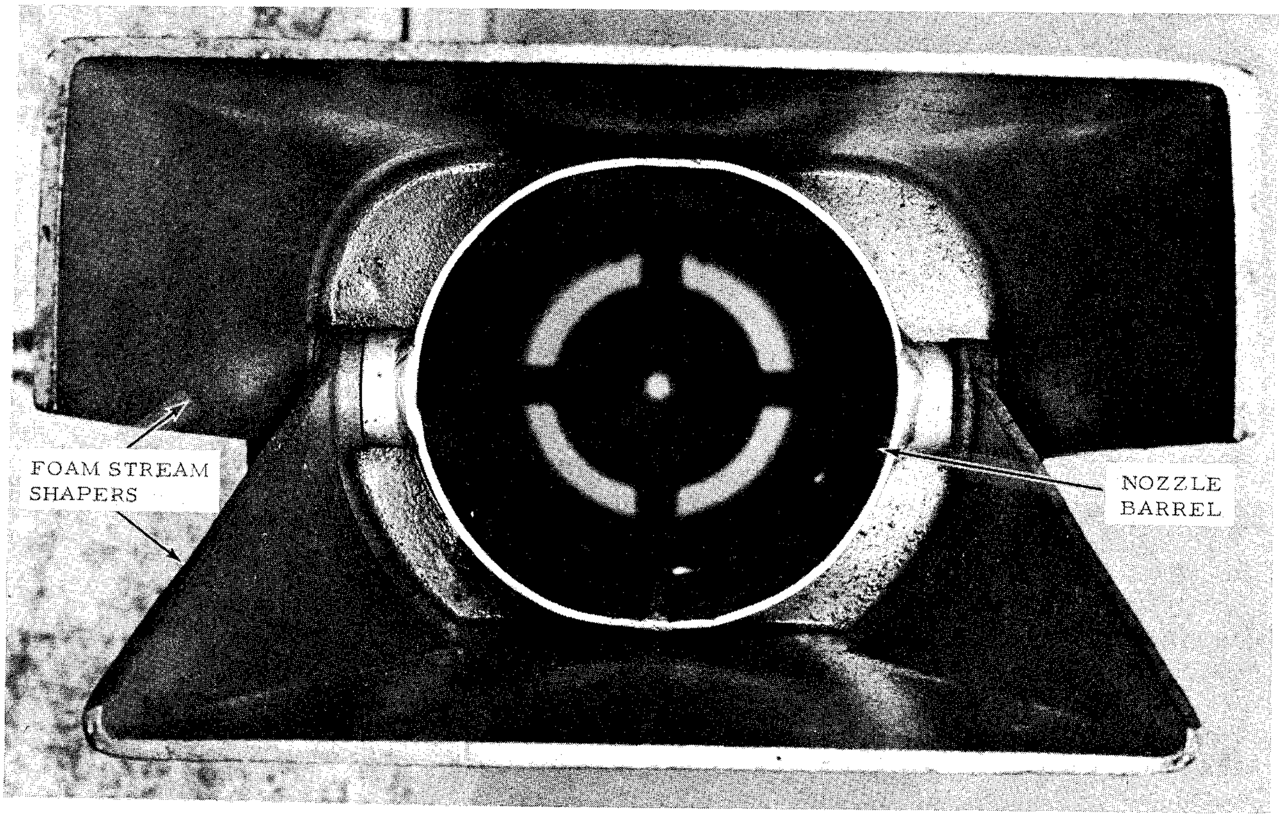


(b) END VIEW OF FOAM NOZZLE A

FIGURE 22 - FOAM NOZZLE A



(a) PROFILE VIEW



(b) END VIEW

FIGURE 23 - FOAM NOZZLE B

Because Nozzle B had been constructed to impart a high shearing action and turbulence to the foam stream during its passage through the nozzle barrel, the effect of changes in the foam solution concentration on the foam quality was considered significant. Therefore, two experiments were performed with protein foam, one at a solution concentration of 6 percent, and one at a concentration of 12 percent by volume. The results of these tests are shown in Table XXXI.

TABLE XXXI

THE EFFECT OF CHANGES IN THE SOLUTION CONCENTRATION ON FOAM QUALITY USING NOZZLE B AND PROTEIN FOAM

Foam Solution Concentration percent	Foam Expansion Ratio	25-Percent-Solution Drainage Time min
6	11.5:1	11:09
12	11.6:1	23:50

These data indicate that an increase in the solution concentration produced a significant increase in the stability of the foam with no appreciable effect on the expansion ratio.

The effect of foam solution concentration was not determined for Nozzle A, because it had been determined for low-energy equipment in the laboratory experiments using the 6-gpm nozzle specified in Reference 6, which produced foam of equivalent quality.

B. Foam-Pump System - The foam-pump system employed in these experiments was a specially designed skid-mounted unit with a nominal solution discharge rate of 500 gpm. The basic system comprised a special type of reciprocating vane rotary pump with screened intake open to the atmosphere. Metered quantities of water and foam liquid were fed into the intake manifold, and air was sucked in to make up the difference in volume. The liquid and air were churned in the pump and homogenized in a stabilizing chamber before passing through the piping to the turret nozzle. The foam-pump system is shown in Figure 24.

FIGURE 24 - FOAM NOZZLE C USING THE STRAIGHT STREAM DISCHARGE

The foam-pump system is flexible and capable of providing foam with a wide range of expansion ratios, 25-percent-solution drainage times and viscosities. The foam-expansion ratio was variable by regulating the air inducted into the pump by controlling the pump rotor speed. The relationship between the foam expansion ratio and the pump rotor speed is shown in Figure 25, which was developed from data supplied by the manufacturer of the unit. The foam viscosity and a 25-percent-drainage time could also be controlled by varying the number of screens in the foam-refining chamber for any given expansion ratio.

Test Results

Foam Ground-Patterns Produced by the Three Dispensing Systems - The foam ground-patterns produced by the three foam-dispensing systems using Orvus K liquid, which was substituted for AFFF and protein foam are presented in Figures 26 through 33. Figures 26 through 29 show the foam patterns produced with Orvus K and protein foam in still air, while Figures 30 through 33 show the effects produced by crosswinds on the foam ground-patterns. These experiments were intended to determine the overall length and width of the foam discharge produced by the straight and dispersed streams for each dispensing system. The profiles were of value in revealing those differences in the foam-discharge configurations which were significant in developing the most effective foam application techniques required to achieve minimum fire control times of the large-scale pool fires.

Discussion and Results of the Foam Quality Experiments - A summary of the foam quality determinations obtained with Nozzles A and B and the foam-pump system using AFFF and protein foam is presented in Table XXXII. No experiments were performed with AFFF using the dispersed foam patterns, because this agent was in short supply and being conserved for the full-scale firefighting tests using the B-47 Stratojet aircraft.

The change in foam viscosity as a function of time, after formation for each of the three systems using AFFF and protein foam, is shown by the profiles in Figure 34. A comparison of the viscosity data curves for protein foam measured 30 sec after formation, which is approximately one-half of the desired fire control time, shows that the viscosity varied from 180 dynes per sq cm for the low-energy air-aspirating system to 550 dynes per sq cm for the high-energy foam-pump system. The air-aspirating system with the higher energy input (Nozzle B) produced foam with intermediate viscosities with both AFFF and protein foam.

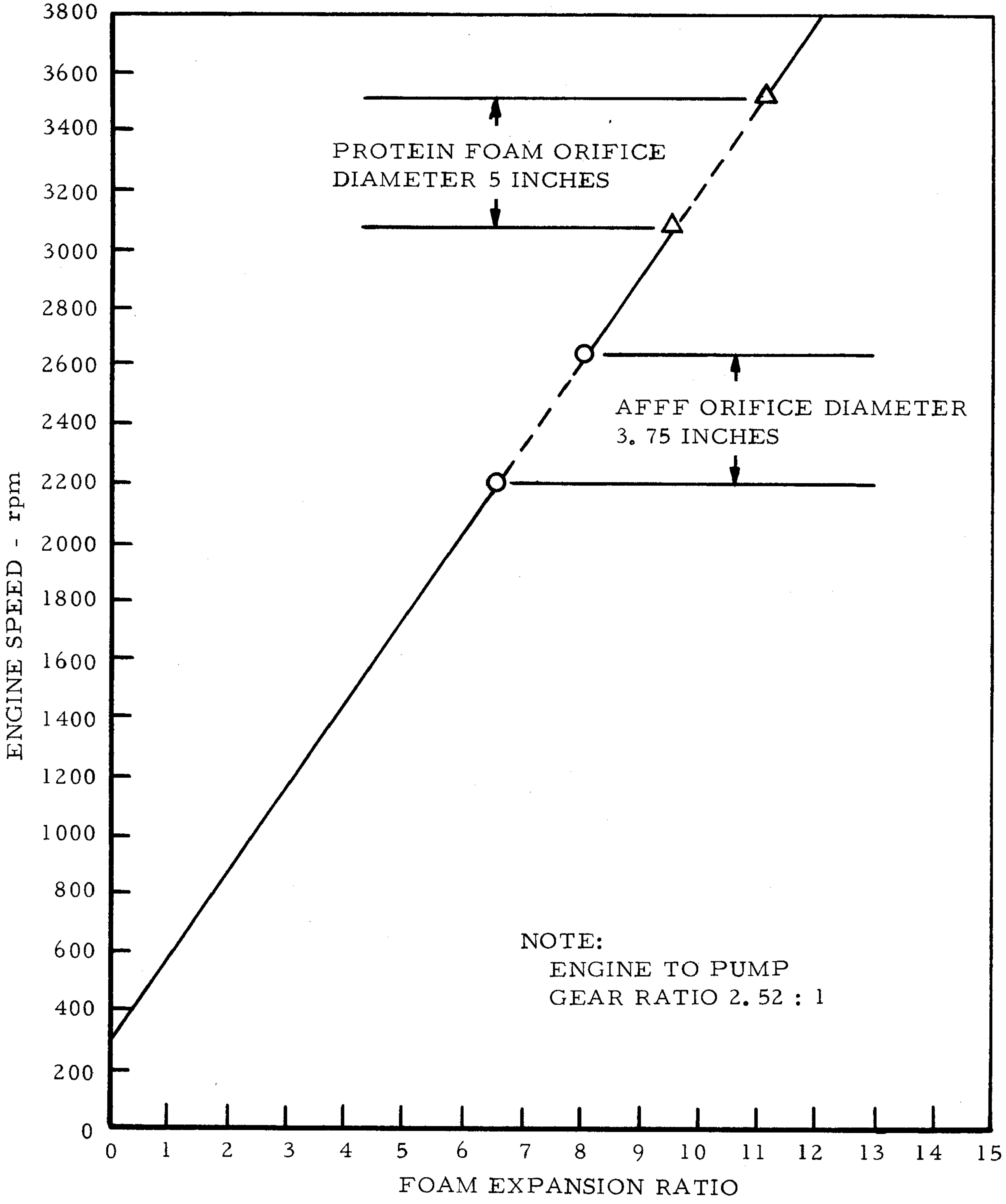


FIGURE 25 - FOAM EXPANSION RATIO AS A FUNCTION OF THE ENGINE SPEED OF THE FOAM PUMP

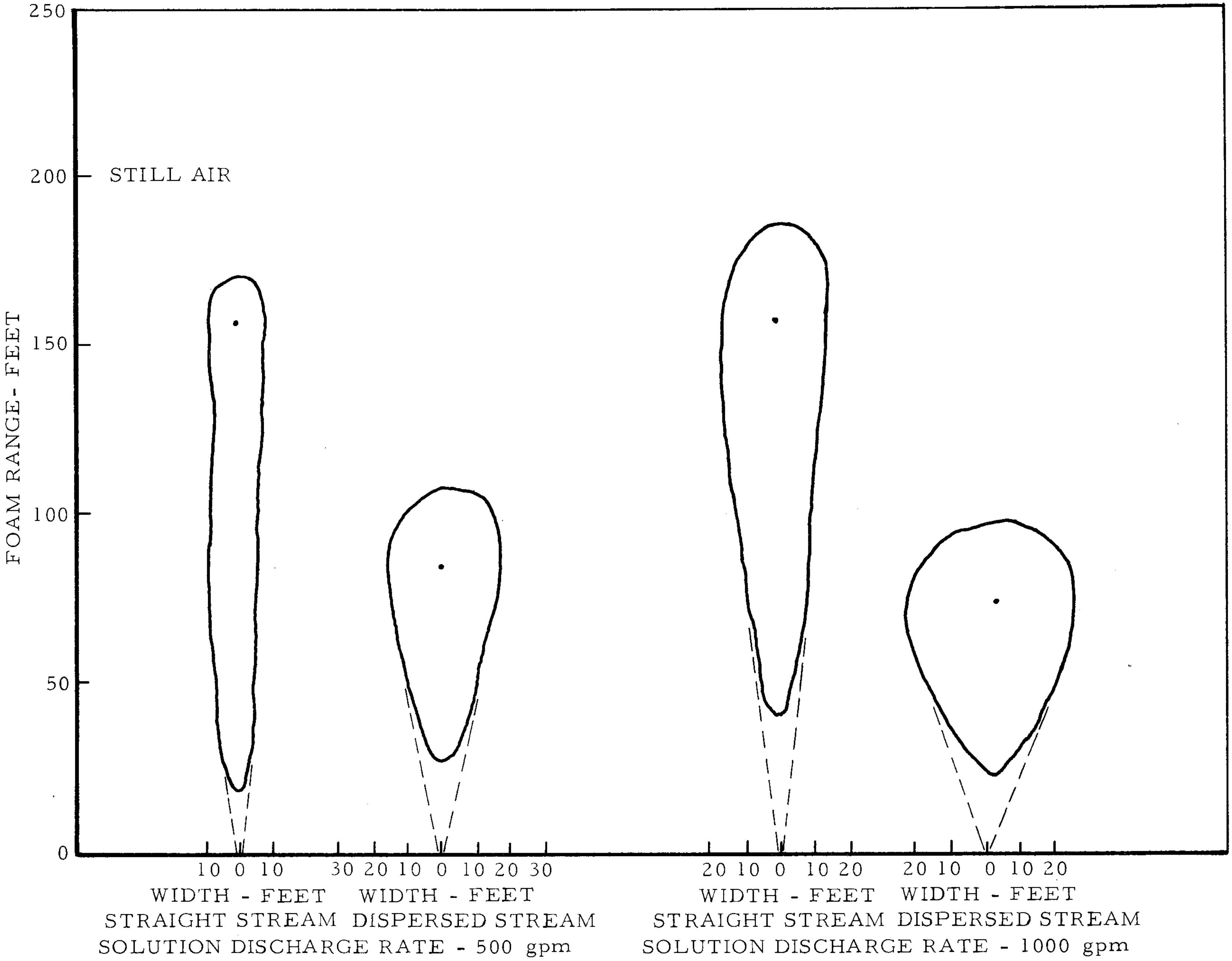


FIGURE 26 - FOAM GROUND-PATTERNS PRODUCED BY NOZZLE A, USING PROTEIN FOAM

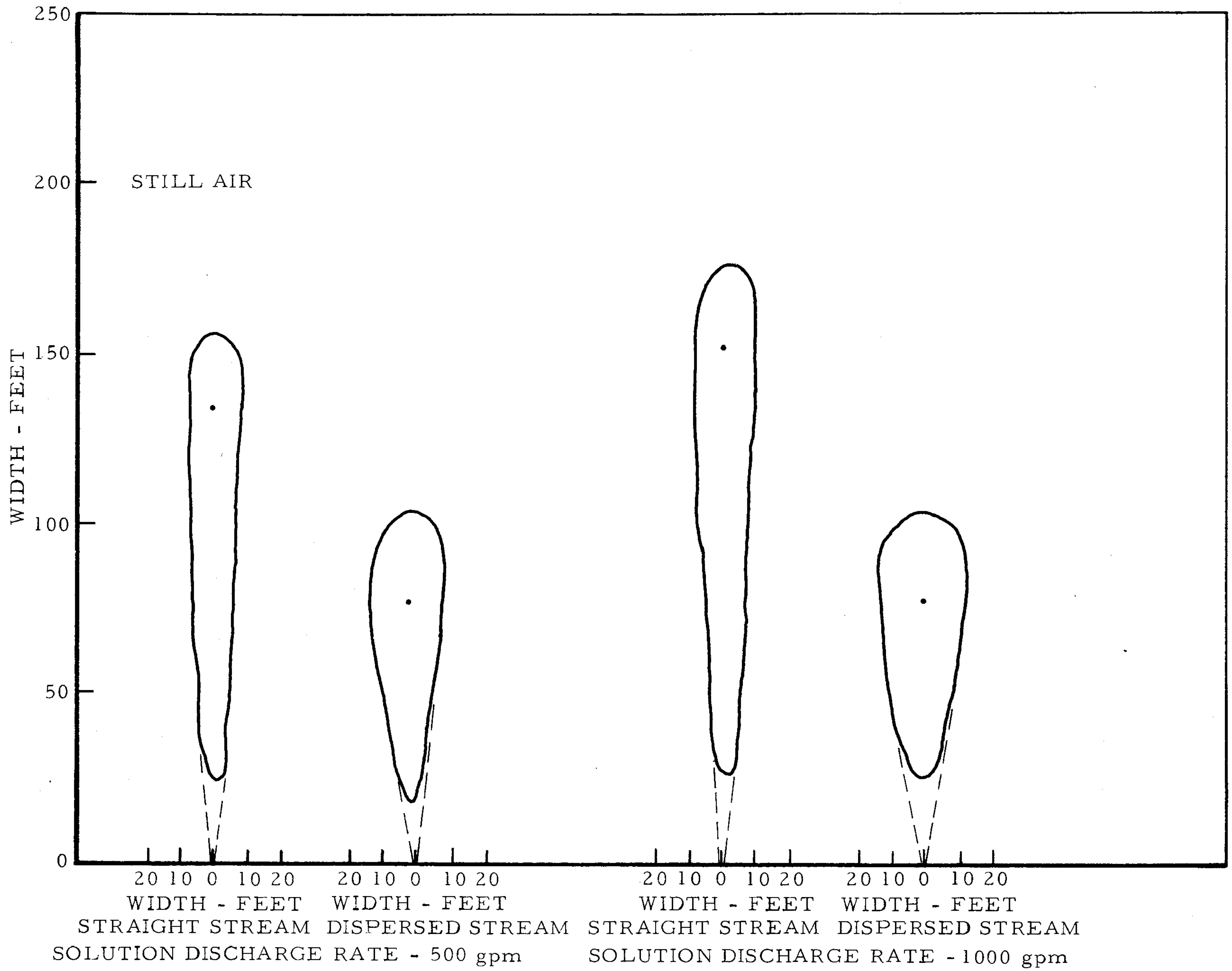


FIGURE 27 - FOAM GROUND-PATTERNS PRODUCED BY NOZZLE A, USING ORVUS K LIQUID

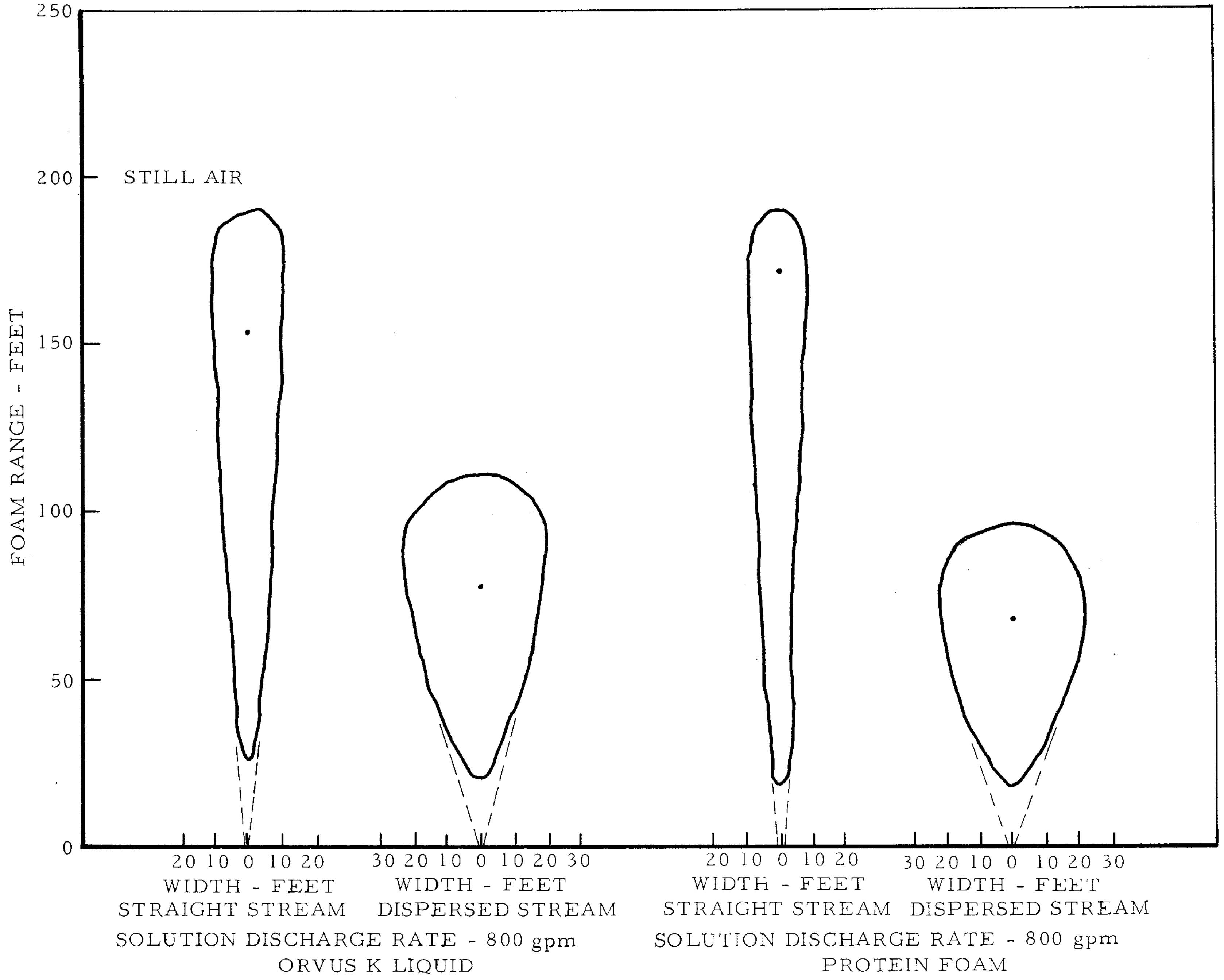
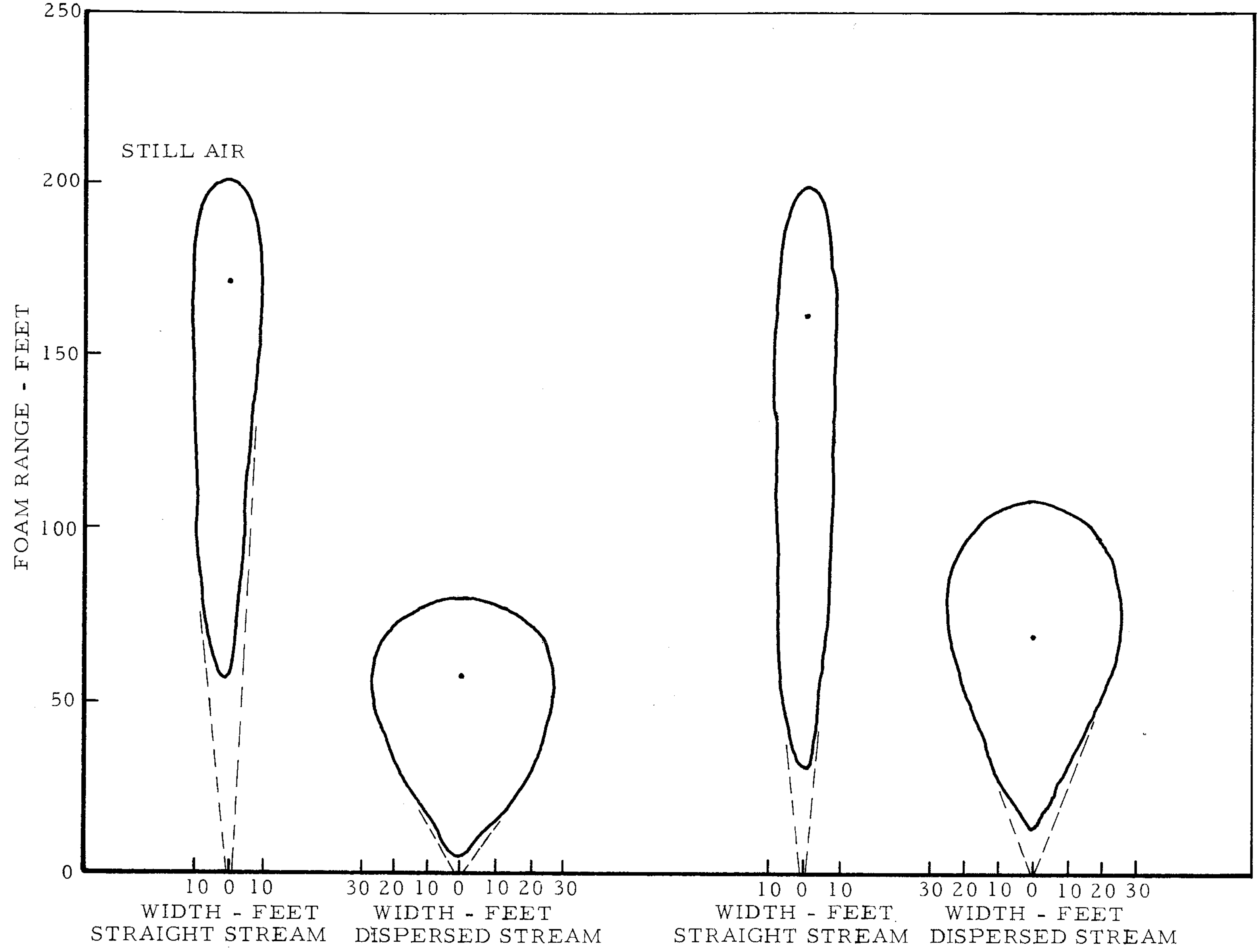


FIGURE 28 - FOAM GROUND-PATTERNS PRODUCED BY NOZZLE B, USING PROTEIN FOAM AND ORVUS K LIQUID



5 INCH ORIFICE
PUMP PRESSURE - psi
ENGINE SPEED - 3500 rpm
PROTEIN FOAM

3.75 INCH ORIFICE
PUMP PRESSURE - 30 psi
ENGINE SPEED - 2250 rpm
ORVUS K LIQUID

FIGURE 29 - FOAM GROUND-PATTERNS PRODUCED BY THE FOAM PUMP, USING PROTEIN FOAM AND ORVUS K LIQUID

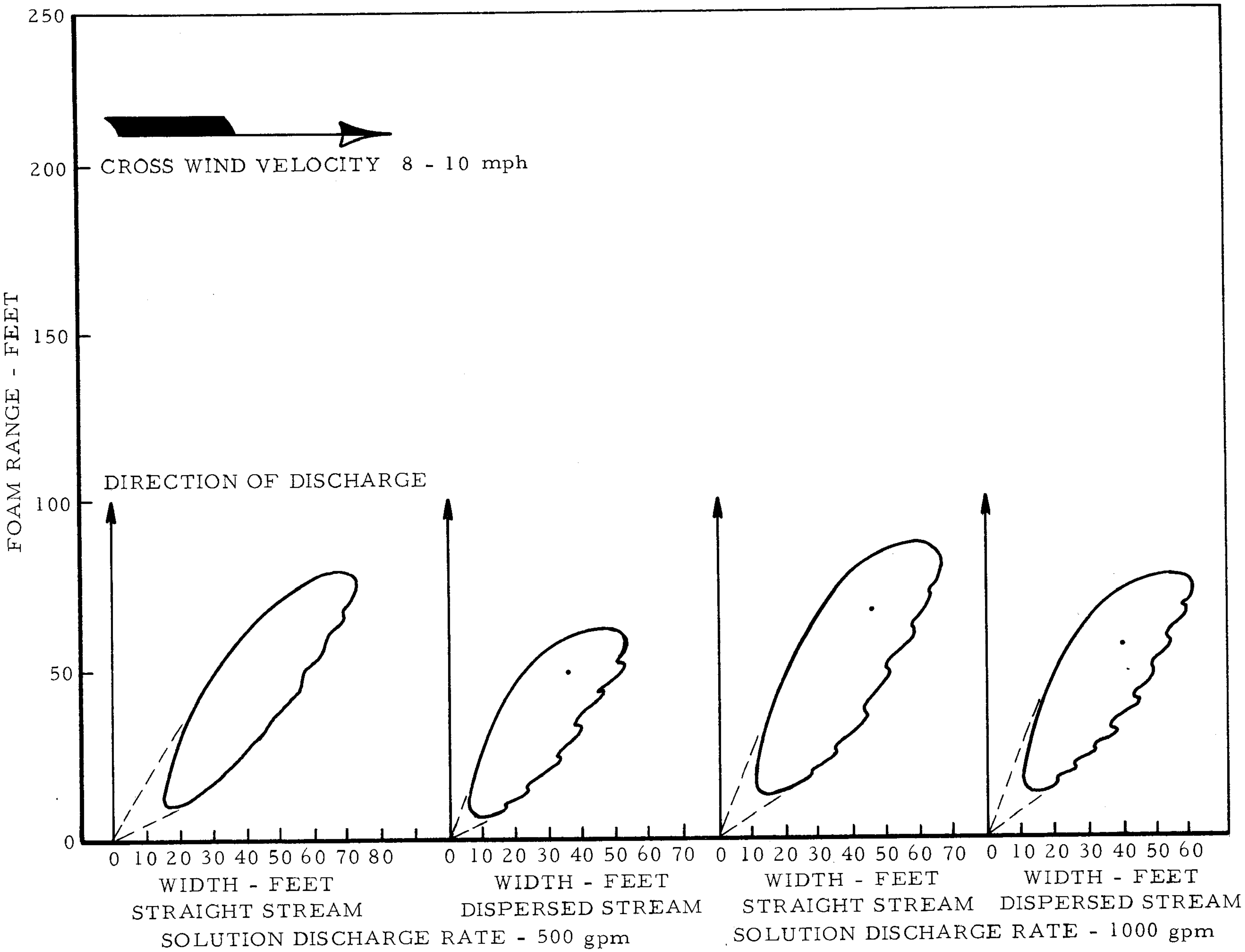


FIGURE 30 - FOAM GROUND-PATTERNS PRODUCED BY NOZZLE A,
USING PROTEIN FOAM IN 8-10 MPH CROSSWINDS

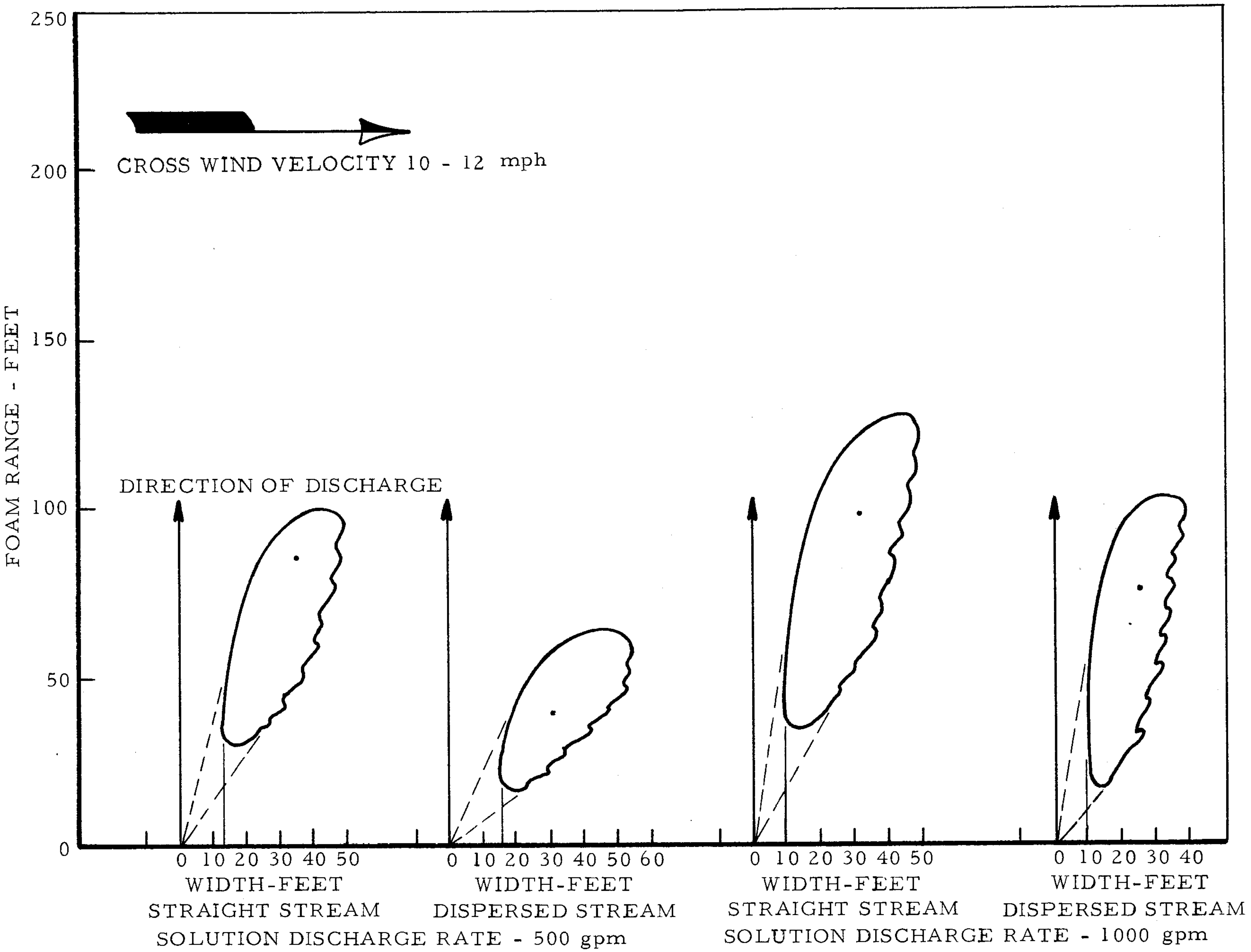


FIGURE 31 - FOAM GROUND PATTERNS PRODUCED BY NOZZLE A, USING ORVUS K LIQUID IN 10-12 MPH CROSSWINDS

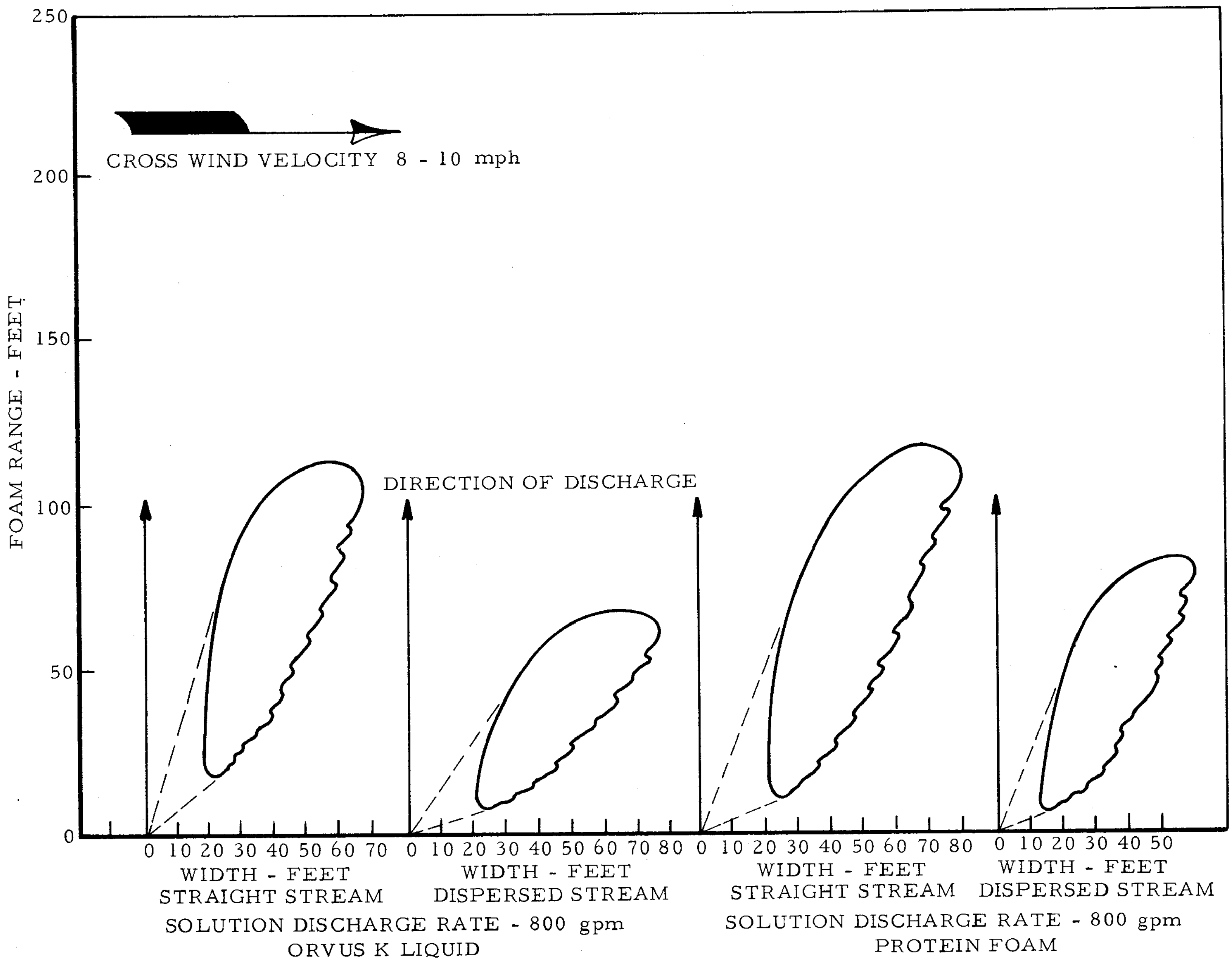


FIGURE 32 - FOAM GROUND-PATTERNS PRODUCED BY NOZZLE B, USING ORVUS K LIQUID IN 8-10 MPH CROSSWINDS

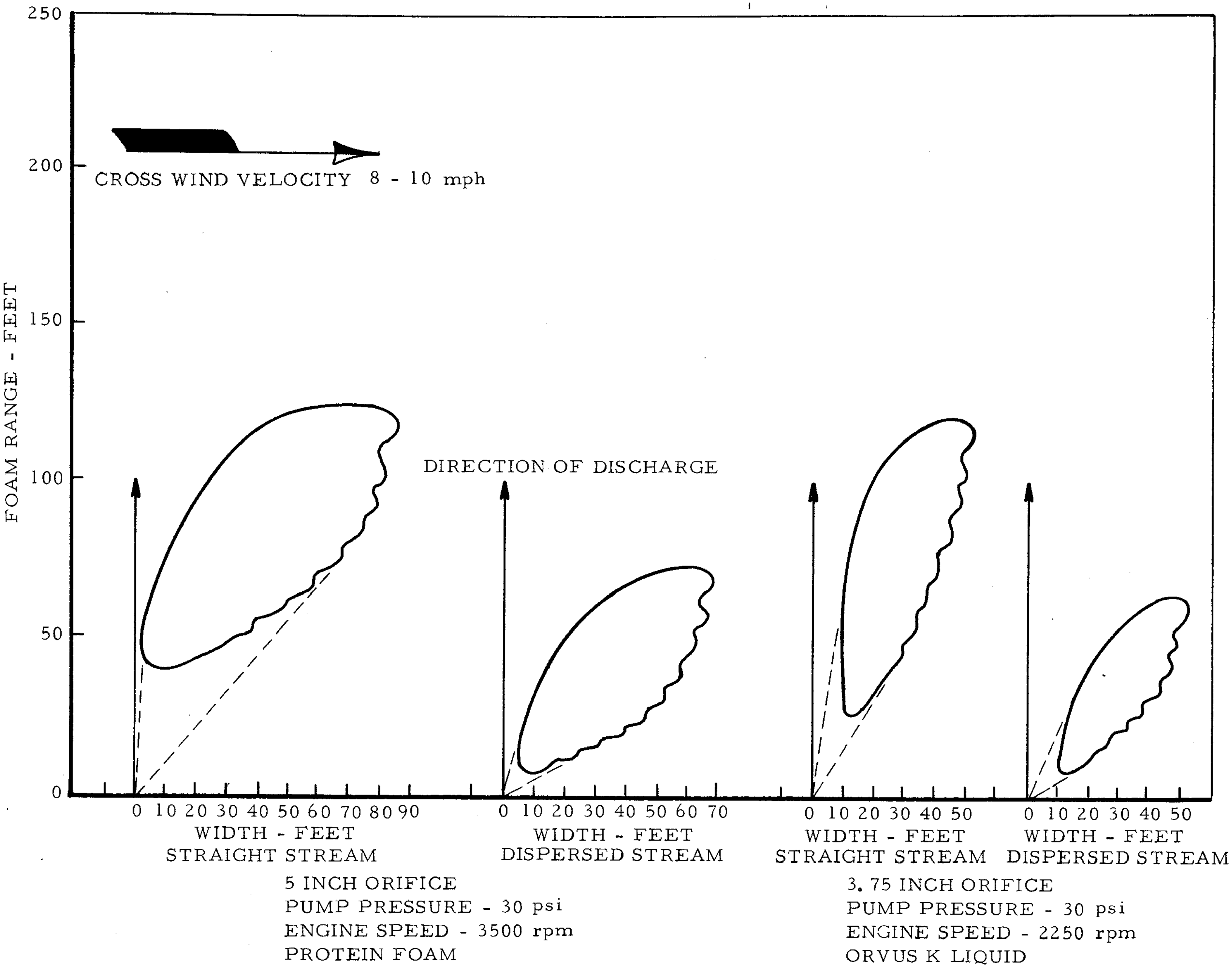


FIGURE 33 - FOAM GROUND-PATTERNS PRODUCED BY THE FOAM PUMP, USING PROTEIN FOAM AND ORVUS K LIQUID IN 8-10 MPH CROSSWINDS

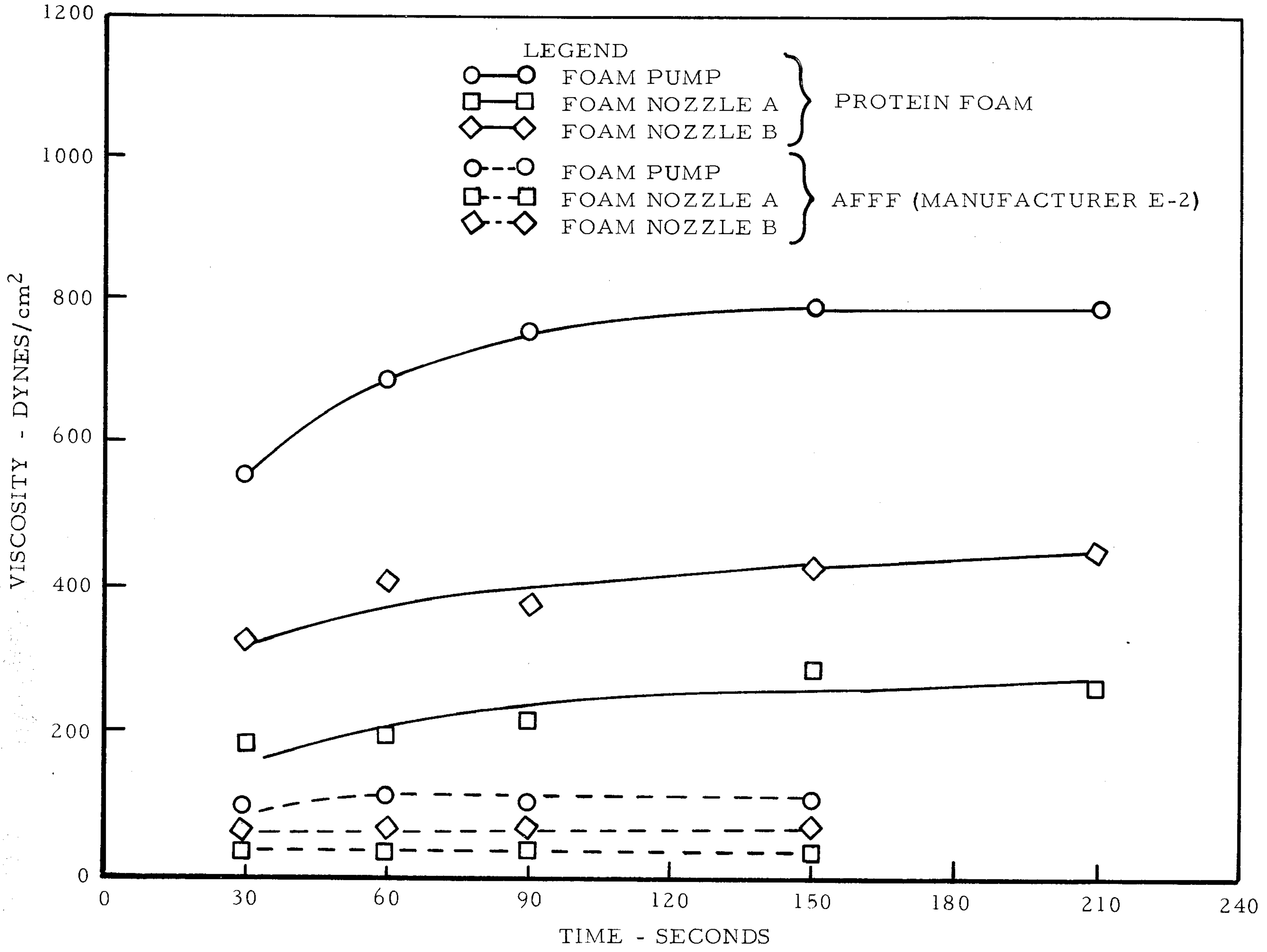


FIGURE 34 - VARIATION OF FOAM VISCOSITY WITH TIME AFTER FORMATION

TABLE XXXII

RESULTS OF THE FOAM QUALITY EXPERIMENTS USING THE FOAM PUMP AND AIR-ASPIRATING NOZZLES WITH PROTEIN FOAM AND AFFF

Equipment	Pressure at the Nozzle psi	Nozzle Discharge Rate gpm	Foam Expansion Ratio		25-Percent-Solution Drainage Time min:sec	
			AFFF	Protein Foam	AFFF	Protein Foam
			Straight Stream			
Nozzle A	250	496	10.8:1	8.2:1	7:09	5:54
Nozzle B	250	780	11.5:1	11.2:1	7:20	11:09
Foam Pump	30 at 3500 rpm	530	8.2:1	12.4:1	7:48	36:06
			Dispersed Stream			
Nozzle A	250	496	No data taken	7.2:1	No data taken	5:54
Nozzle B	250	780	No data taken	8.0:1	No data taken	10:10
Foam Pump	30 at 3500 rpm	510	No data taken	12.3:1	No data taken	30:17

From these viscosity curves, it is apparent that protein foam has a potentially higher intrinsic viscosity capacity than AFFF and that the viscosity increases in proportion to the energy input to the system. In sharp contrast to this behavior, AFFF shows a significantly lower intrinsic viscosity capacity, and the total energy input to the system produces a less significant effect on foam viscosity.

Therefore, high-energy systems such as the foam pump are not capable of producing AFFF with significantly higher viscosities than those which can be obtained with low-energy air-aspirating systems. However, this is not true with protein foams in which the stability of the foam in terms of its solution-drainage rate must be accurately matched with its viscosity so that sufficient fluidity is maintained to establish a uniform and cohesive foam blanket over the fuel surface.

From the data contained in Table XXXII and the viscosity profiles presented in Figure 34, it is apparent that the air-aspirating foam nozzles with different foam turbulation energies the most significant variations in protein foam quality are noted in the 25-percent-solution drainage time and foam viscosity, while the greatest variations in AFFF quality are evidenced as functions of the expansion ratio and foam viscosity. The overall differences in foam quality are greater for protein foam than for AFFF expressed in terms of the expansion ratio, 25-percent-solution drainage time and foam viscosity, when each agent is dispensed by the same air-aspirating equipment.

<u>Large-Scale Fire-Modeling Experiments</u> - The large-scale fire tests were conducted in accordance with the general procedure established in Reference 3. One significant variation in the procedure was that in these experiments the foam solution application rate was varied by changing the fire size, instead of the nozzle discharge rate. Tests were performed in concentric pools of 70, 100, and 140 feet in diameter containing a 4-in.-deep bed of 3/8-in. traprock and enclosed by 10-in.-high earthen dikes. The circular area within the pit was further subdivided into 20-ft-square sections by banking the traprock into 4-in.-high dikes. Each dike in this network contained a 2-ft-wide opening so that all of the individual areas within the circular pit were interconnecting. A panoramic view of the test bed is shown in Figure 35. The purpose of this configuration was to establish a reproducible and more severe fire situation than that commonly employed in water-base pool-fire tests.

The fire test bed contained a cruciform configuration of seven 55-gal steel drums and a 3-dimensional fire positioned in the center of the pool which was sustained

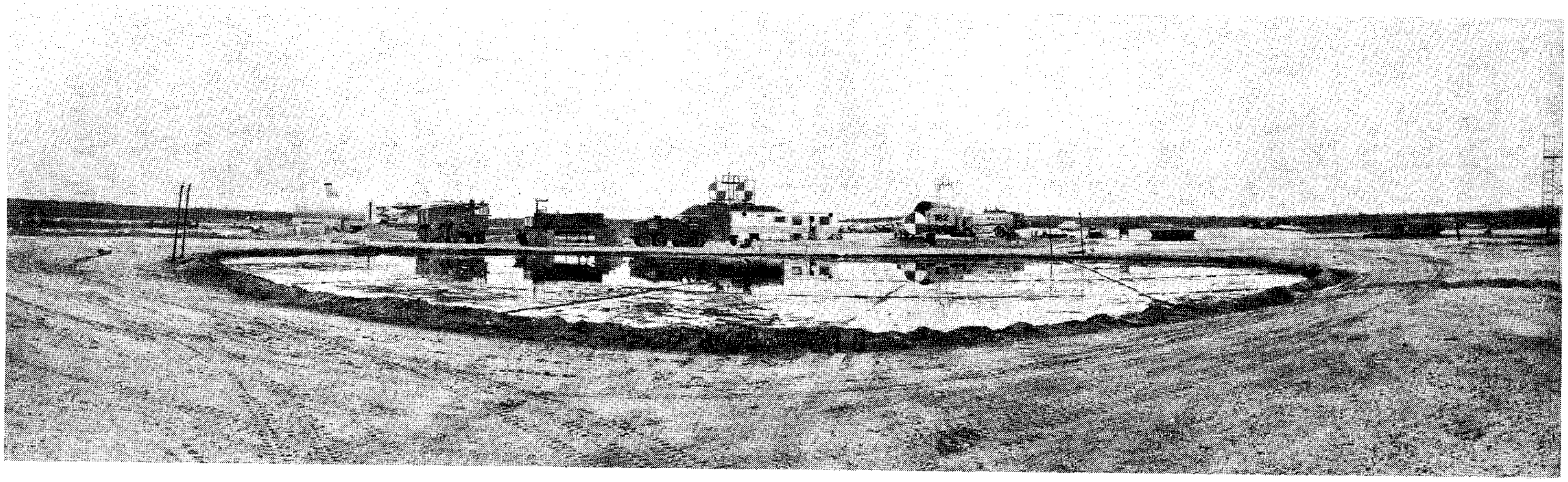


FIGURE 35 - PANORAMIC VIEW OF THE FIRE TEST BED

by directing a jet of JP-4 fuel from a 1/4-in.-diameter stainless steel tube onto the top of the center drum from a height of 3 ft. The fire performance of each foam-dispensing system was monitored by four radiometers elevated on steel poles 8 ft above ground level and positioned in pairs on the diameter of the fire pit at right angles to the wind direction. Thermal data were taken on pen recorders equipped with event markers. Visual analysis of the progress of fire control was provided by two instrumentation cameras exposing 16 mm Kodachrome II color film and operated at 24 frames per sec.

The fire test conditions established for each of the three fire sizes are summarized in Table XXXIII.

The results of the large-scale fire tests are summarized in Figures 36 and 37. The profiles in Figure 36 show the solution application rate as a function of the fire control time for the foam pump and Nozzle A using protein foam and AFFF. From these curves, it is apparent that the higher energy foam pump system achieved a lower fire control time than the lower energy air-aspirating nozzle in all experiments. However, the differences in the fire control times between the two systems are small when dispensing AFFF, but significant reductions were obtained in the fire control times when protein foam was dispensed by the foam pump. The increased effectiveness of protein foam produced by the foam pump is attributed primarily to its greater stability which derives from its longer 25-percent-solution drainage time.

The profiles in Figure 37 show the fire control time as a function of the solution application rate using Nozzle B with protein foam and AFFF. The abscissa, which shows the foam solution application rate, tends to become asymptotic with the data curve for AFFF at a solution application rate of approximately 0.1 gpm per sq ft and for protein foam at approximately 0.2 gpm per sq ft. Therefore, solution application rates in excess of these values would not reduce the fire control time appreciably and would be wasteful of the foam agent.

It will also be noted in Figure 37 that for one test performed with fluoroprotein foam dispensed at a solution application rate of 0.102 gpm per sq ft, the fire control time was between those obtained with protein foam and AFFF at the same application rate. This performance is considered consistent with its chemical composition, which was noted in a previous section of this report, to be a combination of perfluorinated hydrocarbon surfactants and protein foam.

TABLE XXXIII

FIRE TEST CONDITIONS

				Foam Pump		Foam Equipment Air Aspirating			
						Nozzle A		Nozzle B	
Test No.	Fire Diameter ft	Fire Area ft^2	JP-4 Volume. gal	Solution Discharge Rate gpm	Solution Application Rate gpm per sq ft	Solution Discharge Rate gpm	Solution Application Rate gpm per sq ft	Solution Discharge Rate gpm	Solution Application Rate gpm per sq ft
1	70	3846	1155	530	0.138	496	0.129	780	0.203
2	100	7850	2355	530	0.068	496	0.063	780	0.100
3	140	15386	5298	530	0.034	496	0.032	780	0.051

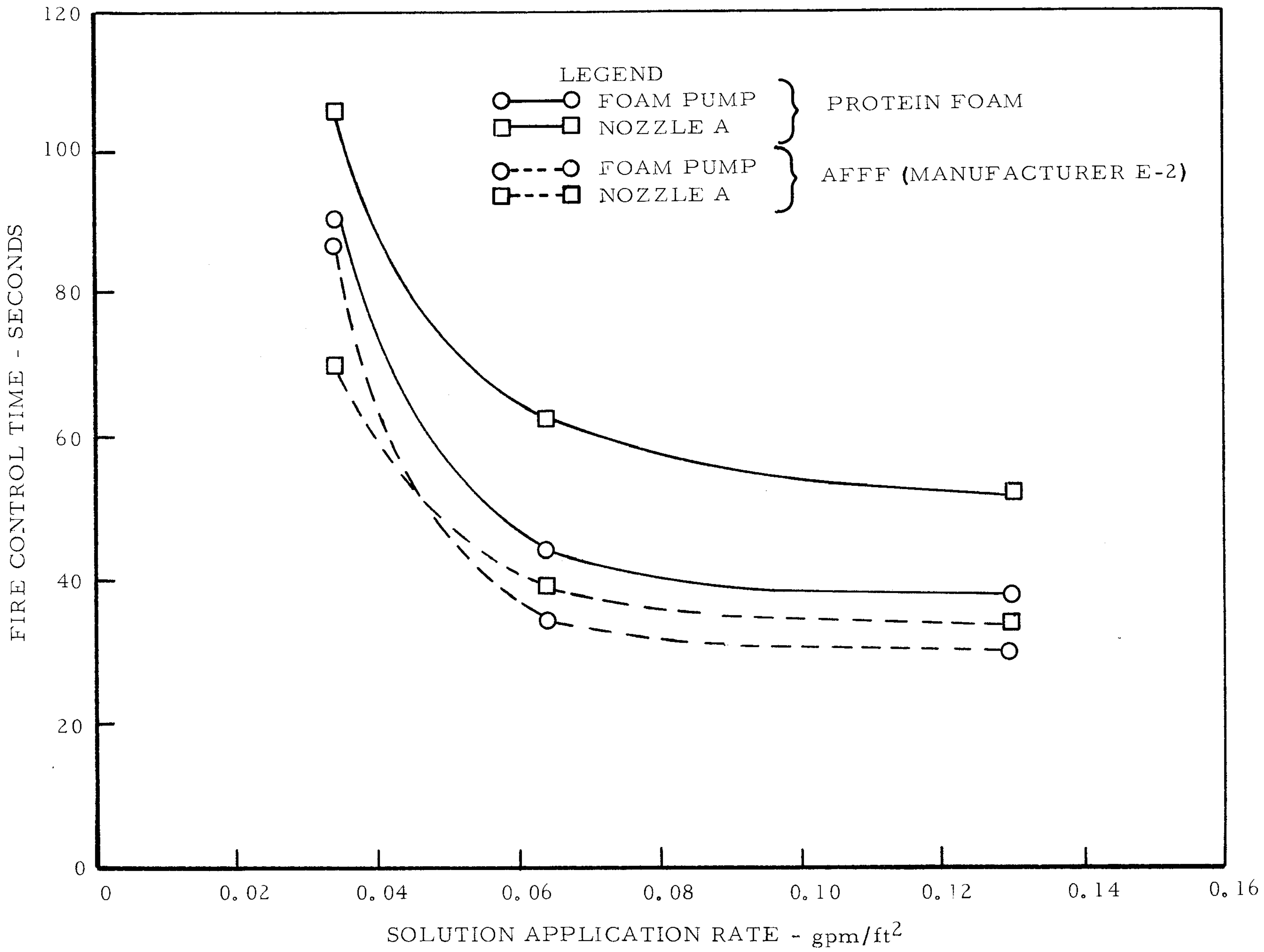


FIGURE 36 - FIRE CONTROL TIME AS A FUNCTION OF SOLUTION APPLICATION RATE USING PROTEIN FOAM AND AFFF WITH NOZZLE A AND THE FOAM PUMP

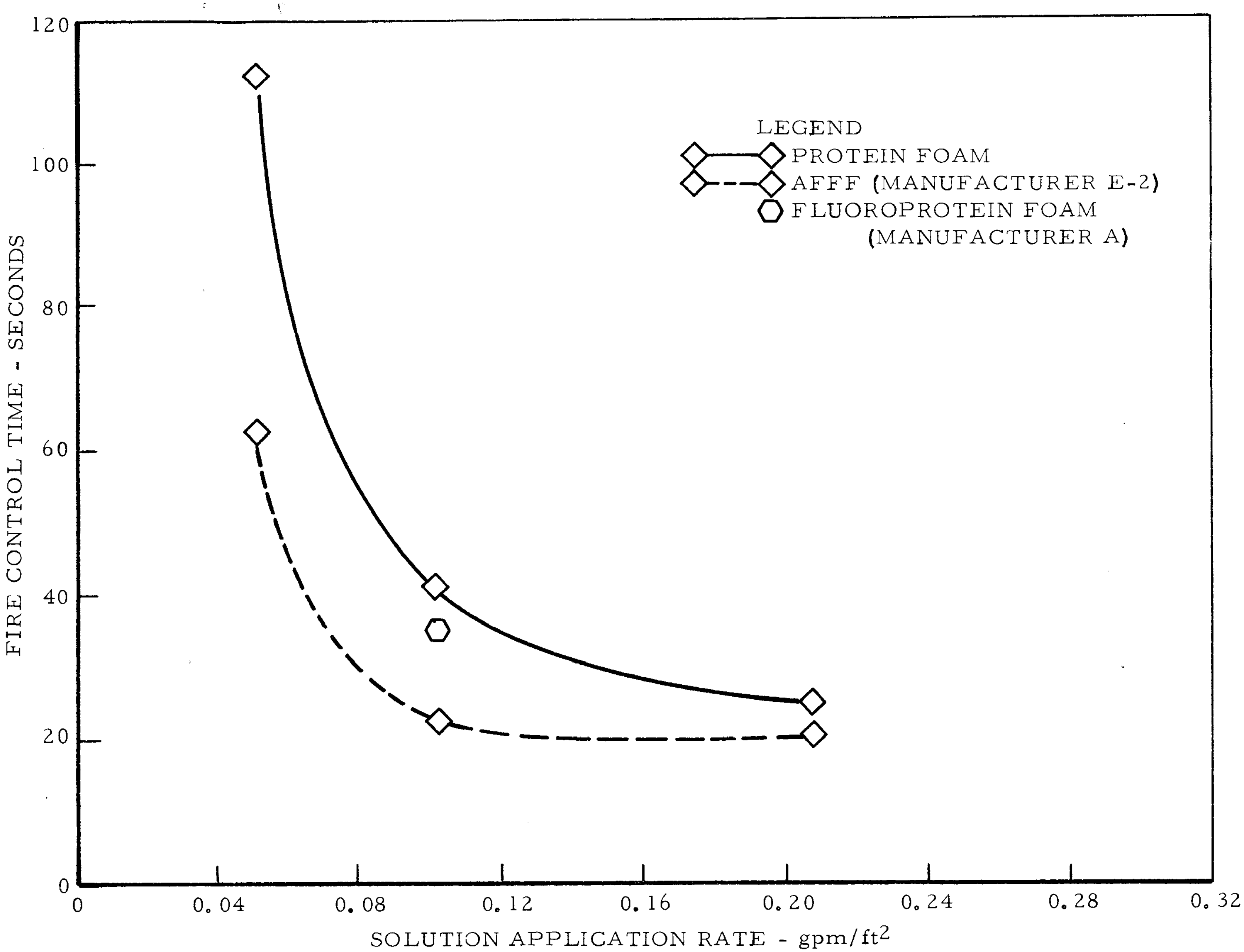


FIGURE 37 - FIRE CONTROL TIME AS A FUNCTION OF SOLUTION APPLICATION RATE USING PROTEIN FOAM AND AFFF WITH NOZZLE B

From the results of the large-scale fire-modeling experiments, it is apparent that current foam dispensing systems, whether of the low- or high-energy type, are suitable for dispensing AFFF with a high degree of effectiveness on JP-4 fuel fires. However, to obtain maximum effectiveness with protein foam, a balance between the 25-percent-solution drainage time, foam expansion ratio and viscosity is necessary. The foam expansion ratio, per se, is a less definitive parameter than either the 25-percent-solution drainage time or the viscosity in influencing the fire control time.

From the data presented in Reference 9, concerning quality of protein foam dispensed by air-aspirating nozzles and the foam pump, two distinct categories are recognized. For air-aspirating nozzles, the "Relative Effectiveness" of protein foam lies between 82.5 and 100 percent for foams with expansion ratios between 8 and 10:1 with 25-percent-solution drainage times from 4 to 5 min. While the protein foam, dispensed by the foam pump, is shown to have a "Relative Effectiveness" between 80 and 100 percent when the expansion ratio is between 15 to 12:1 and the minimum solution drainage time is 20 min. The quality of these foams is representative of the maximum and minimum values obtained with the two basic types of equipment used on current aircraft firefighting vehicles. Between these extremes lies an area which may be considered to have a "Relative Effectiveness" of 100 percent and to include protein foams with expansion ratios between 10 to 12:1 and 25-percent-solution drainage times from 5 to 20 min. This system, which rates protein foams according to their relative effectiveness, does not directly express the findings reported in Reference 29, which indicates that foam-pump foam is almost four times as effective as protein foam applied from current air-aspirating nozzles. The results of comparative tests performed by operators skilled in the most effective techniques for dispensing both air-aspirated and foam-pump foam, show the foam-pump foam to be approximately 1.5 times as effective as air-aspirated foam on large JP-4 fuel fires, 15,386 sq ft (140 ft diameter), which is in closer agreement with Reference 9.

The results of the experiments performed during this effort indicated that the most effective air-aspirated protein foam did, in fact, lie between the maximum and minimum values established for air-aspirated and foam-pump foam shown in Reference 9. The most effective air-aspirated foam was that dispensed by Nozzle B, which had an expansion ratio of approximately 11:1, a solution-drainage time between 10 and 11 min, and a viscosity of 400 dynes per sq cm measured 60 sec after formation.

A practical application of the data obtained from the large-scale fire modeling experiments to actual fire situations is indicated by the curves in Figure 38. These curves represent average values derived from the fire test data. The profiles show the foam application time as a function of the number of square feet of fire area which were brought under control using each foam-dispensing system with AFFF and protein foam.

In these experiments, the solution application rates on the fire were varied by changing the fire area while maintaining a constant foam-solution discharge. The horizontal lines drawn at 40 and 60 sec are intended to emphasize the fact that to preserve the integrity of an aluminum aircraft skin, and to assure the safety of all aircraft occupants in a fire of maximum severity, the fire must be brought under control within 40 to 60 sec after fuel ignition.

The slope of these curves indicates that the number of square feet of fire which each foam is capable of securing increases at a different rate with the time of application, which affords a convenient means for estimating the time required by each agent and foam-dispensing system to control a given size fire. Therefore, these data provide a basis for comparing the relative firefighting effectiveness of different foam-dispensing systems.

As a consequence of these experiments, and more particularly those reported in References 3 and 29, it was apparent that each foam agent and dispensing system had a different solution application rate which could be considered optimum for a particular system and fire-test condition. The curves shown in Figure 39, in which fire control time is plotted as a function of the solution application rate of protein foam, were derived from data contained in Reference 3. These curves show that at a particular solution application rate, the fire control time decreases as the fire size increases. This apparent anomaly is explained by assuming that the foam can be more effectively applied on the larger fires which tends to reduce the fire control time, and this hypothesis was confirmed by photographic analysis of numerous large-scale fire tests.

Comparative Effectiveness of Protein Foam and AFFF Firefighting Foams - One of the primary objectives of the laboratory evaluation of firefighting agents and the large-scale fire tests was to obtain sufficient performance data for protein foam and AFFF upon which to base an estimate of their relative usefulness in combatting large Class B fires at airports.

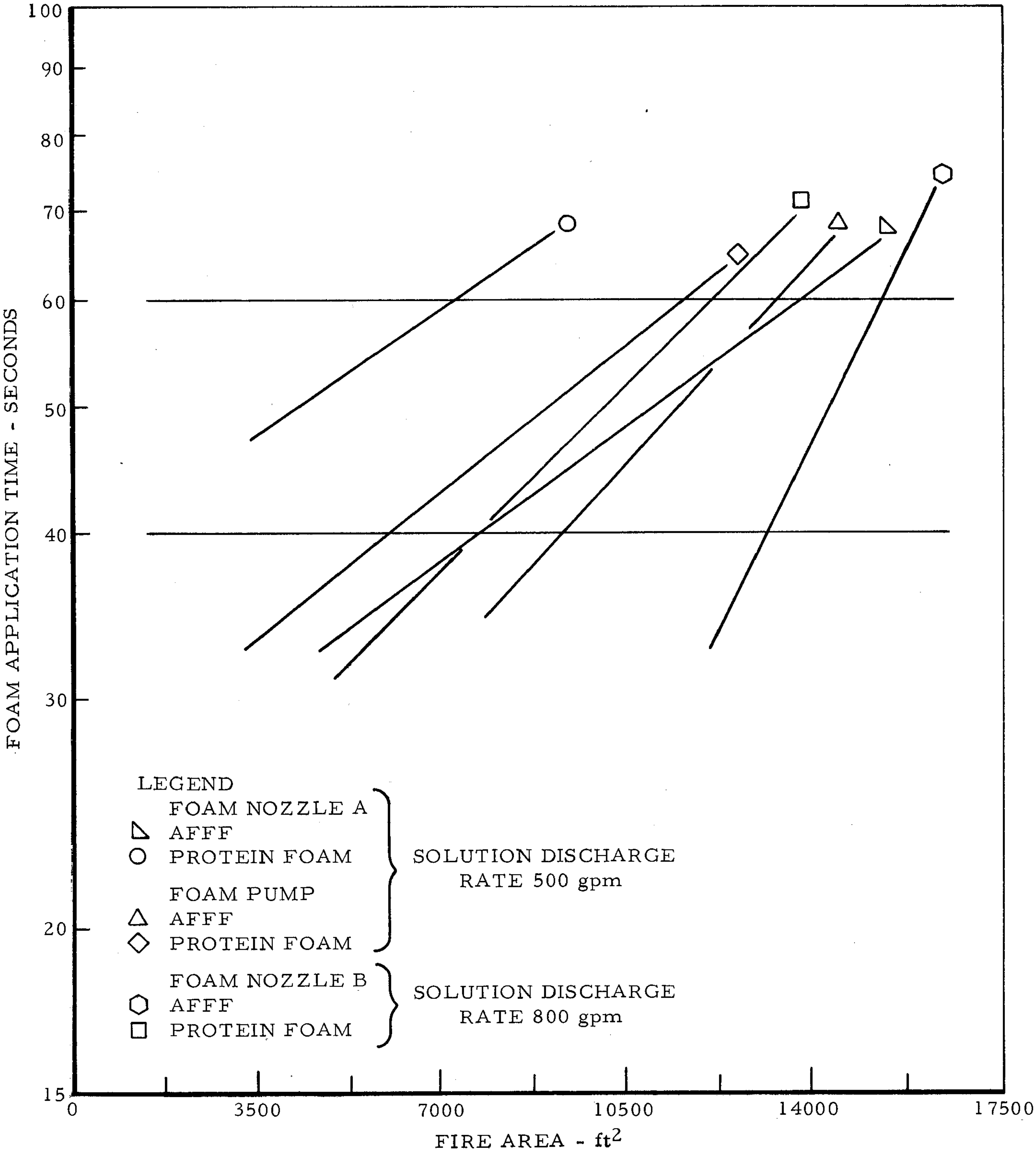


FIGURE 38 - FIRE AREA CONTROLLED AS A FUNCTION OF THE FOAM APPLICATION TIME USING FOAM NOZZLES A AND B AND THE FOAM PUMP WITH AFFF AND PROTEIN FOAM

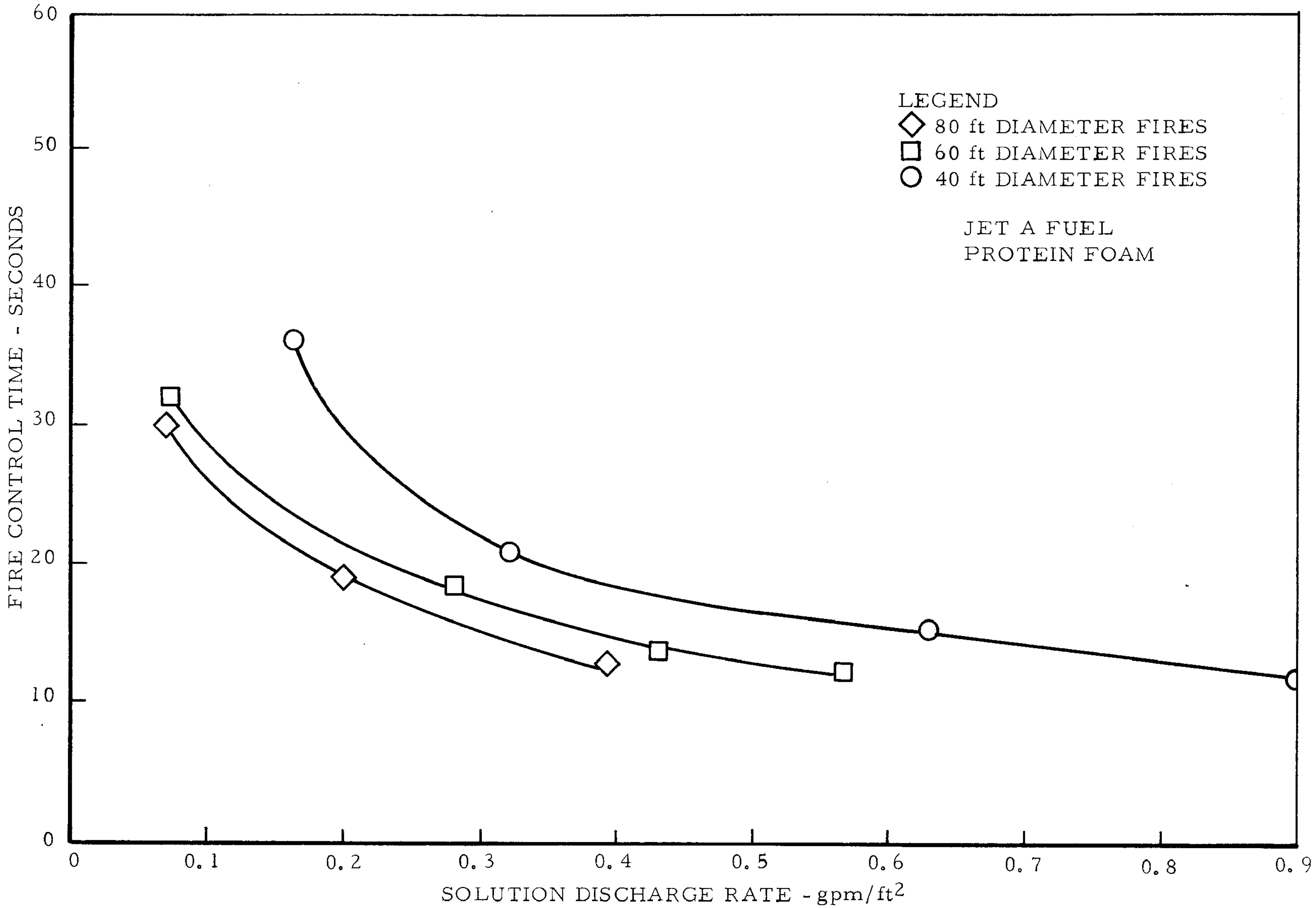
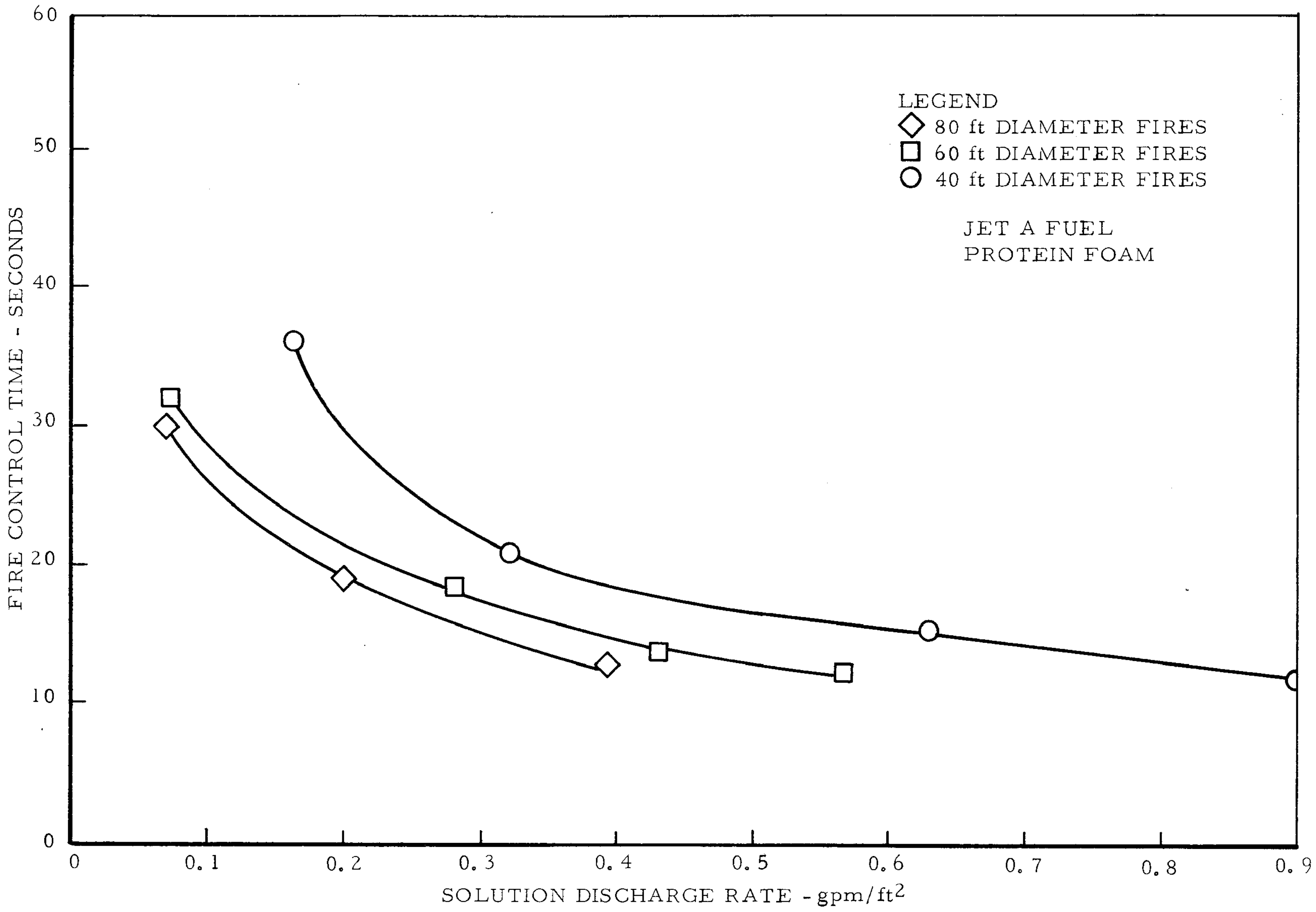


FIGURE 39 - THE VARIATION IN FIRE CONTROL TIME WITH POOL FIRE SIZE

Because of the large number and complexity of the variables associated with conflagrations involving aircraft of different size and configuration, relatively few attempts have been made, by investigators in the field, to evaluate the overall effectiveness of different firefighting foams. The literature abounds with data which attempt to establish the threshold application rates for protein foam and AFFF on test beds which range in size and complexity, from simple indoor pan-fire tests to very realistic fires involving 24,000 sq ft or more of burning fuel distributed around a medium size aircraft. Solution application rates for protein foam and AFFF on test beds within these extremes have been reported, which show the fire control time ratio to vary from 1:2 to 1:10 in favor of AFFF for different foam dispensing equipment. One reason for the wide variation in the data reported in the literature was shown by the results of this effort to be caused by the rather wide variation in the quality of protein foam produced by different dispensing systems and the variation in the fire-test beds. This is evidenced by the profiles in Figure 36, which show that the average difference in fire control times between AFFF and protein foam dispensed by the foam pump, is approximately 21 percent, while the difference in the fire control times using protein foam dispensed by the foam pump and Nozzle A was approximately 32 percent. Therefore, it is apparent that there is a greater difference between the two foam-dispensing systems using the same protein foam, than there is between the foam pump dispensing AFFF and protein foam. Another possible cause for differences in the fire control times between protein foam and AFFF was found to depend upon the degree of efficiency achieved by the firefighting team in the use of the equipment and agent being tested.

An additional objective of the full-scale modeling experiments was to analyze the data and determine the most effective and economical way to combat large Class B spill fire with foam. The results of this analysis provided the guidelines used in subsequent tactical firefighting experiments employing two B-47 Stratojet bombers.

The profiles in Figures 40 and 41 were developed to reveal the fire control mechanism which maintains when foam is dispensed onto a spill fire at a fixed solution rate from a single point of discharge. These profiles show the foam discharge time as a function of the solution application rate, which is based upon the uncontrolled fire area remaining at the time shown on the ordinate. The approximate size of this uncontrolled fire area is shown, at several critical phases during the fire control period, in the upper abscissa. The



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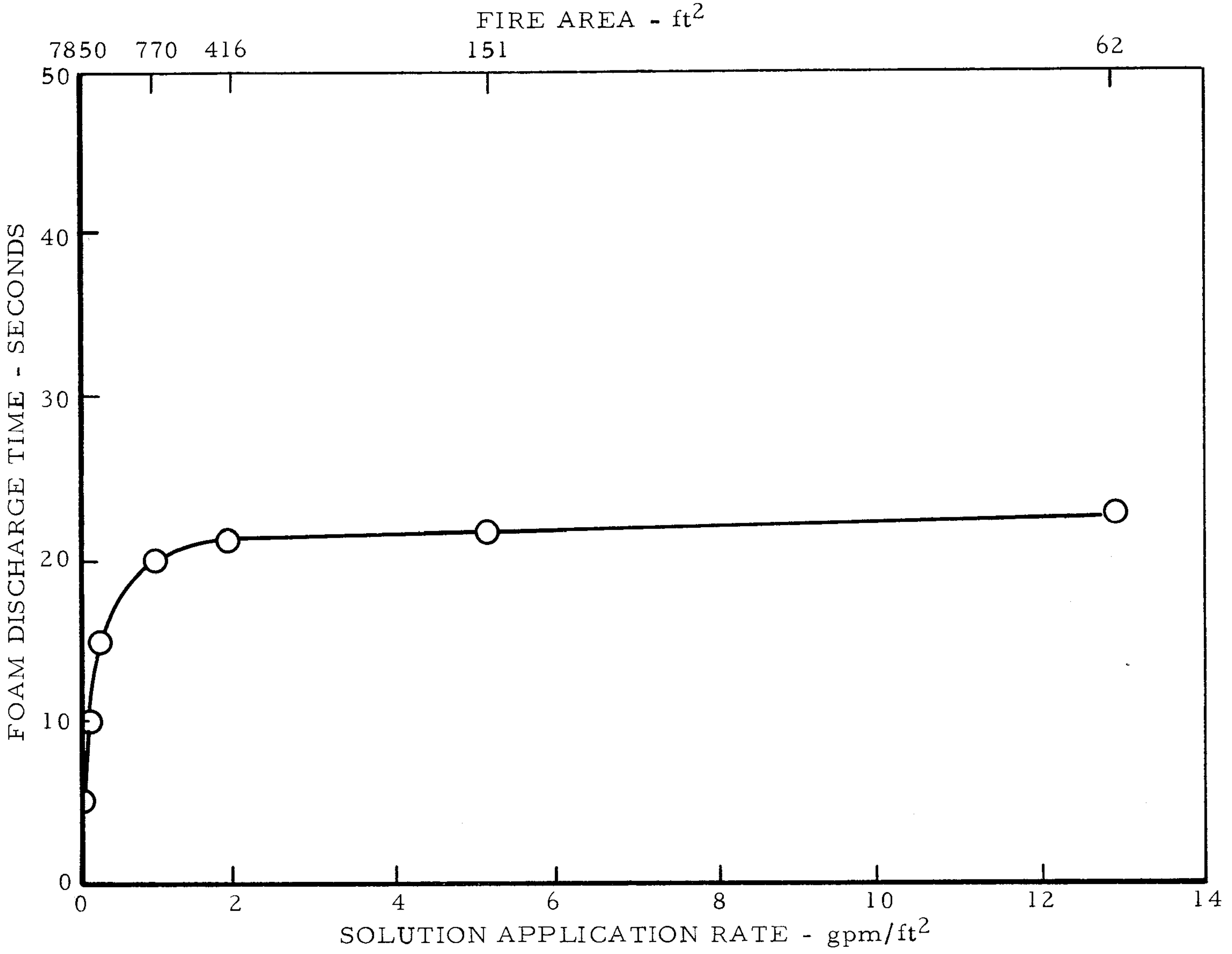


FIGURE 40 - THE CHANGE IN RATE OF AFFF SOLUTION APPLICATION ON THE RESIDUAL FIRE AREA AS A FUNCTION OF THE TIME OF DISCHARGE ON A 100-FOOT DIAMETER JP-4 FUEL FIRE USING NOZZLE B

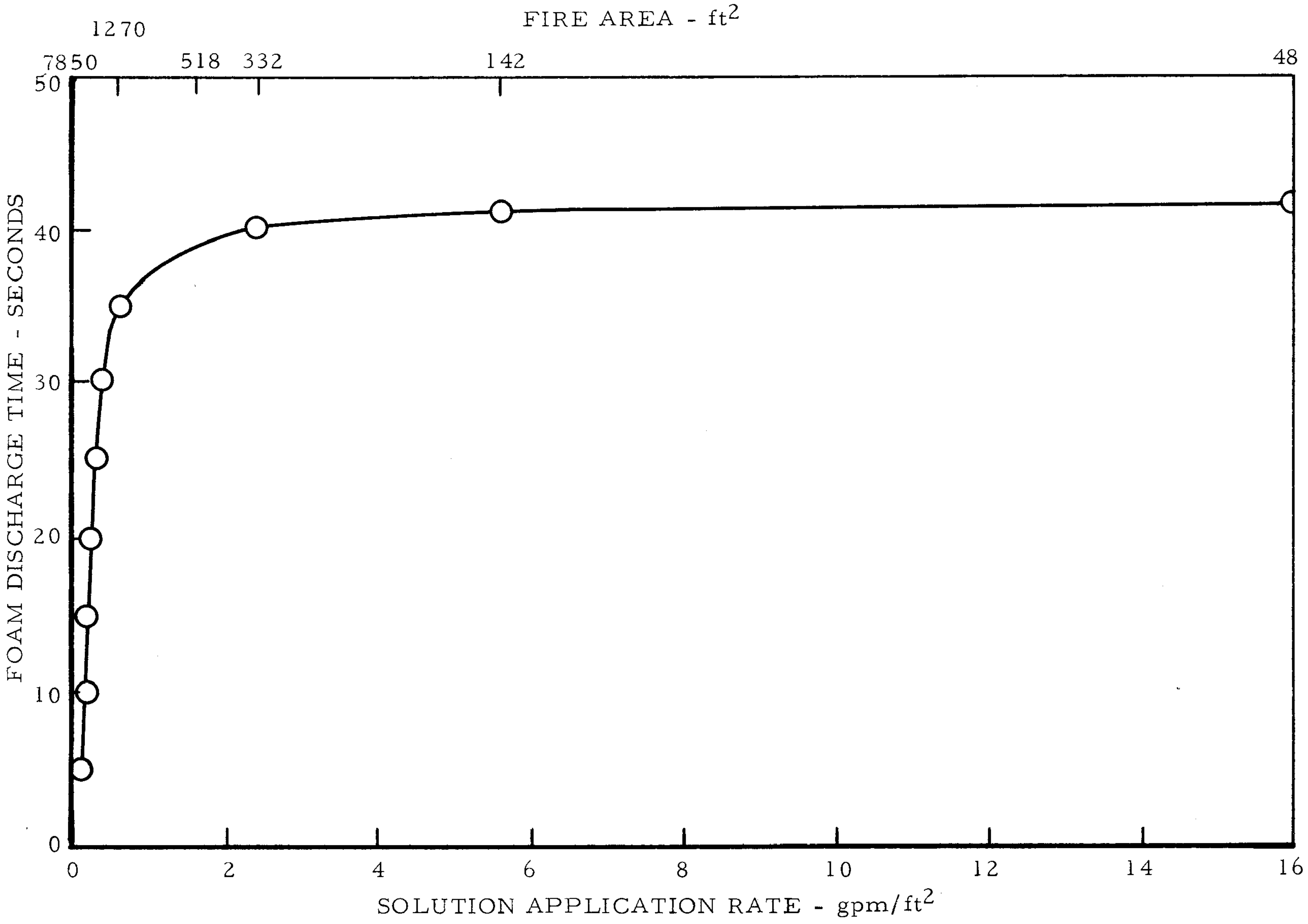


FIGURE 41 - THE CHANGE IN RATE OF PROTEIN FOAM SOLUTION ON THE RESIDUAL FIRE AREA AS A FUNCTION OF THE TIME OF DISCHARGE ON A 100-FOOT DIAMETER JP-4 FUEL FIRE USING NOZZLE B

profile in Figure 40 was obtained using AFFF, in which fire control was obtained in 22.2 sec, and in Figure 41, the fire control time for a similar fire was 41.8 seconds using protein foam. These profiles are basically very similar and indicate that approximately 95 percent of the fire area was brought under control by each agent before the solution application rate exceeded 1.0 gpm per sq ft. Therefore, it is a matter for conjecture as to why it required approximately twice as long for protein foam to control the 100-foot-diameter fire as it did for the AFFF agent. One reason for the difference in the fire control time would seem to be the wide variation in foam viscosity between the two agents which would tend to make protein foam more difficult to distribute uniformly over the fuel surface than AFFF. However, it had been previously demonstrated that protein foams, with the higher viscosities and longer 25-percent-solution draining times, provided the most rapid fire control times. A second, and more plausible reason for the difference, was to assume that a part of the protein foam was decomposed by the plunging action of the foam stream as it was being discharged onto the surface. This hypothesis was confirmed by an analysis of the photographic coverage of numerous fire tests and by visual observation. Therefore, to minimize the destruction of foam by plunging, requires that it be applied as gently as possible over the surface of the fuel, and that the straight stream discharge be limited to situations where maximum reach is mandatory. Another important fact that was derived from a consideration of the profiles in Figures 40 and 41 was that it would be extremely wasteful of the agent to attempt fire extinguishment by means of foam alone. This is particularly evident from the data which show that at the end of the fire control time and the beginning of fire extinguishing, the foam solution application rate using AFFF was approximately 13 gpm per sq ft, and for protein foam it was 16 gpm per sq ft. From these data, it is evident that, where possible, a lower solution application rate should be used, or that small auxiliary units should be used to extinguish peripheral fires after fire control has been obtained by the major foam-dispensing vehicles.

The profiles in Figures 40 and 41 also show that after fire control had been obtained with protein foam and AFFF, the difference in the remaining fire area was 14 sq ft between the two 100-ft-diameter fires, which indicates the adequacy of the fire-monitoring system.

Summary of Results

The results obtained from the foam quality experiments and the large-scale fire-modeling tests using protein foam and AFFF, are:

1. The quality of air-aspirated protein foam and AFFF expressed in terms of the expansion ratio, 25-percent-solution drainage time, and foam viscosity was determined to be a function of the mechanical energy imparted to the foam by turbulation and shearing during its transit through the nozzle barrel.

2. The viscosity and foam solution drainage time of protein foam was found to vary over a wider range than AFFF for equal energy input by the dispensing system during foam formation.

3. The viscometer employed to measure the viscosity of the foams used in the large-size fire-modeling experiments was of value in determining this important physical property.

4. The effect of increasing the concentration of firefighting foam solutions was to cause an increase in the foam expansion ratio, 25-percent-solution drainage time and foam viscosity and the magnitude of the increase in these properties was a function of the equipment design and foam agent employed.

5. The quality of protein foam determined to be the most effective in combatting large traprock-base JP-4 fuel fires, using two different air-aspirating nozzles, had an expansion ratio between 11:1 and 12:1, a 25-percent-solution-drainage time of approximately 11 min and a viscosity of 320 dynes per sq cm measured 30 sec after formation.

6. In the large-scale fire-modeling experiments, highly effective AFFF foam had an expansion ratio between 10:1 and 11:1, a 25-percent-solution drainage time between 7 and 8 min, and a viscosity of 60 dynes per sq cm measured 30 sec after formation.

7. The foam pump was capable of imparting greater energy to the foam solution during formation than the air-aspirating systems used in these experiments which resulted in foams with higher viscosities and longer 25-percent-solution drainage times.

8. The protein foam and AFFF discharged from the two air-aspirating nozzles and the foam pump had equivalent range in still air. With crosswind velocities of 8 to 12 mph, the range was reduced by 38 to 47 percent.

9. The overall firefighting effectiveness of protein foam and AFFF was estimated to be from 1.25 to 1.31 times greater for AFFF than it was for protein foam.

10. The specific foam solution application rate on fuel spill fires increased continuously from the time foam application was started until the time the fire was extinguished, which required excessively high rates after fire control had been obtained.

Conclusions

Based upon the results of a laboratory evaluation of firefighting foams and from large-scale fire-modeling experiments, it is concluded that:

1. Protein foam and AFFF are effective in combatting large traprock base JP-4 fuel fires and are considered acceptable agents for evaluation in the full-scale fire tests using B-47 Stratojet aircraft.

2. After large spill fires have been brought under control by means of the primary foam deluge discharge, the foam solution application rate should be reduced to conserve the agent, or auxiliary agents should be used to extinguish small peripheral fires.

3. The foam-pump system and the two air-aspirating nozzles produce significantly different quality of AFFF and protein foam and each agent and dispensing system is considered worthy of evaluation in the full-scale fire-modeling tests using the B-47 Stratojet aircraft.

VII FULL-SCALE FIRE-MODELING EXPERIMENTS USING B-47 STRATOJET AIRCRAFT

Introduction

Objective: The objective of the full-scale fire-modeling experiments was to determine the minimum application rate and quantity of each class of fire-extinguishing agent necessary to prevent the aluminum skin on a medium-size aircraft from melting under severe-fire conditions. From these data it was possible to extrapolate the agent requirements for both larger and smaller aircraft.

Background: Numerous large-scale fire tests reported in the literature were concerned primarily with estimating the time required to evacuate a limited number of occupants from specific sections of an aircraft by establishing a fire-free path of foam to the fuselage. These experiments, in general, ignored the effect of the intense thermal radiation generated by a free-burning pool fire on fuselage integrity and the element of time available to effect total evacuation of personnel before the fuselage skin failed (melted) and the fuel tanks either ruptured or exploded. This rationale is commensurate with the necessity to save lives over property. However, the data presented in Reference 2 show that fuselage failure time is very closely associated with occupant survival time. Therefore, in the interest of saving lives, the foam-solution discharge rate and the quantity of agent(s) required to protect a large aircraft in a severe accident involving fire, should be based upon the need to maintain fuselage integrity insofar as possible.

Discussion and Results

Test Procedures: The goal of each of the four full-scale fire-modeling experiments was to determine the minimum rate of application of each firefighting foam agent necessary to control a JP-4 fuel fire estimated to be consistent in magnitude with the size and total fuel capacity of the B-47 aircraft. The basic approach to meeting these objectives was to measure the time required to control the ground-fire with foam and the additional time necessary to completely extinguish peripheral and 3-dimensional fires by means of auxiliary agents. The fire test conditions required the application of Class A, B, C, and D fire-extinguishing agents.

The overall fire test environment is schematically presented in Figure 42. The test aircraft was positioned in the center of an earthen diked fire pit with the centerline of the fuselage approximately parallel with the wind direction. The terrain within the bunded area consisted of a 5-in.-deep layer of 3/8-in. traprock. The pit was charged with JP-4 fuel delivered through a system of underground piping from two 5,000-gal storage tanks. The height of the fuel was adjusted by the addition of water to the pit so that it was just level with the surface of the traprock. All experiments were performed with the aircraft in the wheels-up position and a clay embankment was built up around the fuselage where it contacted the ground to prevent the fuel from entering the fuselage.

The overall firefighting effectiveness of each experiment was determined by four radiometers mounted, in pairs, on 8-ft-high steel poles positioned at the pool perimeter on the diameter and at right angles to the wind direction. The degree of protection provided the aircraft's fuselage skin and wings was measured by 12 thermocouples embedded in the metal and recorded on instruments located in an instrument trailer. Motion pictures of each test were obtained for documentation and data analysis from locations on top of the fuel storage tanks and from the tops of two strategically located vans.

In each experiment the primary objective was to provide protection to the aircraft within the survival time (Reference 4) of aluminum fuselage skin under the conditions established. Therefore, the thermocouple data showing the temperature rise of the fuselage skin are most significant, while the radiometer data are considered more representative of the overall success of the firefighting effort expressed as the fire control time. In these experiments, fire control time was defined as the total elapsed time between the initiation of the extinguishing operation to that time when the heat flux, as measured by the radiometers, was reduced to 0.20 Btu per sq ft per sec. This differentiation is necessary because the goal of the firefighting team was to protect the aircraft from damage by laying a blanket of foam adjacent to the fuselage and extending it outward until the fire was brought under control and extinguished, which in several tests, resulted in the fuel burning excessively long in front of the radiometer mounts, even though the fuselage was out of immediate danger.

The particular goals of Experiments 1 and 2 were to estimate the overall firefighting effectiveness of foam Nozzle B using AFFF and protein foam. While the objectives of Experiments 3 and 4 were to compare the firefighting effectiveness of these foams dispensed by the foam pump and foam Nozzle A on the same fire at the same time.

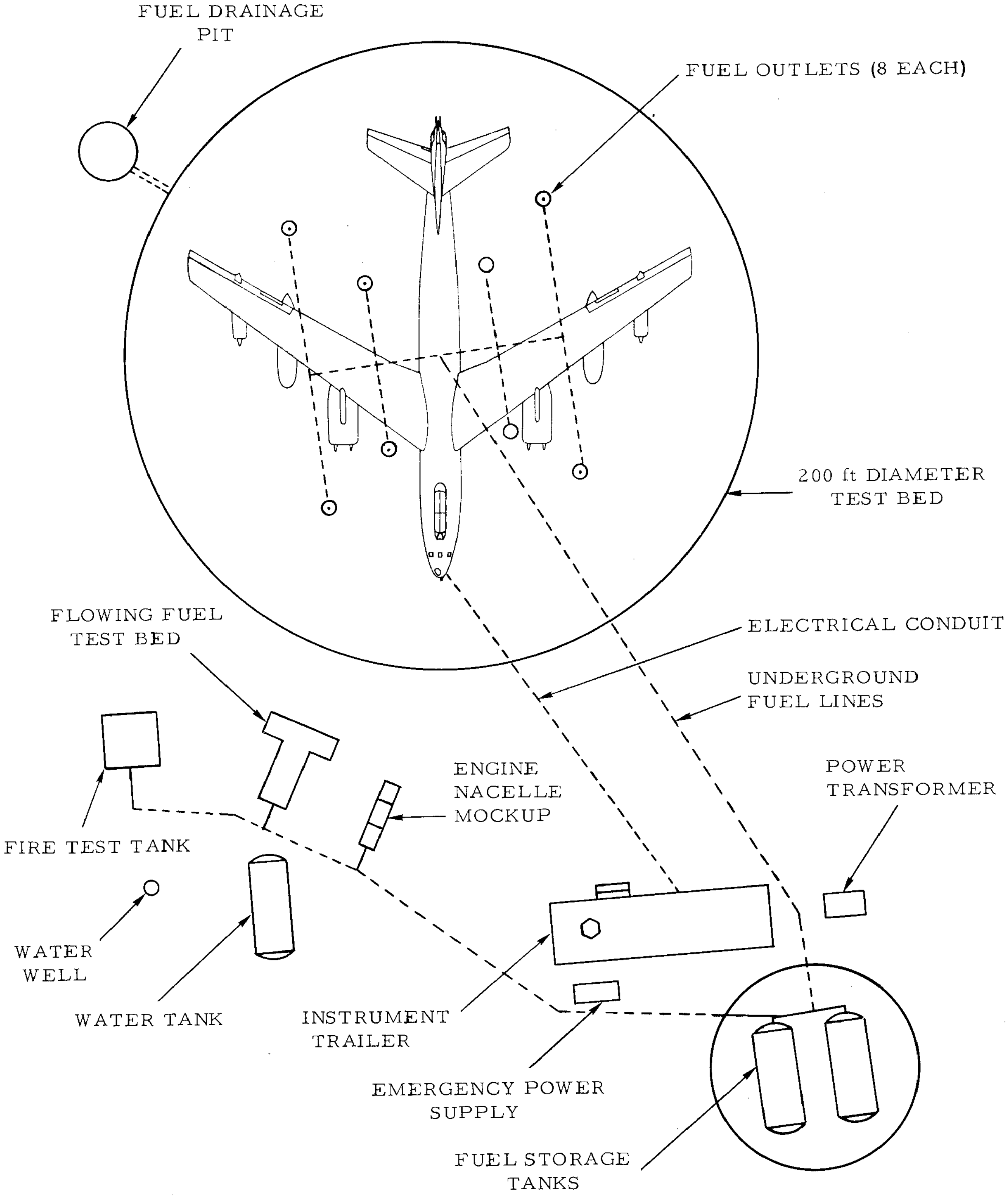


FIGURE 42 - SCHEMATIC DRAWING OF THE FIRE TEST BED

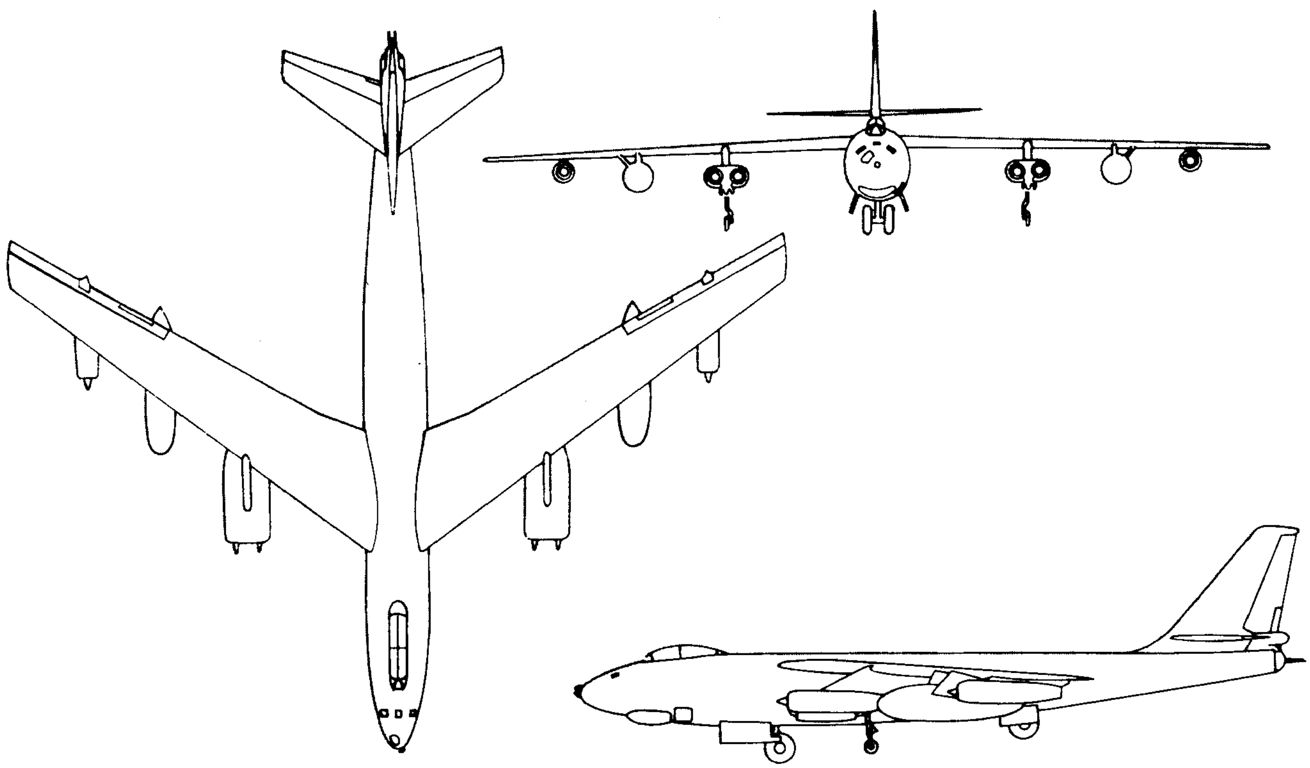
Experiment No. 1 Using Two Foam Nozzles B and AFFF (Manufacturer E-2) - The first experiment employed a B-47 aircraft (Figure 43) positioned in the center of a 15,386-sq ft (140-ft diameter) circular fire pit charged with 6,500 gal of JP-4 fuel. The fire test bed is shown schematically in Figure 44. The four inboard engines of the aircraft had been removed as well as a 12-ft section of the wing, including the outboard engine on the starboard side. However, an auxiliary fuel tank on the starboard side remained in position. All of the fuel tanks had been purged and the hydraulic systems removed to prevent any possible explosions. An engine fire was simulated in the port outboard engine by discharging JP-4 fuel from a 1/4-in.-diameter stainless steel tube at the rate of 3 gpm into the engine nacelle.

The large-scale tests conducted as part of another phase of this project indicated that approximately 7,800 sq ft of fire surface could be controlled within 23 sec with an AFFF solution application rate of 0.104 gpm per sq ft. This area was equivalent to approximately one-half of the total fire area around the aircraft, and therefore, two points of foam discharge would be capable of protecting the fuselage skin from melting within the estimated critical 40-sec fire exposure time, providing the preburn time did not exceed 17 sec. Therefore, the burn conditions established comprised a preburn time of 17 sec followed by a 23 sec discharge of AFFF.

The primary firefighting agent employed in the first experiment was a 6-percent premixed AFFF solution dispensed by two Nozzles B mounted on two modified crash-fire vehicles.

The auxiliary agents included a dry-chemical powder, a halogenated hydrocarbon, and a magnesium fire extinguishing agent. The dry-chemical powder was CDC, dispensed from a 1,000-lb truck-mounted unit at the rate of 10 lb per sec from each of two handlines on the starboard side of the aircraft and from a 1,500-lb trailer-mounted unit at the rate of 10 lb per sec from each of two handlines, on the portside of the fuselage. The halogenated hydrocarbon was CB dispensed from one 40-gal truck-mounted unit at the rate of 20 gpm. The magnesium fire-extinguishing agent (TEC) was dispensed from two 10-lb dry-chemical hand-portable extinguishers on the extensive fires which developed along the leading edges of the wings and some sections of the fuselage.

A. Fire Test Results - The thermal data obtained during the course of the experiment are presented in Figures 45, 46, and 47. The temperature rise of the aluminum skin on the



AIRCRAFT DIMENSIONS

WING SPAN 116 FEET
OVERALL LENGTH 107 FEET 1.5 INCHES
HEIGHT (TO TOP OF FIN IN TAXI ATTITUDE 28 FEET)
TREAD (BETWEEN OUTRIGGERS 44 FEET 4 INCHES)

GROSS WEIGHTS

DESIGN GROSS WEIGHT 125000 POUNDS
FUEL (APPROXIMATE) 413140 POUNDS

FIGURE 43 - THE B-47 STRATOJET AIRCRAFT

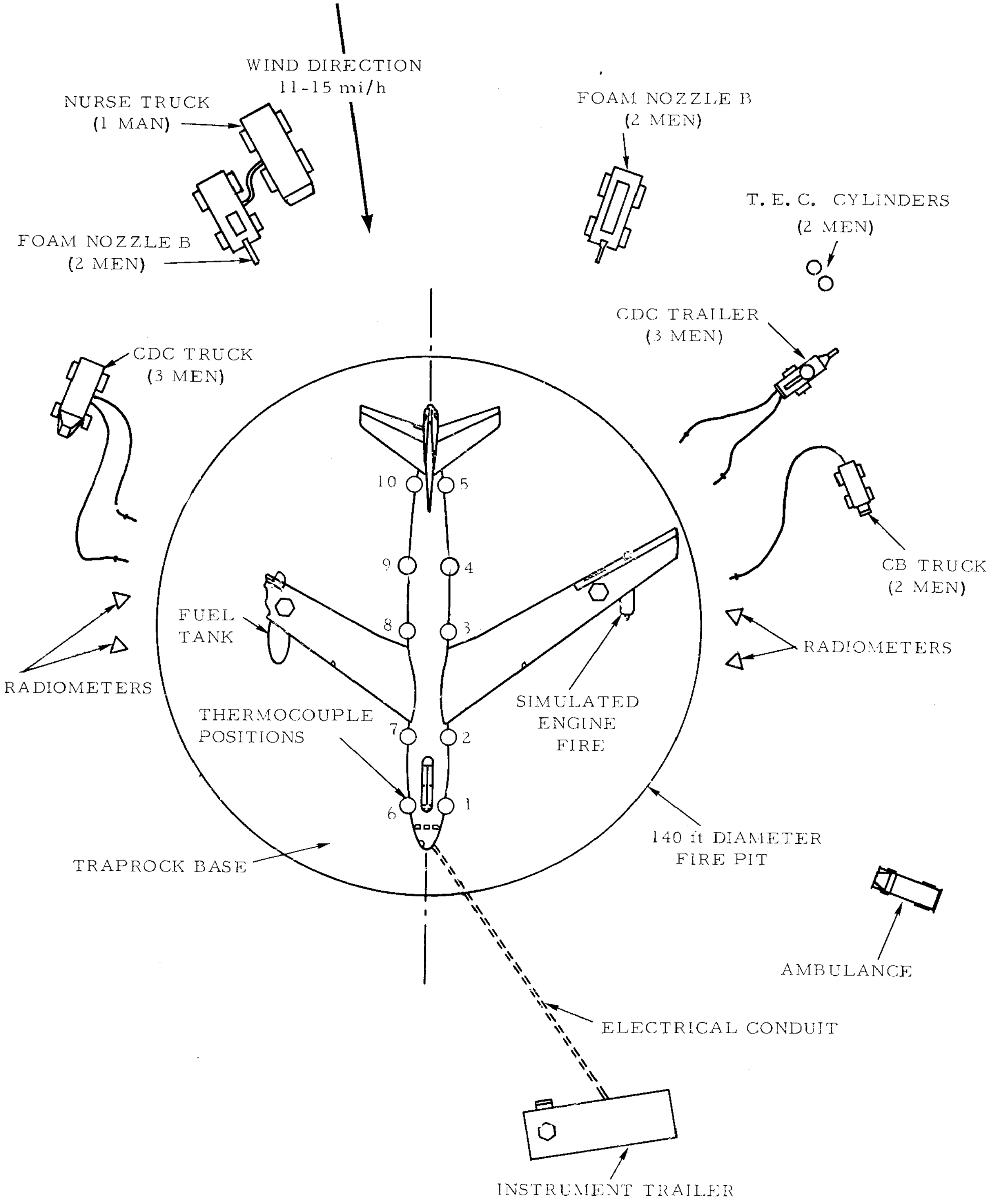


FIGURE 44 - EXPERIMENT NO. 1 TEST BED CONFIGURATION
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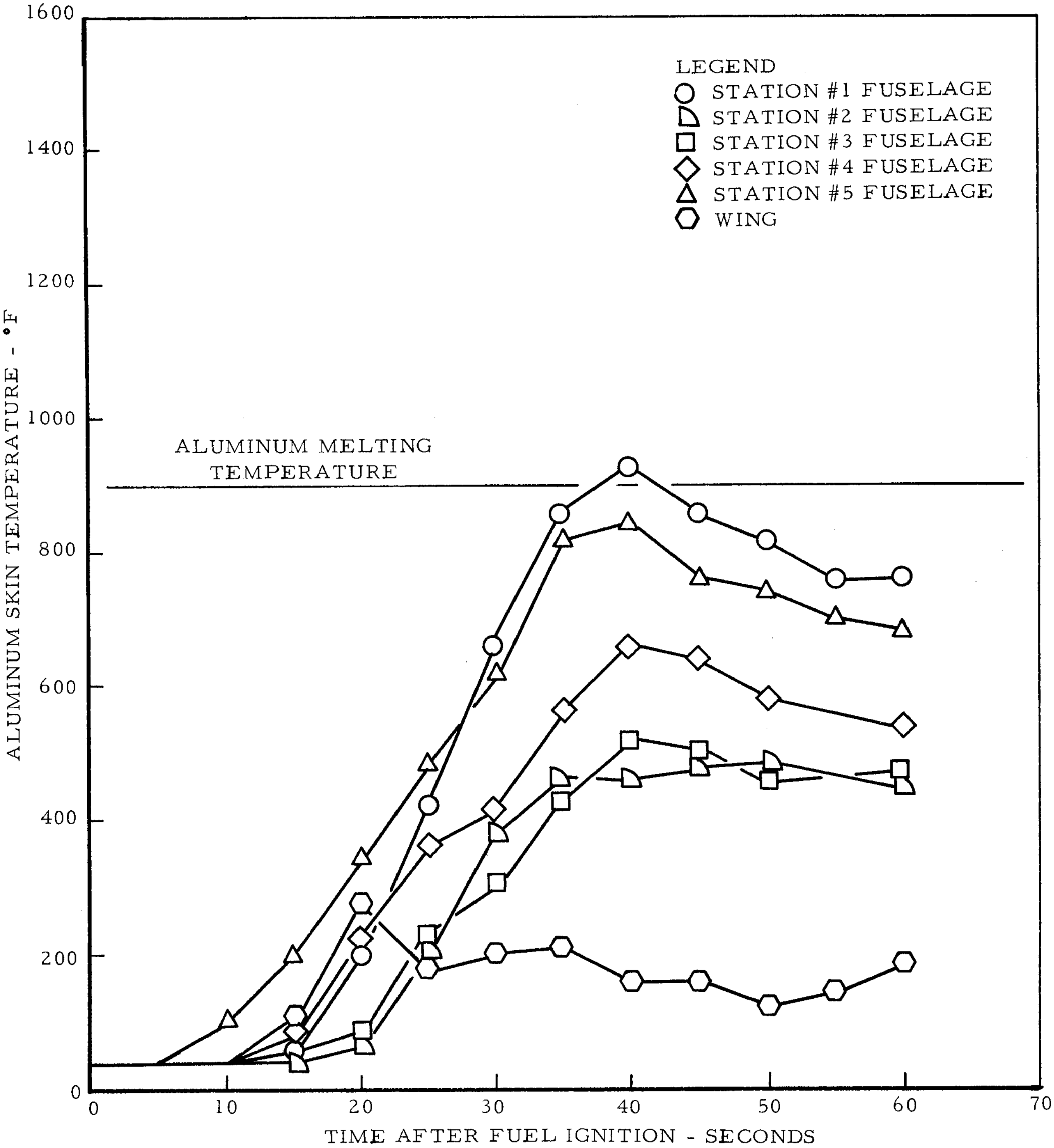


FIGURE 45 - THERMOCOUPLE DATA FROM THE PORTSIDE OF THE B-47 AIRCRAFT (TEST NO. 1)

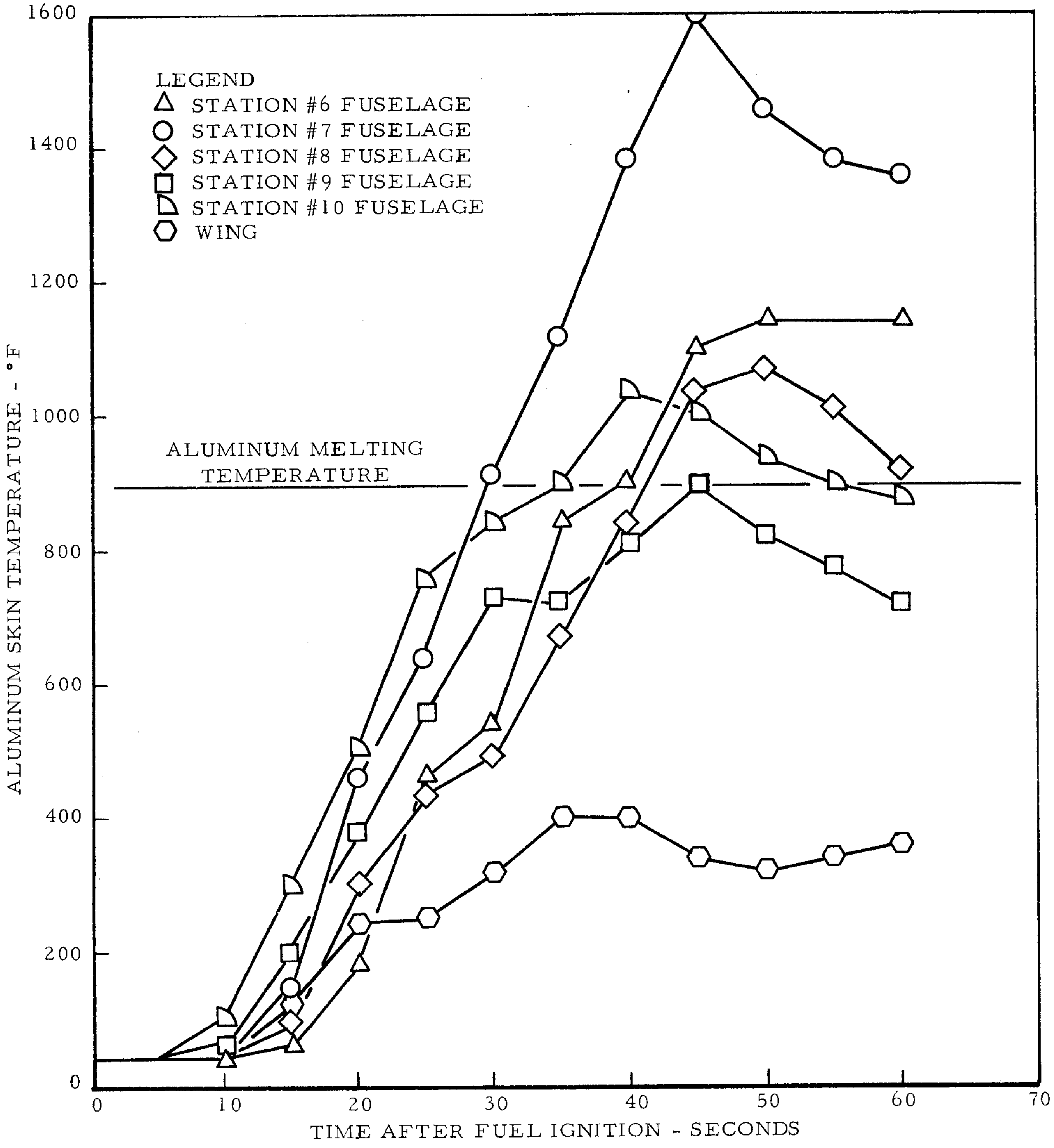


FIGURE 46 - THERMOCOUPLE DATA FROM THE STARBOARD SIDE OF THE B-47 AIRCRAFT (TEST NO. 1)

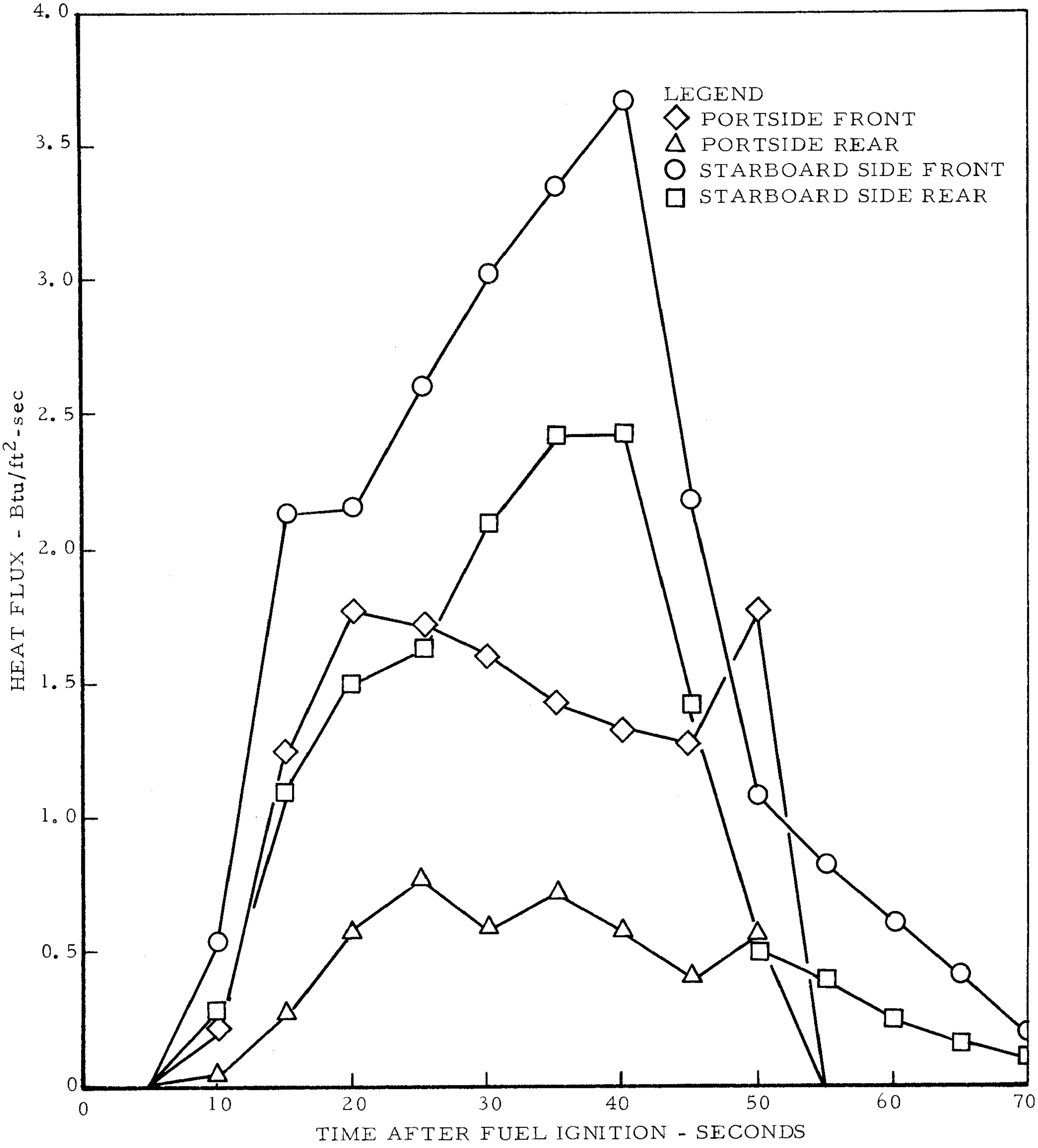


FIGURE 47 - RADIOMETER DATA SHOWING THE PROGRESS OF FIRE CONTROL (TEST NO. 1)

portside of the aircraft during the progress of the fire is shown by the profiles in Figure 45, and on the starboard side in Figure 46 where the temperature is plotted as a function of the time after fuel ignition. From the curves presented in Figure 45, it is evident that, except for the thermocouple at Station 1, which was near the cockpit and on the downwind side of the fuselage, the skin temperature remained below the incipient melting temperature of 900°F for aluminum (Reference 4). The highest skin temperature recorded on the portside of the aircraft (Station 1) was approximately 930°F which maintained for approximately 4 sec. Therefore, it may be assumed that the portside of the aircraft was adequately protected from melting by the agent employed, and foam application was at or near the critical application rate. A photograph of the portside of the B-47 aircraft 40 sec after the start of foam application is shown in Figure 48.

The thermal radiation on the port and starboard sides of the aircraft during the fire control stage is presented in Figure 47, where the heat flux measured by the four radiometers is plotted as a function of time after fuel ignition. These curves show that on the portside of the aircraft, the actual fire control time measured by both the radiometer facing the empennage as well as the radiometer monitoring the cockpit area was approximately 35 sec. This rapid control time resulted in a reduction in the heat flux to a level which was ineffectual in causing further damage to the fuselage skin within approximately 21 sec after foam discharge started, as shown by the profiles in Figure 47.

Tests performed under simple pool fire conditions (Figure 37) using the same foam-dispensing equipment and agent at an equivalent solution application rate resulted in fire control in 23 sec.

The thermal data obtained on the starboard side of the aircraft, using a similar foam-dispensing system, were not representative of the true firefighting effectiveness of either the agent or equipment. This was caused by the failure of the dispensing equipment to achieve the required solution pressure at the foam nozzle to provide the necessary foam-discharge range during the first crucial seconds of foam application after the preburn period. The profiles shown in Figure 46 in which the fuselage skin temperature is plotted as a function of time after fuel ignition, show that the skin temperature in the vicinity of Station 7 reached the incipient melting temperature for aluminum in approximately 30 sec and that all of the thermocouples, except the one on the wing, reached a temperature of 900°F or higher within 45 sec after fuel ignition.

FIGURE 48 - PORTSIDE OF THE B-47 AIRCRAFT 40 SECONDS AFTER FUEL IGNITION (TEST NO. 1)

The radiation level on the starboard side of the aircraft is shown in Figure 47, where the heat flux is plotted as a function of time after fuel ignition. In these profiles the radiometer facing the empennage of the aircraft showed control of the ground fire in 46 sec after foam application started while the radiometer facing the cockpit showed control in approximately 50 sec, or an average for the starboard side of approximately 48 sec. By comparing the fuselage skin temperature with the incipient melting temperature of aircraft aluminum of approximately 900°F, it is apparent that the aircraft skin melted at positions 6, 7, and 10 within 40 sec, and that the skin at positions 8 and 9 failed within an additional 5-sec period.

After fire control had been obtained with foam on the portside of the aircraft, CB was dispensed into the engine nacelle for approximately 9 sec to extinguish the flowing JP-4 fuel fire. This operation was followed approximately 80 sec after fuel ignition by a 37-sec discharge of CDC on the remaining peripheral ground fires. On the starboard side of the aircraft the CDC discharge was started approximately 102 sec after fuel ignition and continued until the agent was exhausted. TEC was also dispensed successfully on a large complex magnesium fire that developed inside the fuselage on the starboard side after the fuselage skin failed.

Failure to obtain control of the fire on the starboard side of the aircraft within the critical time period led to the destruction of the fuselage skin, which resulted in the development of extensive Class A materials fires inside the cockpit and fuselage with numerous Class D (magnesium) fires dispersed throughout the aircraft structure. The wide distribution of magnesium parts in this aircraft would require relatively large quantities of Class D extinguishing agents dispensed from many different points to achieve rapid control and extinguishment after having once been ignited. Because of the extensive Class A and Class D fires and the prolonged fire control time, a hazardous condition developed as a result of secondary foam formation, which is peculiar to AFFF when used on the more volatile fuels such as JP-4. The Class A and Class D fires continued to serve as ignition sources for the secondary foam which had formed, and small blue flames started to wick across the foam blanket until several areas of fuel, from which the foam had been blown by the wind, were ignited. The interior coating on the auxiliary fuel tank, under the starboard wing, also presented a serious source of reignition of the secondary foam after the top aluminum skin had melted. From a practical standpoint, it was not the size of this fire which created the most serious problem, but rather the large quantity of firefighting agents which was necessary to extinguish this small but complex fire configuration. Probably the most effective way to have attacked this fire would have been with a high-pressure water spray. By the time the auxiliary fuel tank fire had been extinguished, the interior of the fuselage had been extensively damaged and the foam truck had exhausted its supply of foam solution, so the effort to save the fuselage was abandoned.

An additional hazard sometimes associated with the fire-rescue mission involving military aircraft, such as the B-47, is the presence of live ordnance on board. A detailed evaluation of this particular problem was beyond the scope of this investigation; however, the need to obtain the most rapid fire control time possible is apparent from the fact that a 750-lb bomb exposed to a large free-burning pool fire will reach the detonation temperature of 400°F in 1 1/4 min (Reference 55).

As a result of the test, it was evident that obtaining control of the exterior fuel spill fire on the starboard side in 70 sec was inadequate to save the aircraft from eventual destruction because of skin melting on the starboard side and the development of catastrophic Class A and Class D fires inside the fuselage. Therefore, it is evident that in situations where the fuselage cannot be prevented from melting, it is necessary to have an adequate supply of Class A and Class D fire extinguishants available to control the interior cabin or fuselage fires.

Experiment No. 2 Using Two Foam Nozzles B and Protein Foam - The second experiment made use of the second B-47 aircraft which was positioned in the center of the 140-ft-diameter fire test pit in the wheels-up positon and diked with earth where it contacted the ground. The test-bed configuration was similar to that employed in the first experiment and is shown schematically in Figure 49. The fire test bed was instrumented in a manner similar to that used in Experiment No. 1, and, in addition, the fuselage was coated with a zinc chromate primer and painted with an intumescent paint conforming to the requirements in Reference 59. A photograph of the completed test article is shown in Figure 50.

In an effort to delay the ignition of the Class A and Class D materials inside the fuselage and cockpit areas in the event of a major failure of the fuselage skin, such as occurred in the first experiment, a system of 11 water sprinklers was located in those areas considered particulary hazardous and activated prior to fuel ignition. Four sprinklers were installed in the cockpit, one in the crawl space, two in the bomb bay and two in each of the wheel wells. An engine

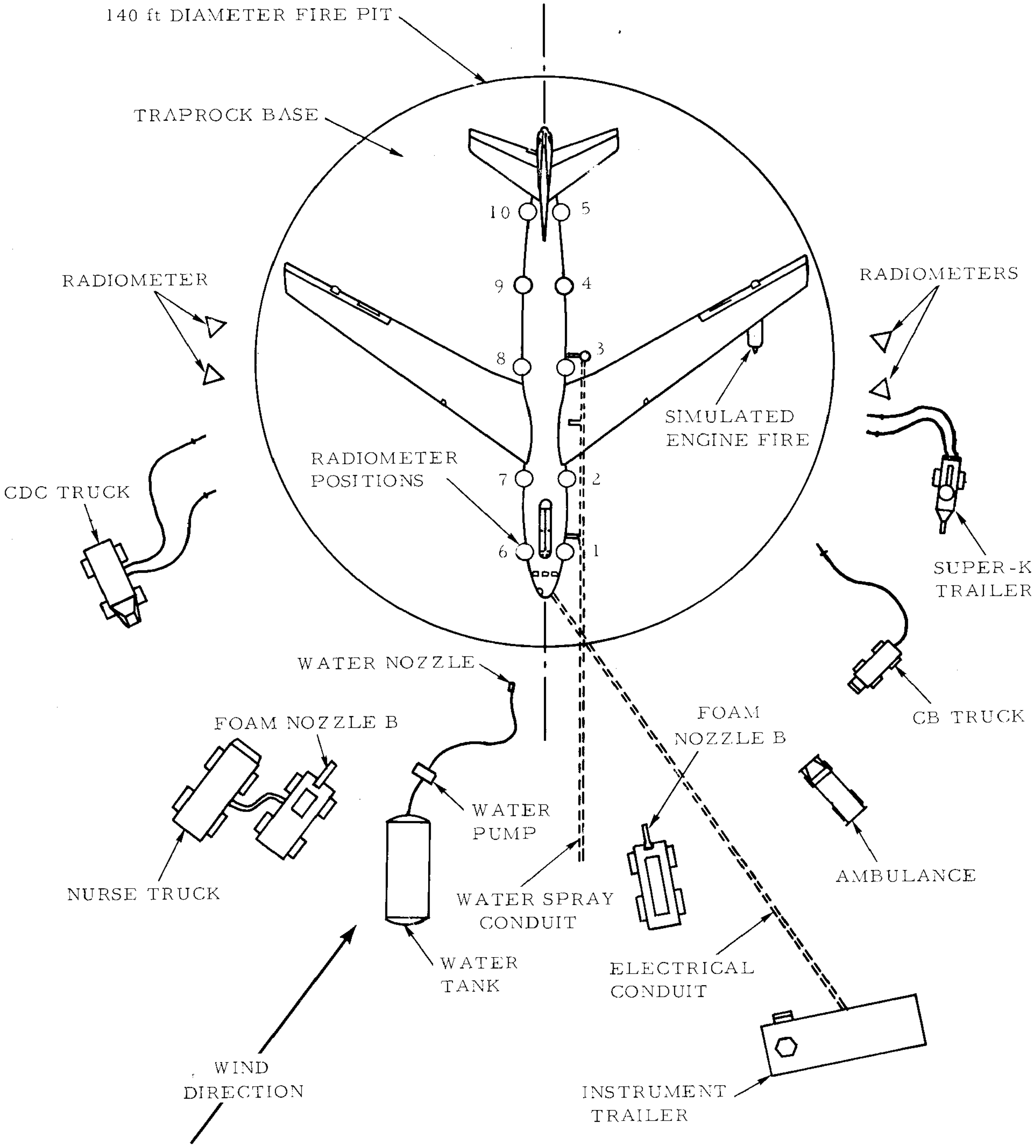


FIGURE 49 - EXPERIMENT NO. 2 TEST BED CONFIGURATION
(NOT TO SCALE)

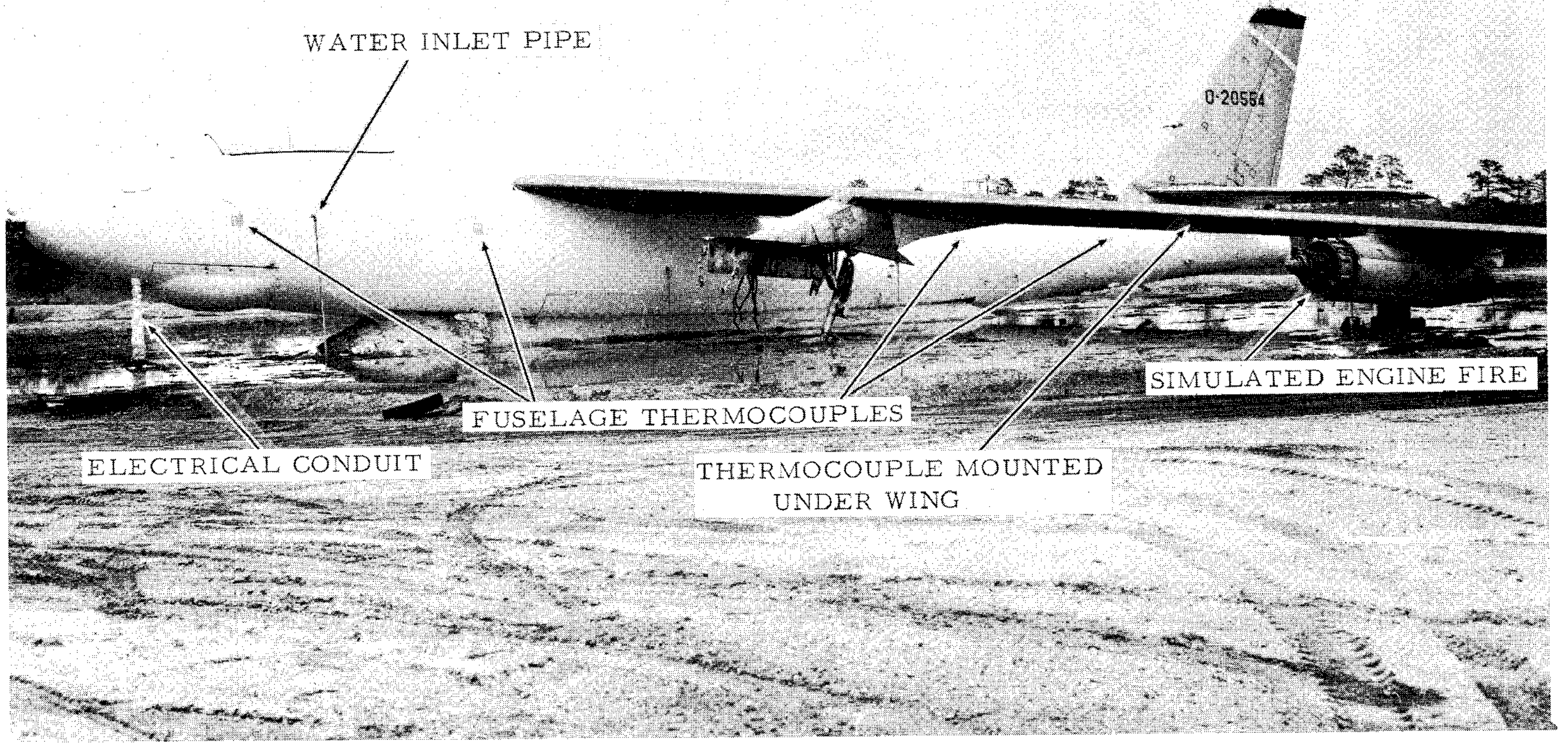


FIGURE 50 - THE B-47 AIRCRAFT COATED WITH INTUMESCENT PAINT (TEST NO. 2)

fire was simulated in the port engine by discharging JP-4 fuel from a 1/4-in-diameter stainless steel tube at the rate of 3 gpm into the engine nacelle, as in the previous experiment.

The primary firefighting agent, in Experiment No. 2, was a 6-percent premixed solution of protein foam (Reference 6) dispensed by two Nozzles B mounted on two modified crash-fire vehicles positioned as shown in Figure 49.

The auxiliary agents included two different types of dry-chemical powders, a halogenated hydrocarbon and a magnesium fire-extinguishing agent. One dry-chemical powder (CDC) was dispensed on the starboard side of the aircraft from a truck-mounted unit at the rate of 10 lb per sec from each of two handlines. The second dry-chemical powder (Super K) was discharged from a 1,500-lb trailer-mounted unit at the rate of 10 lb per sec from each of two handlines, on the portside of the fuselage. The halogenated hydrocarbon (CB) was dispensed from one 40-gal truck-mounted unit at the rate of 20 gpm. The magnesium fire-extinguishing agents available for use were MET-L-X in 30-lb cylinders and TEC in 10-lb hand-portable extinguishers.

A. Fire Test Results - The thermal data developed during the experiment are presented in Figures 51 through 53. The temperature rise of the aluminum skin on the portside (downwind) of the aircraft during the progress of the fire is shown by the profiles in Figure 51 and on the starboard side in Figure 52, in which the temperature is plotted as a function of the time after fuel ignition. From the curves plotted in Figure 51, it is apparent that the fuselage skin temperature at Station 1 in the cockpit area did not exceed 760°F, which was obtained 50 sec after fuel ignition. No data were obtained from Station 2, but at Stations 3, 4, and 5 the skin temperature reached the incipient melting temperature for aluminum between 40 and 53 sec after fuel ignition, which suggests that foam application may have been hindered by the quartering wind off the starboard side and by the wing on the portside of the aircraft. Figure 49 shows that on the portside of the aircraft the fire truck had been positioned as close to the centerline of the fuselage as possible in an effort to minimize the effect of adverse wind conditions and the wing obstruction, but without any appreciable beneficial effect on foam distribution.

The profiles presented in Figure 52 show that all stations on the starboard (upwind) side of the fuselage exceeded the melting point for aluminum between 36 and 49 sec after fuel ignition and that Station 6 and the wing area were

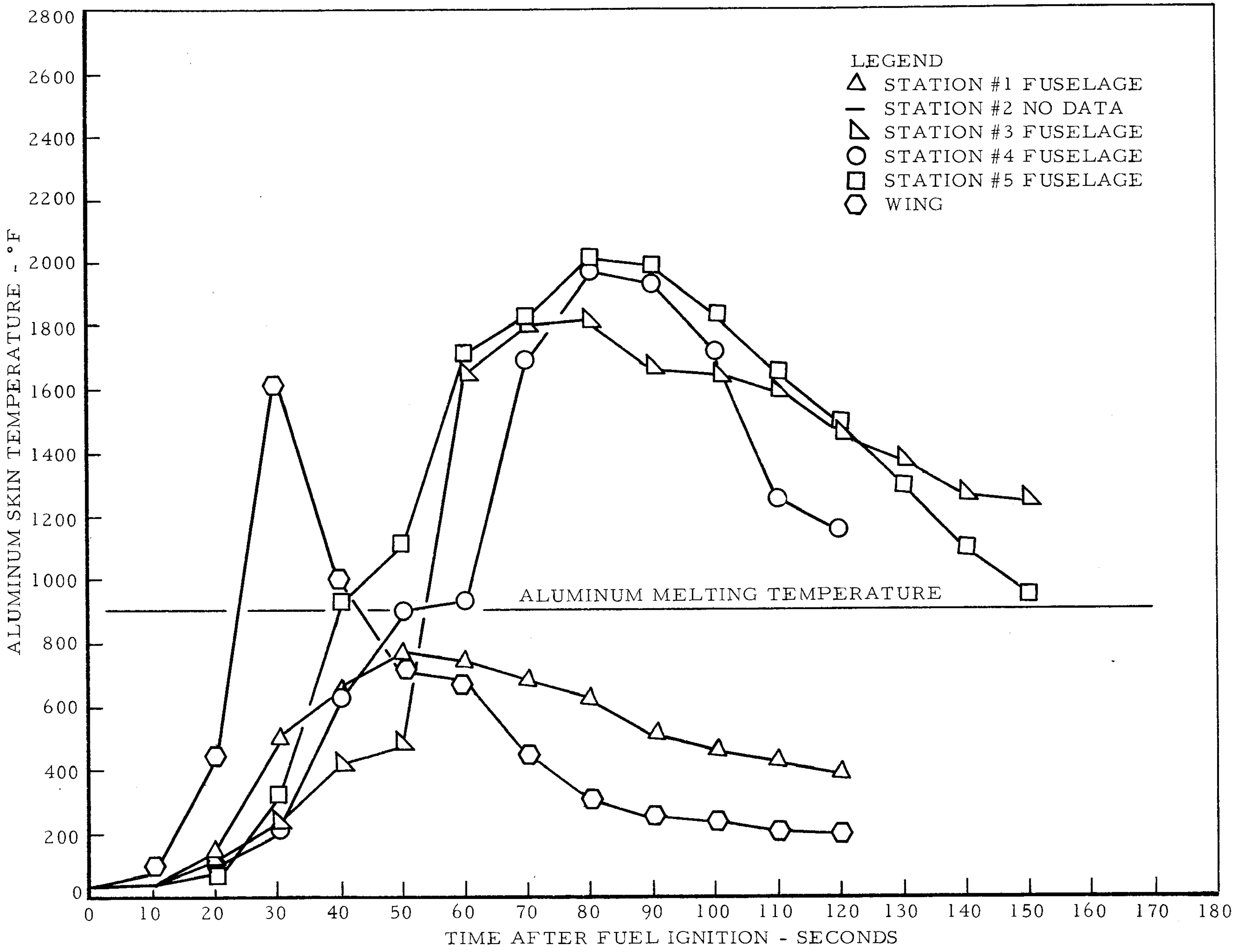


FIGURE 51 - THERMOCOUPLE DATA FROM THE PORTSIDE OF THE B-47 AIRCRAFT (TEST NO. 2)

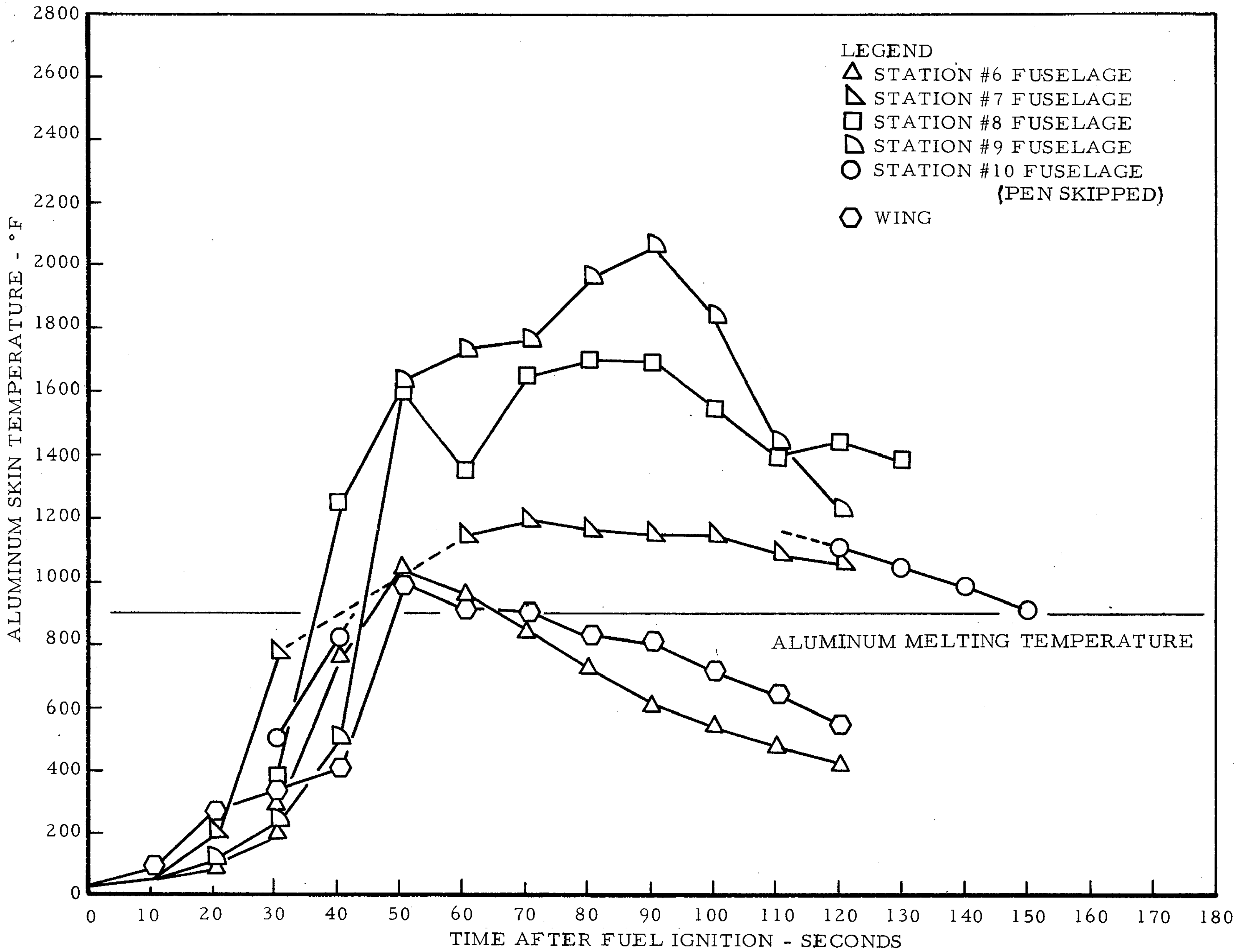


FIGURE 52 - THERMOCOUPLE DATA FROM THE STARBOARD SIDE OF THE B-47 AIRCRAFT (TEST NO. 2)

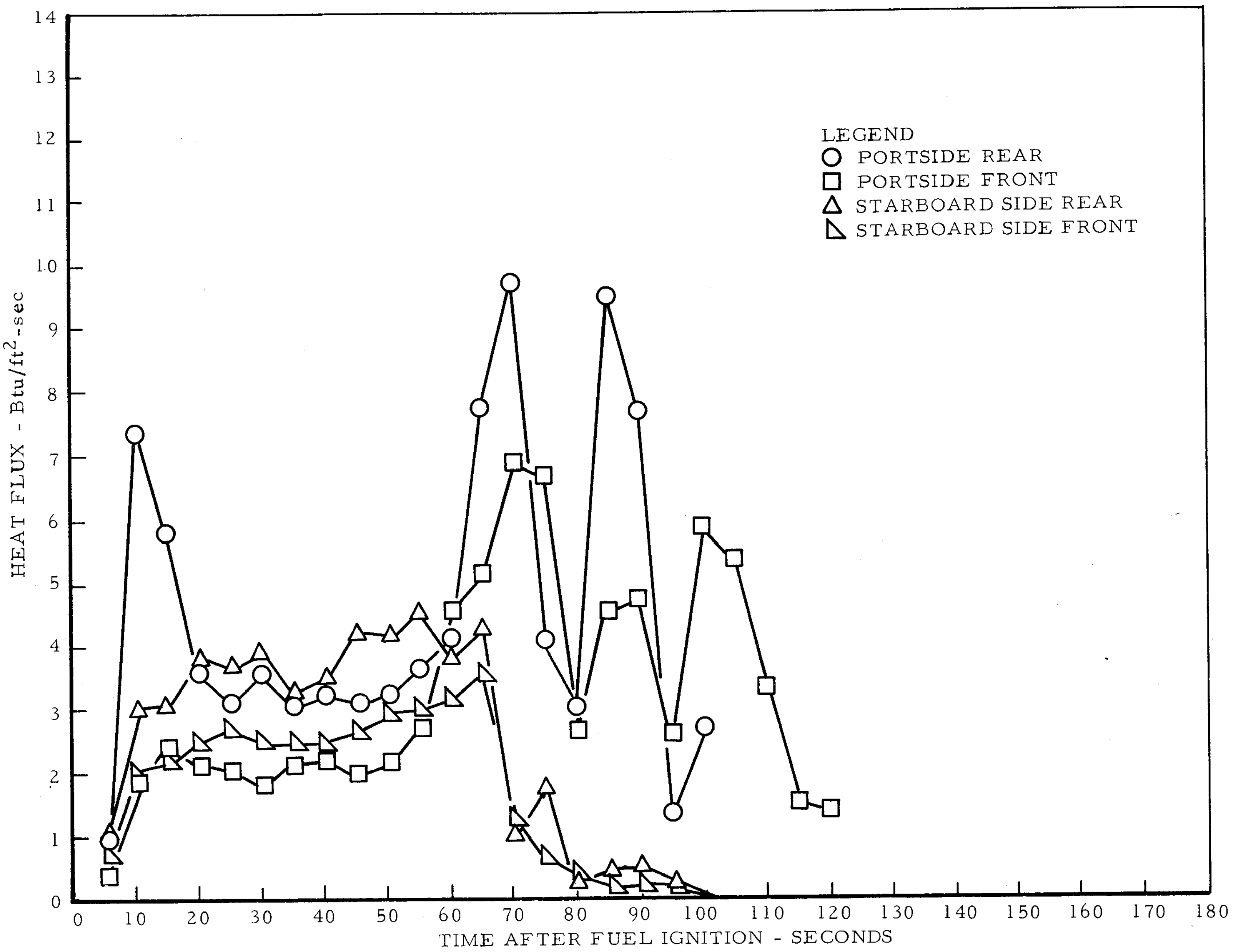


FIGURE 53 - RADIOMETER DATA SHOWING THE PROGRESS OF FIRE CONTROL (TEST NO. 2)

brought below 900°F within 65 seconds after fuel ignition. Stations 8, 9, and 10 were downwind of the wing, which seriously hindered the development of a continuous foam blanket over the burning fuel surface in that area.

The progress of fire control is shown in profiles in Figure 53, in which the fire control time is plotted as a function of the heat flux. From these data it is evident that fire control was not obtained on the starboard side of the fuselage until 80 sec after fuel ignition, while on the portside fire control was not obtained during the total monitoring period which was approximately 120 sec. The excessively long preburn time of 35 sec on the starboard side of the aircraft was caused by a slower than normal build-up of pressure by the dispensing equipment which resulted in an actual fire control time of 45 sec after the start of foam application. Under simple pool-fire conditions using the same agent and dispensing equipment, the fire control time was determined to be approximately 40 sec (Figure 37). Therefore, the fire control time on the upwind (starboard) side of the fuselage closely approximates that obtained in the full-scale fire tests presented in a previous section of this document. Similar data were not obtained for the portside of the aircraft because the heat flux remained above 0.20 Btu per sq ft per sec established as the fire control parameter.

After fire control had been obtained on the starboard side of the fuselage, CDC dry-chemical powder was discharged in an attempt to extinguish the fire. However, by this time massive damage had been done to the aircraft and numerous internal Class A and Class D fires were in progress. During this effort all of the CDC (1000 pounds) was discharged at the discretion of the operator.

On the port side of the fuselage, the initial discharge of Super K was started approximately 94 sec after fuel ignition and discharged intermittently at the discretion of the operators during the following 100 sec.

No CB or TEC were used in this experiment because the engine fire had been inadvertently extinguished by Super K, and TEC could not be effectively applied to the burning magnesium parts because of interference by the other firefighting operations.

Water spray and fog were effectively employed by handlines in the final stages of the operation to control and finally extinguish the Class A and Class D fires inside the fuselage.

An analysis of the data indicates that protein foam was not applied on either the port or starboard side of the aircraft at a sufficiently high rate to effectively control the fire within the 40-sec fire control time necessary to protect the fuselage skin from fire damage (melting) after the excessively long preburn time. An estimate of the foam solution application rate which would have been required to protect the fuselage from damage (Figure 37), indicates that the rate would have had to be increased from approximately 0.10 gpm per sq ft to a minimum of 0.20 gpm per sq ft.

Experiment No. 3 Using Foam Nozzle A and the Foam Pump Dispensing AFFF (Manufacturer E-3) - The third experiment employed the same test bed as that used in Experiment No 2. However, the fuselage aft of the wing and the empennage had been severely damaged by the previous fire and were replaced insofar as possible with the empennage and fuselage parts salvaged from the first B-47 aircraft, which had been less severely damaged. This provided a reasonable facsimile of the test article, even though there was no fuselage skin where Stations 4 and 9 had been located in the intact aircraft.

In this experiment, the fire pit diameter was reduced to 9,500 sq ft (110-ft diameter) to maintain the same solution application rate employed with foam Nozzles B in the first two tests, and the fuel charge was reduced to 5,000 gal (0.53 gal per sq ft) of JP-4. A simulated jet engine fire was established as in the previous experiments and the interior water-spray system rigged to control the potential interior Class A and Class D fires as effectively as possible. The fire-test bed is shown schematically in Figure 54. In this experiment AFFF was dispensed on the starboard side of the aircraft by Nozzle A at an application rate of 0.10 gpm per sq ft, and on the portside from the foam pump at an application rate of 0.11 gpm per sq ft.

Preparations were made to dispense Super K and CDC as well as TEC and CB at the same rates and from the same equipment that was used in the previous experiments.

A. Fire Test Results - During this experiment, which required a tail approach to the aircraft, the wind shifted, as shown in Figure 54, and this adversely affected the range and pattern of the foam stream during the course of the firefighting operation.

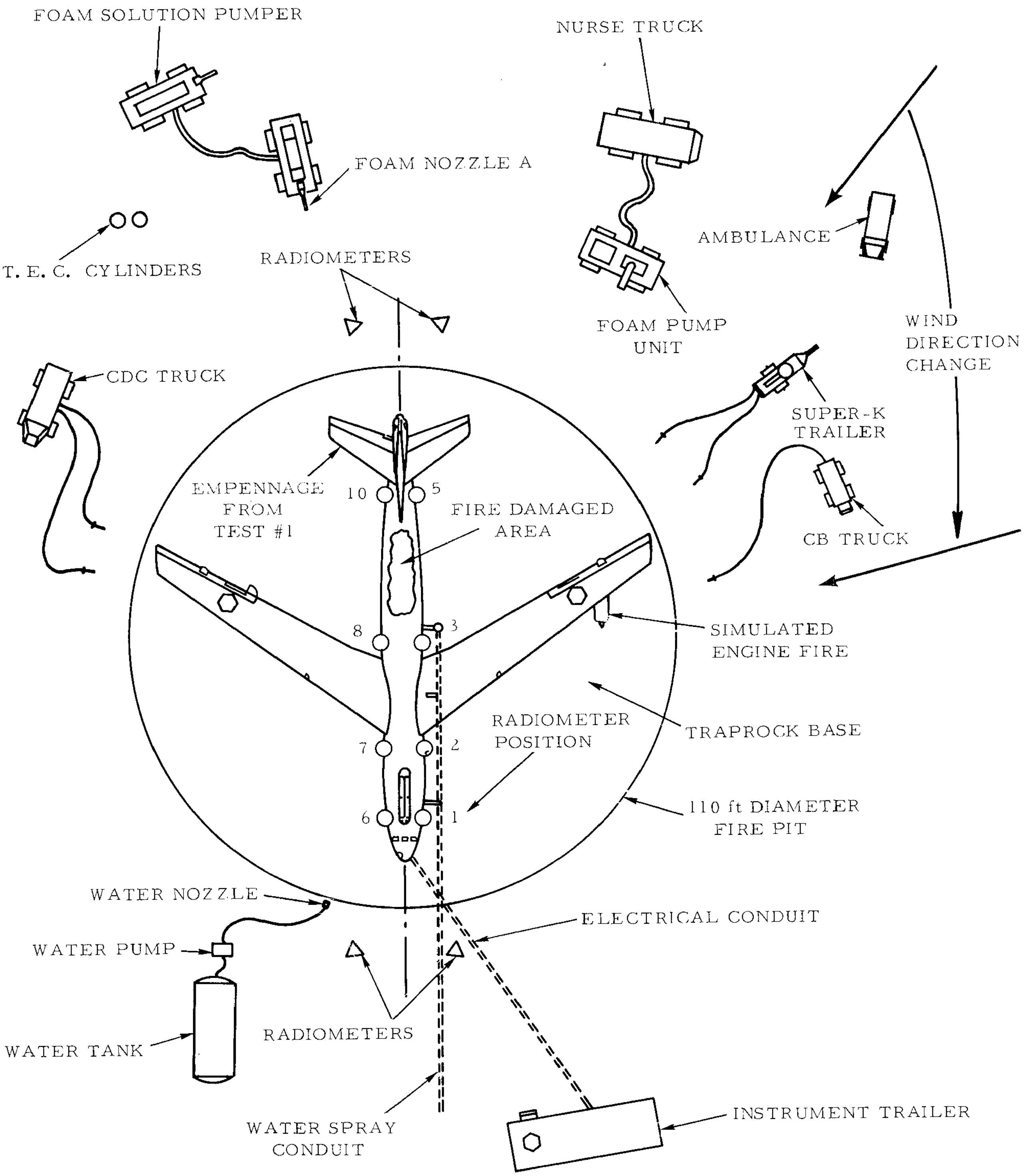


FIGURE 54 - EXPERIMENT NO. 3 TEST BED CONFIGURATION (NOT TO SCALE)

The thermal data obtained during the experiments are presented in Figures 55 through 57. The temperature rise of the aluminum skin on the portside of the fuselage is shown in Figure 55 and on the starboard side in Figure 56, in which temperature is plotted as a function of time after fuel ignition. From the profiles presented in Figure 55, it is evident that the temperature at Stations 1, 2, 3, and 5 on the portside of the fuselage rose above 900°F between 15 and 30 sec after fuel ignition. This exceptionally rapid rise was caused by the flames having access to both sides of the skin through large openings in the fuselage. However, the temperature at all fuselage stations was reduced below 900°F within 63 sec after fuel ignition.

The thermal effects of the fire on the starboard side of the aircraft are presented in Figure 56, from which it is evident that the fuselage skin temperature at Stations 8 and 10 was reduced below the incipient melting point of aluminum within 35 sec after fuel ignition, and that the temperature at Stations 6 and 7 never exceeded 600°F throughout the monitoring period.

Radiation levels on the port and starboard sides of the aircraft are shown in Figure 57. These data indicated that the fire was brought under control on the starboard side using Nozzle A in approximately 40 sec, and on the portside using the foam pump in approximately 50 sec after fuel ignition. However, since the preburn time on each side of the aircraft was 15 sec, the actual fire control time achieved by Nozzle A was 25 sec and for the foam pump it was 35 sec. Under equivalent pool-fire conditions (Figure 36), employing the same agent and foam dispensing equipment, the fire control time for the foam pump was 30 sec and for foam Nozzle A it was 34 sec.

Figure 58 presents photographs of four critical phases of the fire control and extinguishing operation during Experiment No. 3.

The use of auxiliary agents was limited to water-spray discharge to control and extinguish the interior fuselage Class A and Class D fires after control had been obtained, and to the application of Super K on the portside approximately 50 sec after fuel ignition to extinguish peripheral fires. No CB was required because the simulated engine fire had been extinguished by the discharge from the foam pump.

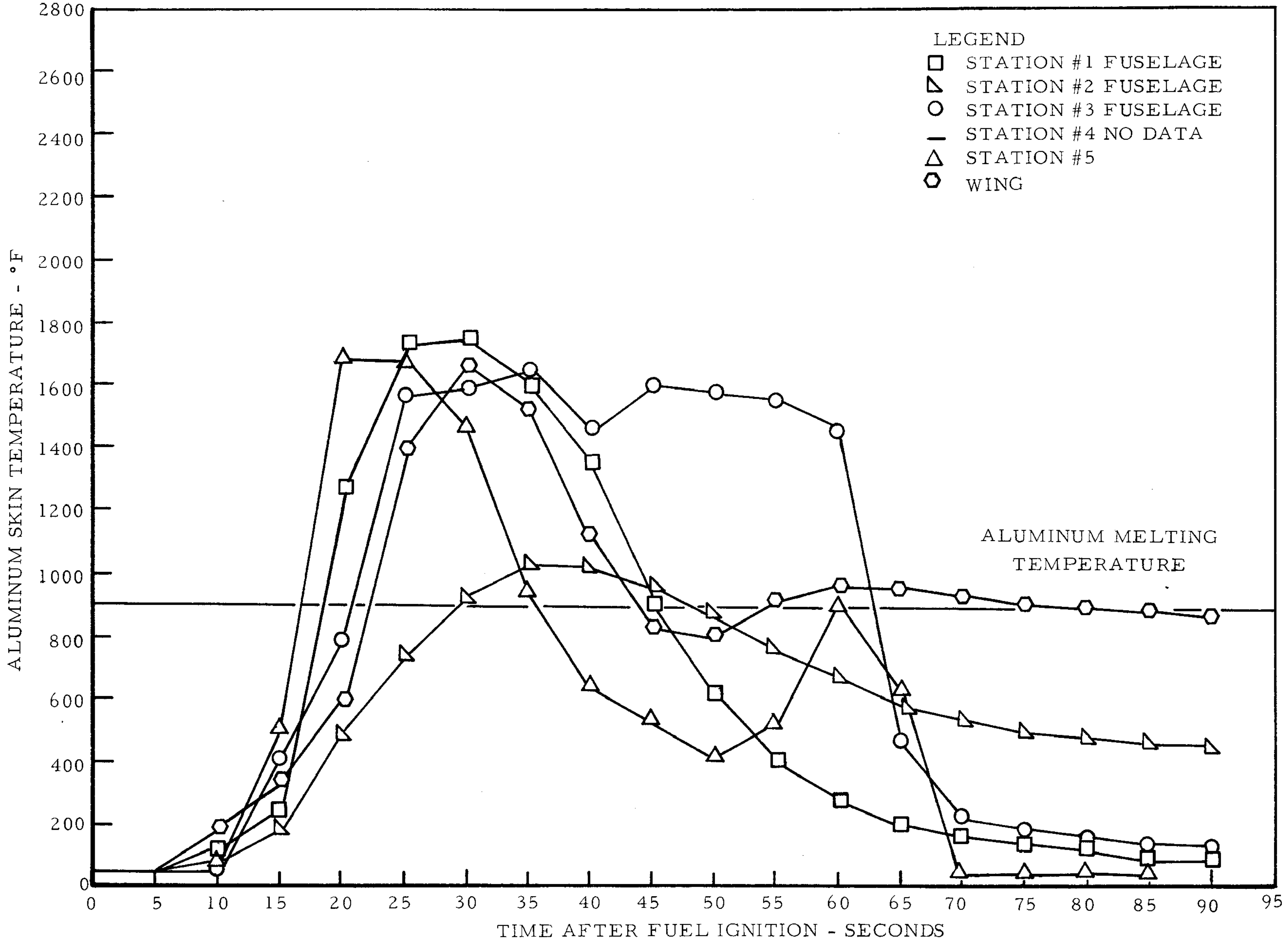


FIGURE 55 - THERMOCOUPLE DATA FROM THE PORTSIDE OF THE B-47 AIRCRAFT (TEST NO. 3)

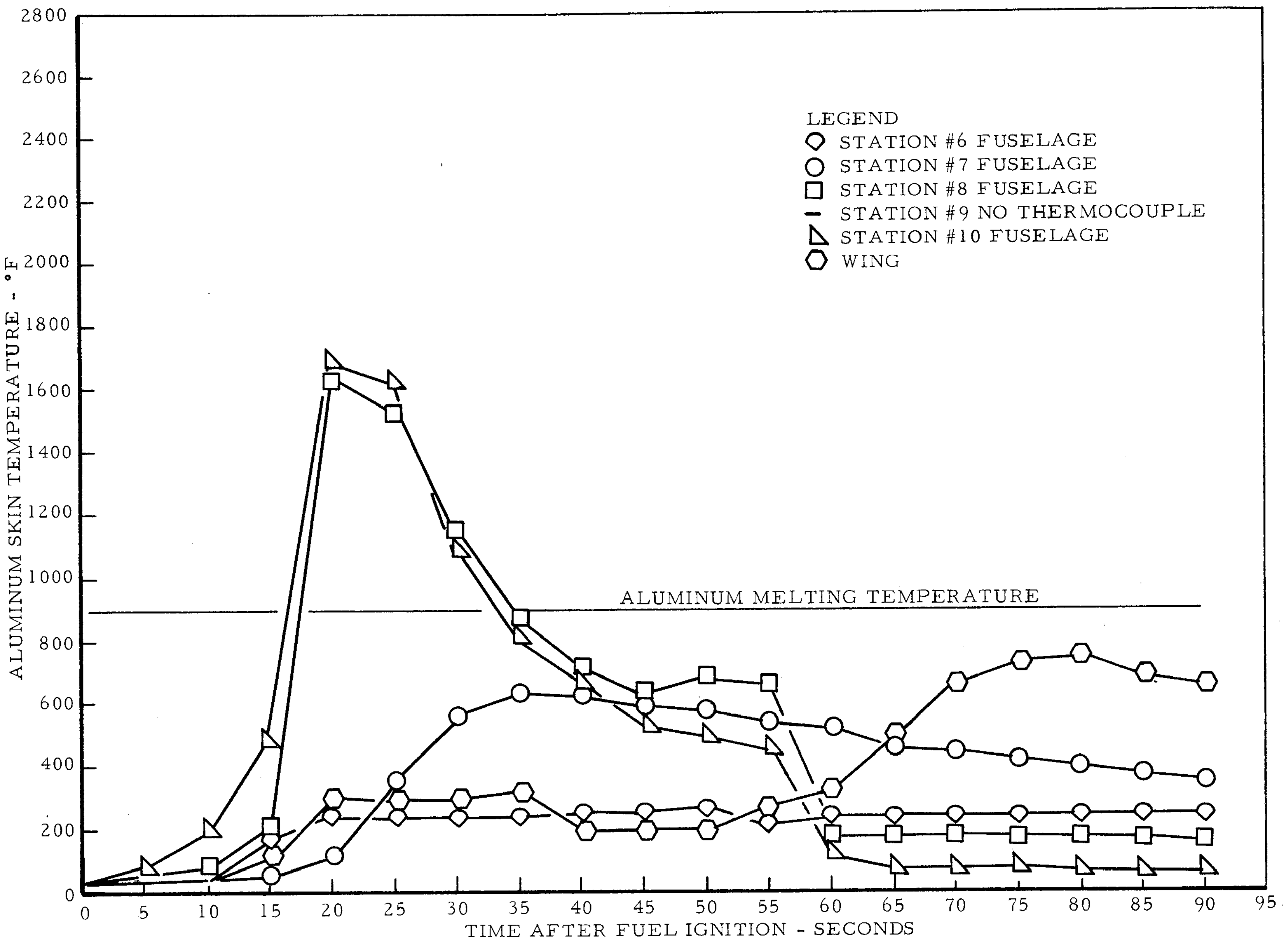


FIGURE 56 - THERMOCOUPLE DATA FROM THE STARBOARD SIDE OF THE B-47 AIRCRAFT (TEST NO. 3)

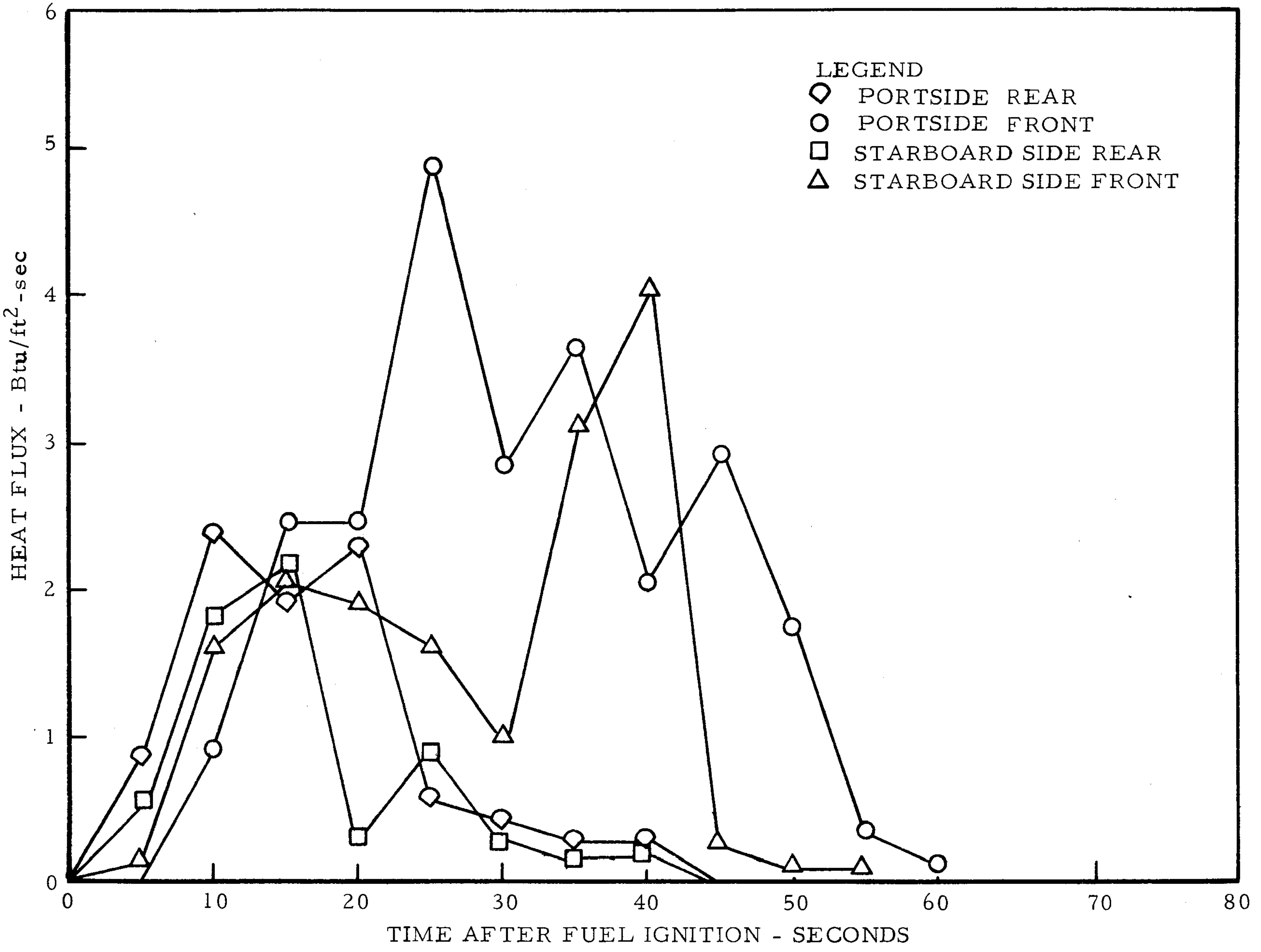
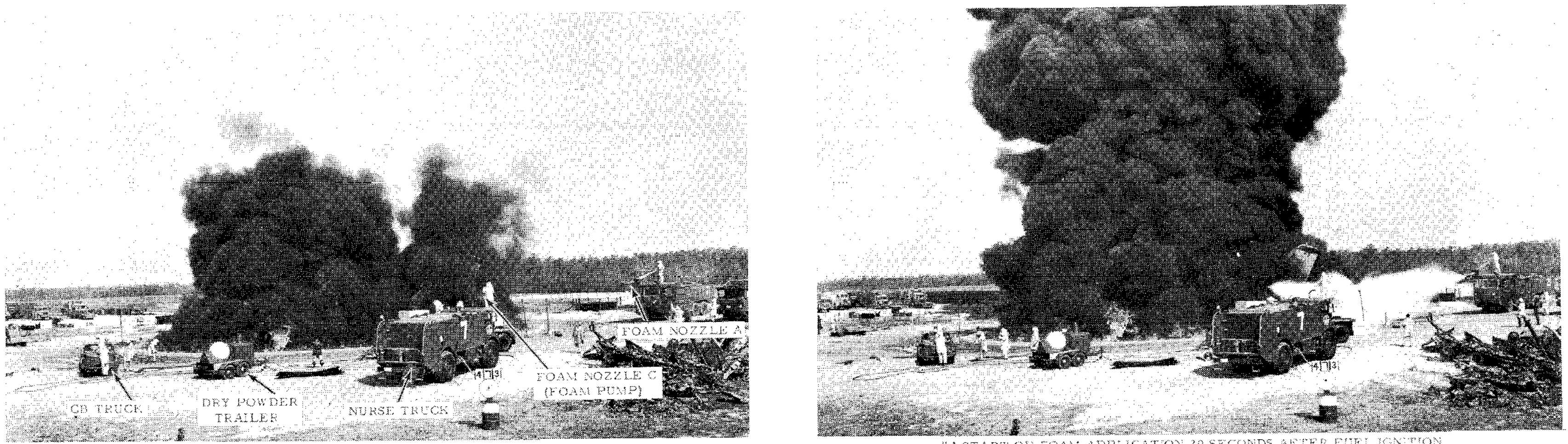
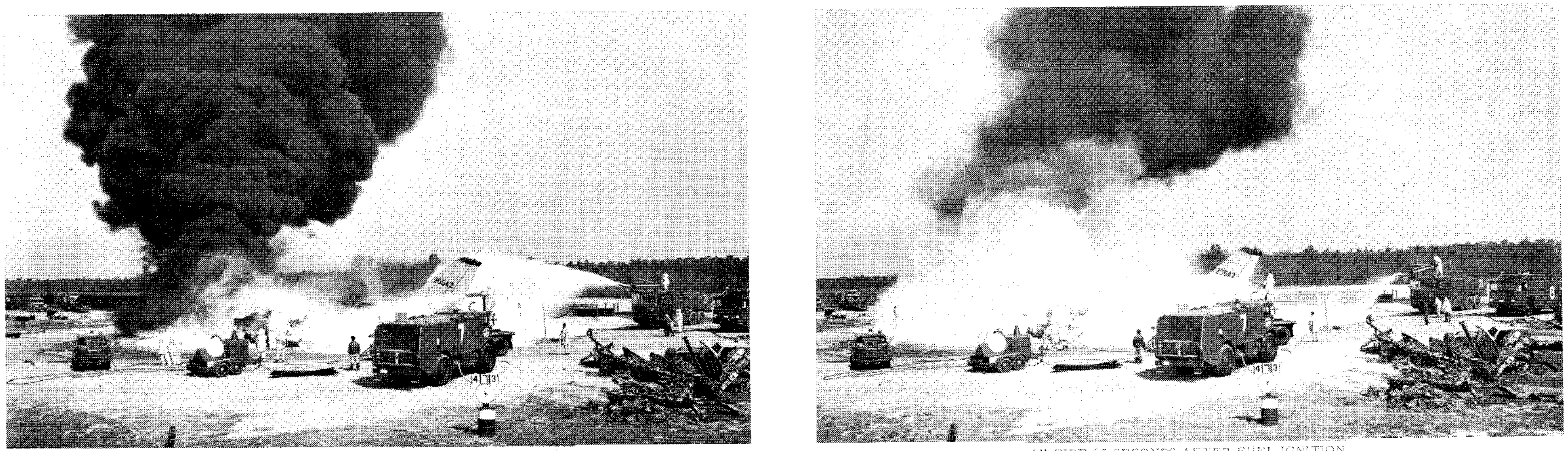


FIGURE 57 - RADIOMETER DATA SHOWING THE PROGRESS OF FIRE CONTROL (TEST NO. 3)



(a) FIRE 8 SECONDS AFTER FUEL IGNITION

(b) START OF FOAM APPLICATION 20 SECONDS AFTER FUEL IGNITION



(c) FIRE APPROACHING CONTROL AFTER 50 SECONDS

(d) FIRE 65 SECONDS AFTER FUEL IGNITION

FIGURE 58 - CRITICAL PHASES DURING FIRE CONTROL AND EXTINGUISHING

Experiment No. 4 Using Foam Nozzle A and the Foam Pump Dispensing Protein Foam - The fourth experiment employed a similar test-bed configuration to that used in Experiment No. 3 (Figure 59). The size of the fire pit (110 ft diameter) and the JP-4 fuel charge (5,000 gal) were the same as in the previous test. In this experiment a 6-percent premixed solution of protein foam was dispensed by Nozzle A on the starboard side of the aircraft at the rate of 0.10 gpm per sq ft and by the foam pump on the portside at the rate of 0.11 gpm per sq ft. A jet engine fire was simulated, as in the previous experiments, and the interior water-spray activated prior to fuel ignition to suppress the interior Class A and Class D material fires.

Because of the severity of the two previous fires, approximately 65 to 70 percent of the fuselage skin had been destroyed. Therefore, the data obtained in an attempt to measure skin temperatures were unrealistic because at most stations, flames impinged freely on both sides of the thermocouple mounts. Another factor which contributed to the inaccuracy of the thermocouple data was the intense Class A and Class D fires which developed in the interior wreckage during the preburn time that continued to burn and influence the thermocouple readings after the exterior fuel fires had been brought under control. Therefore, an estimation of the firefighting effectiveness of protein foam dispensed from the foam pump and Nozzle B is based entirely upon the radiometer data presented in Figure 60, and from an analysis of the photographic instrumentation.

Preparations were made to dispense Super K and CB on the portside of the aircraft and CDC on the starboard side. Both TEC and MET-L-X were available for extinguishing the Class D fires.

A. Fire Test Results - The thermal radiation on the port and starboard sides of the aircraft is shown by the profiles in Figure 60 where heat flux is plotted as a function of time after fuel ignition. These data show that the starboard side was controlled in 180 sec and the portside in 142.5 sec after fuel ignition, and these values were corroborated by an analysis of the photographic instrumentation. Since the fire preburn time on each side of the fuselage was 25 sec, the actual control time after the start of foam application was 117.5 sec on the portside, using the foam pump, and 155 sec on the starboard side using foam Nozzle A. Under pool-fire conditions of equal size (Figure 36), using the same agent and foam-dispensing equipment, the fire control time was 38 sec for the foam pump and 55 sec using foam Nozzle A. The difference between the fire control times obtained under pool-fire conditions and those determined to be required to control both sides of the aircraft is attributed to the complex fire configuration which was developed by the presence

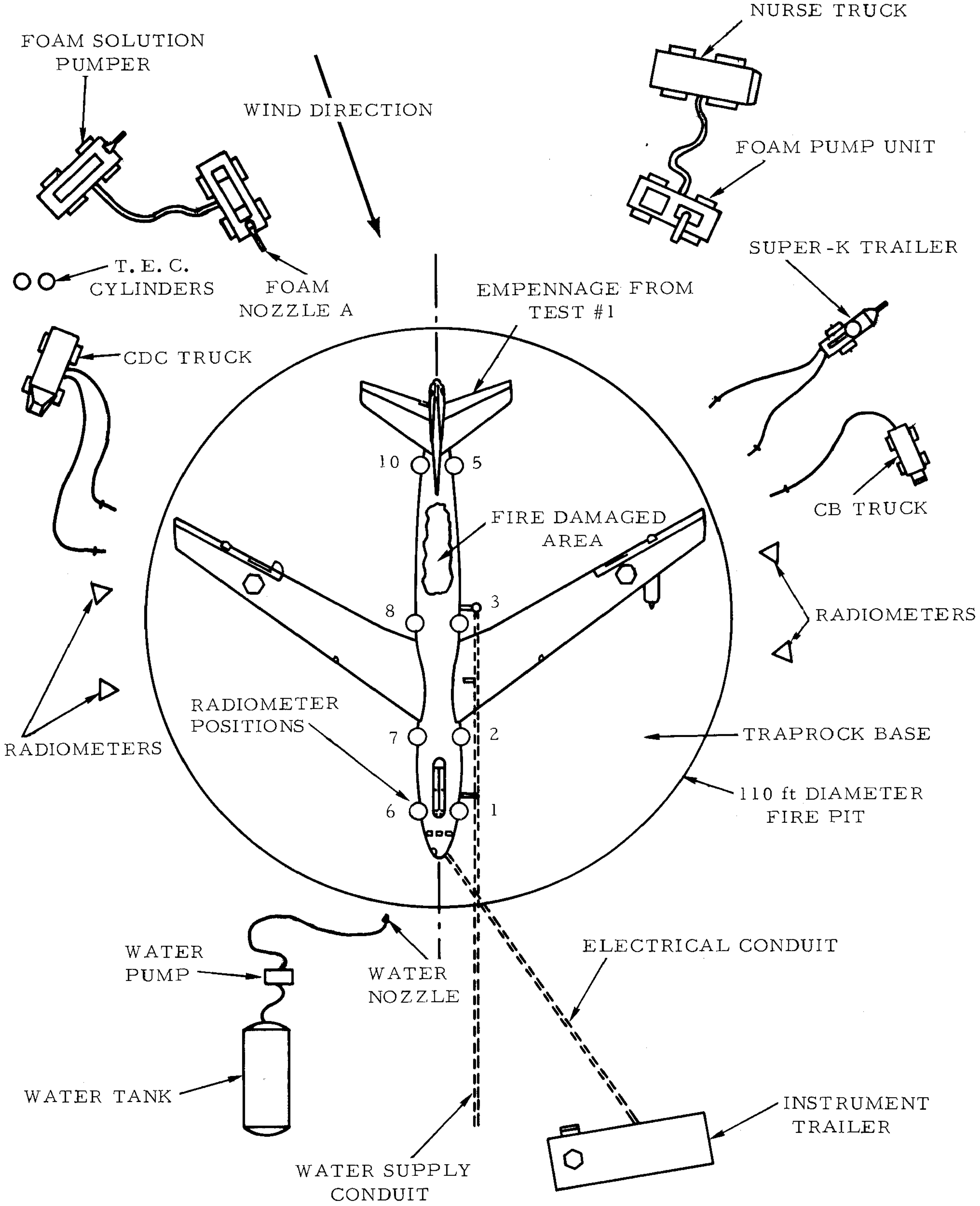


FIGURE 59 - EXPERIMENT NO. 4 TEST BED CONFIGURATION (NOT TO SCALE)

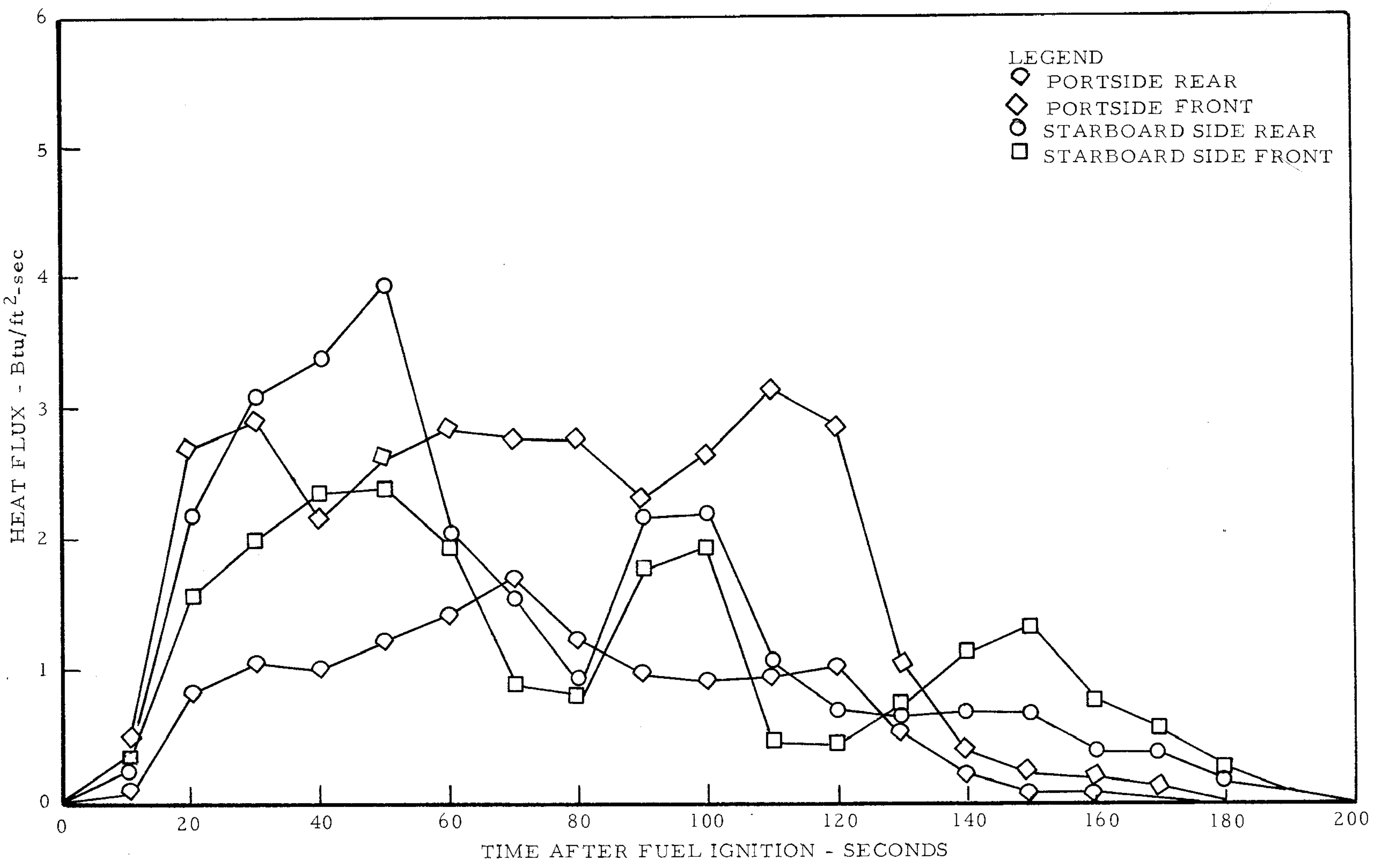


FIGURE 60 - RADIOMETER DATA SHOWING THE PROGRESS OF FIRE CONTROL (TEST NO. 4)

of the B-47 aircraft. Therefore, it is considered unrealistic to base the firefighting effectiveness of individual foam-dispensing systems solely on the results obtained under simple pool-fire conditions or under test-bed conditions which are not representative of aircraft accidents.

Approximately 22 sec before fire control had been obtained on the starboard side, CDC was discharged in an attempt to extinguish the fire, but without complete success. Water spray was also used by the firefighters as an exercise to gain experience in the use of this agent in the control and extinguishment of magnesium metal and Class A fires, but by this time the fuselage was a mass of twisted metal and the effort to extinguish all of the remaining fires was abandoned.

A summary of the fire control times for the four experiments employing the B-47 aircraft are presented in Table XXXIV.

TABLE XXXIV

SUMMARY OF THE FIRE CONTROL TIMES USING THE B-47 AIRCRAFT

	Test No 1		Test No 2		Test No 3		Test No 4	
	Starboard	Port	Starboard	Port	Starboard	Port	Starboard	Port
Equipment Approach	Rear		Front		Rear		Rear	
Fire Diameter - ft	140		140		110		110	
Solution Rate - gpm	780	780	780	780	496	530	496	530
Solution Application Rate - gpm per sq ft	0.10	0.10	0.10	0.10	0.10	0.11	0.10	0.11
Dispensing Equipment	Nozzle B	Nozzle B	Nozzle B	Nozzle B	Nozzle A	Foam Pump	Nozzle A	Foam Pump
Foam Agent	AFFF	AFFF	Protein	Protein	AFFF	AFFF	Protein	Protein
Fire Preburn Time - Sec	22	19.5	35	25	15	15	25	25
Fire Control Time After Ignition - Sec	76 front 68 rear	55 front 54 rear	80 front 80 rear	none	47 front 33 rear	58 front 43 rear	180 front 180 rear	145 front 140 rear
Average Fire Control Time After Ignition - Sec	70	54.5	80	none	40	50.5	180	142.5
Fire Control Time After Start of Foam - Sec	50 front 46 rear	35.5 front 34.5 rear	45 front 45 rear	none	22 front 18 rear	43 front 28 rear	155 front 155 rear	120 front 115 rear
Average Fire Control Time After Foam - Sec	48	35	45	none	25	35.5	155	117.5
Fire Damage to Fuselage Skin	Severe	Very minor	Severe	Severe	Minor	Severe	No data	No data
Control Time of Equivalent Pool Fires - Sec	23	23	40	40	34	30	55	38

VIII. A METHOD FOR ESTIMATING THE GROUND FIREFIGHTING REQUIREMENTS FOR AIRCRAFT

General

One of the major objectives of this effort was to estimate the discharge rates and the quantities of firefighting agents necessary to provide protection of airfield operations involving different sizes of military aircraft. This was construed to include not only major aircraft accidents involving fires, but also those fire hazards incident to aircraft maintenance, engine runup, fuel spills, overheated wheels and brakes, and refueling operations. It was, of course, apparent that the agents and dispensing equipment required to protect an aircraft from fire damage in a major aircraft accident would be more than adequate to cope with any latent fire hazards associated with normal airfield operations and maintenance, and so, no special tests were conducted in this regard in addition to those performed during the course of the laboratory experiments.

The distinction which is sometimes made between the ground firefighting requirements of tactical military and civil aircraft is occasionally overemphasized. The military currently operates a number of different types of transports which are common commercial aircraft with different internal configurations. Therefore, the firefighting requirements for military and civil aircraft within this category are assumed to be similar.

The real differences which influence the firefighting techniques, employed with military and civil aircraft, are those associated with the presence of armament that may be aboard at the time of the accident and the problems associated with the crews' release from their ejection seats or making a forceable entry into the fuselage. The broad concept of making a snatch-rescue from modern fighter aircraft was never an easy task, and the difficulty is increasing rapidly with changes in basic aircraft design. Improved aircraft performance has necessitated the development of stronger canopies with sophisticated automatic control devices which complicate forceable entry of the cockpit, if required. The height of the cockpit above ground has also increased with the size of the aircraft so that it may be necessary to either climb the fuselage or pitch a ladder to effect pilot rescue. Therefore, it is unrealistic to rely primarily on the crash crew to evacuate the air crew within the time available to effect the rescue mission after their arrival at the accident site. The rescue crew must now rely more heavily on effective firefighting, where previously they might have relied on speed of action to minimize personnel exposure to fire conditions.

Accordingly, the basic approach established in this effort to estimate the minimum fire rescue requirements was to launch an aggressive attack with foam, intended to overwhelm the fire within the time available before the fuselage skin melted and to achieve subsequent extinction by means of auxiliary agents or a reduced rate of foam application. The auxiliary agents were confined in these experiments, insofar as possible, to running liquid fuel fires; the inhibition of enclosed spaces such as wing voids; and fires associated with wheel wells and engine nacelles. A holding action was not considered sufficient in an actual fire situation because of the danger of exploding or heat-ruptured fuel tanks and related hazards and from the possible development of catastrophic Class A, Class C, and Class D fires inside the fuselage.

Discussion

A Determination of the Critical Fire Area Around an Aircraft Fuselage: Before a determination of the firefighting requirements necessary to protect different size aircraft from fire could be made, it was necessary to consider various means of estimating the largest probable fuel spill area which could be anticipated for the different sizes of aircraft. A survey of the literature conducted in an effort to determine trends in the spill fire sizes associated with different category aircraft was unrewarding. Therefore, it was necessary to direct attention to the "critical fire area" around an aircraft fuselage based upon a consideration of the flame characteristics of free-burning JP-4 fuel fires. The critical fire area around an aircraft fuselage is defined, in this effort, as the area adjacent to the fuselage extending outward in all directions beyond which a large fuel spill will not melt the aluminum skin regardless of the duration of the fire exposure time. The critical fire area is, in fact, that area which must be secured by foam to protect the fuselage from fire damage.

The approach to the problem of estimating the critical fire area around an aircraft was to use the fuselage length as one parameter and to determine the second parameter by measuring the distance on each side of the fuselage which would have to be secured by a blanket of foam to protect the aircraft skin from melting under severe fire conditions. From previous experiments it had been determined that the most severe fire conditions existed when the wind direction was perpendicular to the fuselage; hence, this situation was established as one of the test requirements. Wind strongly influences the flame burning characteristics of large pool fires; therefore, initial testing was conducted under moderate wind velocities between 10 and 12 mph which was indicated to produce a flame angle of approximately 45° (Reference 56). The flame angle is defined as the angle of tilt of the flame from the vertical.

Experiments, performed at NAFEC, with the test bed presented in Figure 61, show that a JP-4 fuel fire 40 ft wide and 318 ft long in the form of a horseshoe located 60 ft on the upwind side of a 40-ft-long stainless steel covered section of a four-engine commercial jet aircraft would not cause damage (melting) to a 0.090-in-thick aluminum aircraft skin (Reference 4) within 40 sec after fuel ignition when the wind velocity was between 10 and 12 mph. The maximum temperature reached within 40 sec was 880°F, but all of the thermocouples, embedded in the fuselage skin on the upwind side, reached 900°F within 116 sec after fuel ignition. An extrapolation of the available data indicated that an aluminum fuselage would be subject to fire damage if the separation distance upwind between the fuselage and the fire was less than 80 ft during prolonged fire exposure, as a result of flame trailing (Reference 57) caused by the 10 to 12 mph wind. A photograph of the flame-enveloped fuselage section is shown in Figure 62.

Other experiments performed to determine the effect of JP-4 fuel fires located on the downwind side of the fuselage indicated that when the fire was removed 20 ft from the fuselage no damage to the aluminum skin resulted when the wind velocity was between 10 and 12 mph. From these data it was evident that with a wind velocity of 10 to 12 mph, the critical dimension perpendicular to the fuselage which defines the critical fire area, should include the 80-ft distance upwind, and the 20-ft distance downwind, plus the nominal width of the fuselage of the aircraft. This method for estimating the critical fire area around an aircraft (see preceding paragraph) is considered valid when the fuselage length is in excess of 60 ft.

The critical fire area around aircraft involved in smaller fires was somewhat more difficult to establish because of the greater effect that wind had in disrupting the fire plume from relatively small spill fires upwind from the fuselage. Experiments performed on the 40-ft stainless steel covered cabin section of a commercial aircraft (Reference 4) did indicate that if a 10-ft-wide and 40-ft-long JP-4 pool fire was placed parallel and 20 ft from the upwind side of the fuselage, a fire exposure time of 100 seconds was required after fuel ignition before the aluminum skin reached the incipient melting temperature of 900°F.

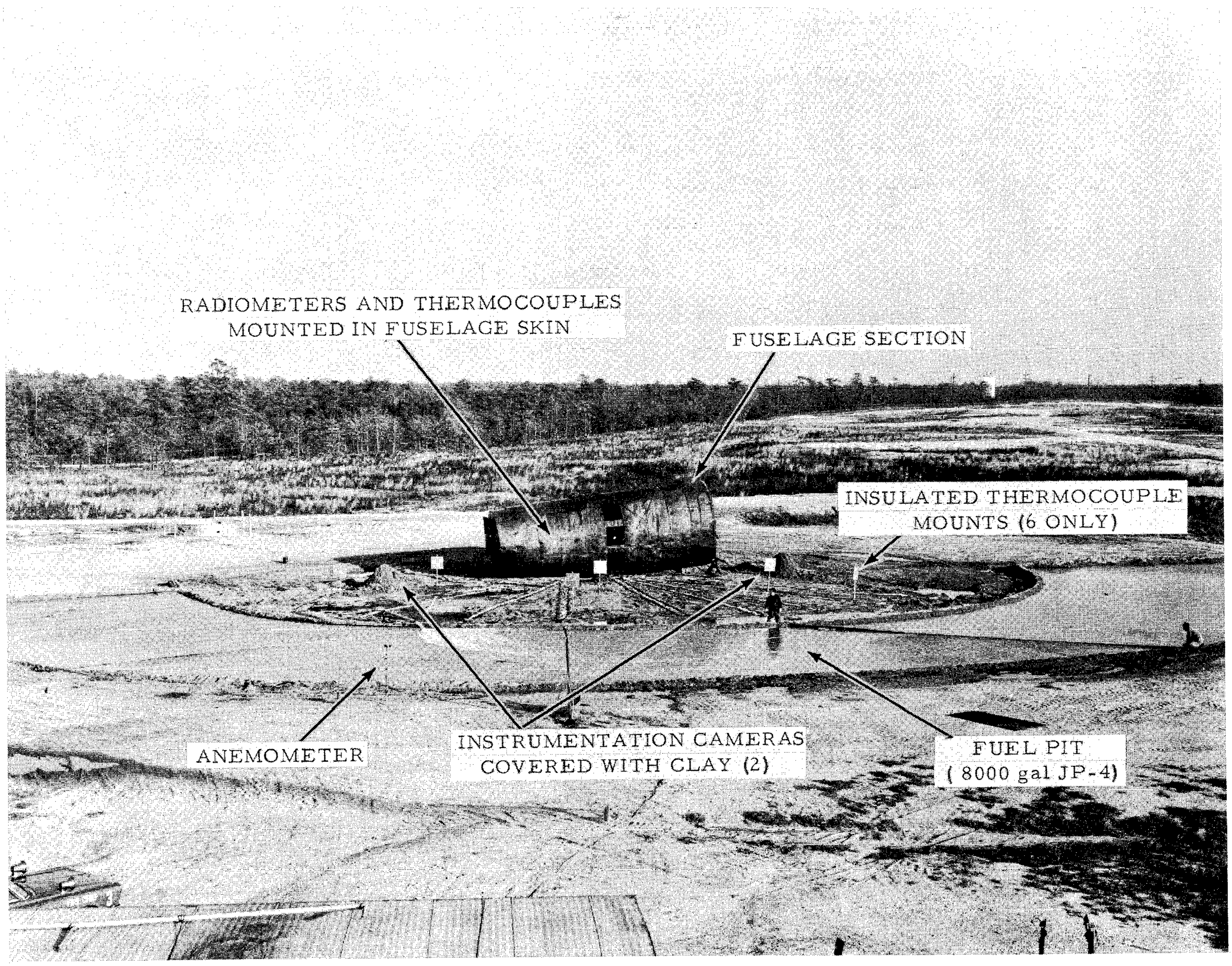


FIGURE 61 - FIRE TEST BED USED TO DETERMINE THE CRITICAL FIRE AREA AROUND AN AIRCRAFT FUSELAGE

FIGURE 62 - THE COMPLETELY FLAME ENVELOPED FUSELAGE DURING THE TEST TO DETERMINE THE CRITICAL FIRE AREA AROUND AN AIRCRAFT FUSELAGE

Therefore, an estimation of the dimension perpendicular to the fuselage of an aircraft (60 ft or less) involved in small fires, see preceding paragraph, which is considered to define the critical fire area, should include a 20-ft distance on both sides of the fuselage plus an allowance for the width of the fuselage.

The critical fire area determined by the test procedures outlined is shown by the rectangular area enclosed within the dashed lines around a B-47 aircraft in Figure 63.

However, this area is customarily represented as a circular fire pit of equal size with the aircraft located in the center, and this method of presentation is employed in the future.

As indicated previously, the critical fire area around an aircraft determined by multiplying the fuselage length by the perpendicular distance determined as above, is not intended to represent either the average, maximum, or minimum spill fire size associated with a particular aricraft, nor does it define a safe occupant escape area under all conditions, but is rather that area around an aircraft which must be secured with a blanket of foam to protect the fuselage skin from melting. The critical fire area, therefore, serves only as a means for categorizing aircraft in terms of the magnitude of the potential fire hazard in which they may become involved. The actual fire size associated with different aircraft incidents is currently being studied by ICAO, the NFPA, and other concerned organizations on a worldwide basis, and the results may be expected to contribute materially to a better understanding of the fire size associated with different types of aircraft incidents.

The type and quantity of auxiliary agents to accompany a given quantity of foam agent could not be reliably determined during the experiments with the B-47 aircraft. This was because when foam application was completely successful, no auxiliary agents were required; but when the fuselage skin melted and extensive Class A and Class D fires developed within the aircraft, all of the auxiliary agents available were expended without extinguishing the fires. However, water spray and fog were found to be effective against Class A fires and for controlling the burning rate of the magnesium metal in Tests 2

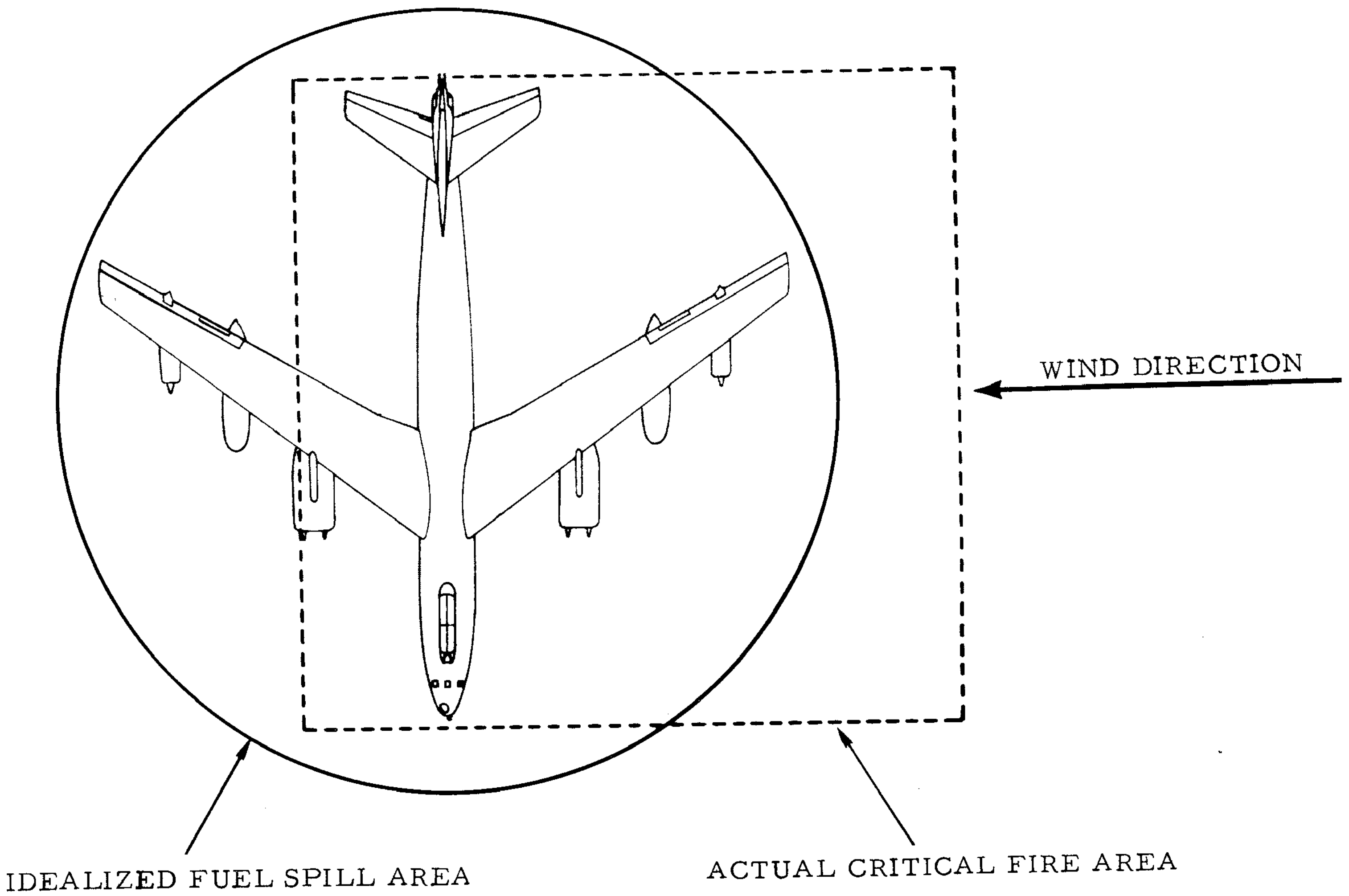


FIGURE 63 - THE CRITICAL FIRE AREA AND IDEALIZED FUEL SPILL AREA AROUND A B-47 STRATOJET AIRCRAFT

through 4. Foam, a Class B firefighting agent, should not be used in an attempt to cool the fuselage skin of an aircraft during the initial foam attack (Reference 2). The most effective coolant generally available for this purpose is either water spray or fog, which may be applied with caution so as not to disrupt the established foam blanket, after fire control has been obtained.

Categorizing Aircraft as Fire Hazards: In any attempt to broadly categorize aircraft into different groups according to the fire hazard they present by fuselage length alone, it is at once apparent that certain anomolies inevitably develop. One of the most glaring differences is the total fuel capacity of the different aircraft within a given length category. The primary factor determining fuel capacity is the service in which the aircraft is to be employed. Therefore, it is evident that within any given length category, certain aircraft present a greater intrinsic fire hazard than other aircraft, based upon the fuel capacity. The full-scale fire tests revealed the fundamental parameters in any aircraft accident involving ground fire to be those associated with the wind effects on free-burning pool fires and the resulting flame-trailing phenomena, as well as the maximum quantity of fuel carried aboard an aircraft which might be spewed over the critical fire area. Therefore, the potential hazard associated with a given aircraft can be realistically expressed in terms of the fuel spill density within the critical fire area and its total free-burning time. The fuel spill densities and burning times presented in Table XXXV were calculated for several aircraft using the critical fire area and the total fuel capacity of each aircraft. The fuel burning times were based upon a fuel burning rate of 0.089 gpm per sq ft for JP-4, 0.082 gpm per sq ft for Jet A, and 0.102 gpm per sq ft for aviation gasoline for large pool fires. The fuel-spill density may also serve as a means for estimating the magnitude of the potential hazard which could result from ruptured or exploding fuel tanks, if the ground fire is not brought under control before serious damage can occur to the protective aircraft skin. A knowledge of the potential fuel spill densities would assist firefighting teams to estimate the potential hazard associated with each individual aircraft within a particular length category.

Deployment of Equipment Around Aircraft of Different Sizes Involved in Fire: The deployment of foam-dispensing vehicles around the fire perimeter of different size aircraft is shown in Figures 64 through 69. Figures 64, 66, and 68 show the configuration used when the wind is parallel with the fuselage, and Figures 65, 67, and 69 when it is perpendicular to the fuselage.

TABLE XXXV

POTENTIAL FUEL SPILL BURN-TIMES FOR DIFFERENT SIZE AIRCRAFT

Aircraft Size	Fuselage Length ft	Critical Fire Area sq ft	Maximum Aircraft Fuel Capacity gal			Fuel Density gal per sq ft	Estimated Fuel Burning Time min
			JP-4	Jet A	Aviation Gasoline		
F-104A	55	2,475	1,484	--	--	0.599	6.73
DC-3	64	2,880	--	--	688	0.238	2.33
B-47	107	12,840	18,240	--	--	1.41	15.90
DC-9-10	104	12,480	--	3,722	--	0.298	3.63
C-5A	245	29,400	49,000	--	--	1.67	18.7
747	258	30,960	--	47,210	--	1.53	18.7

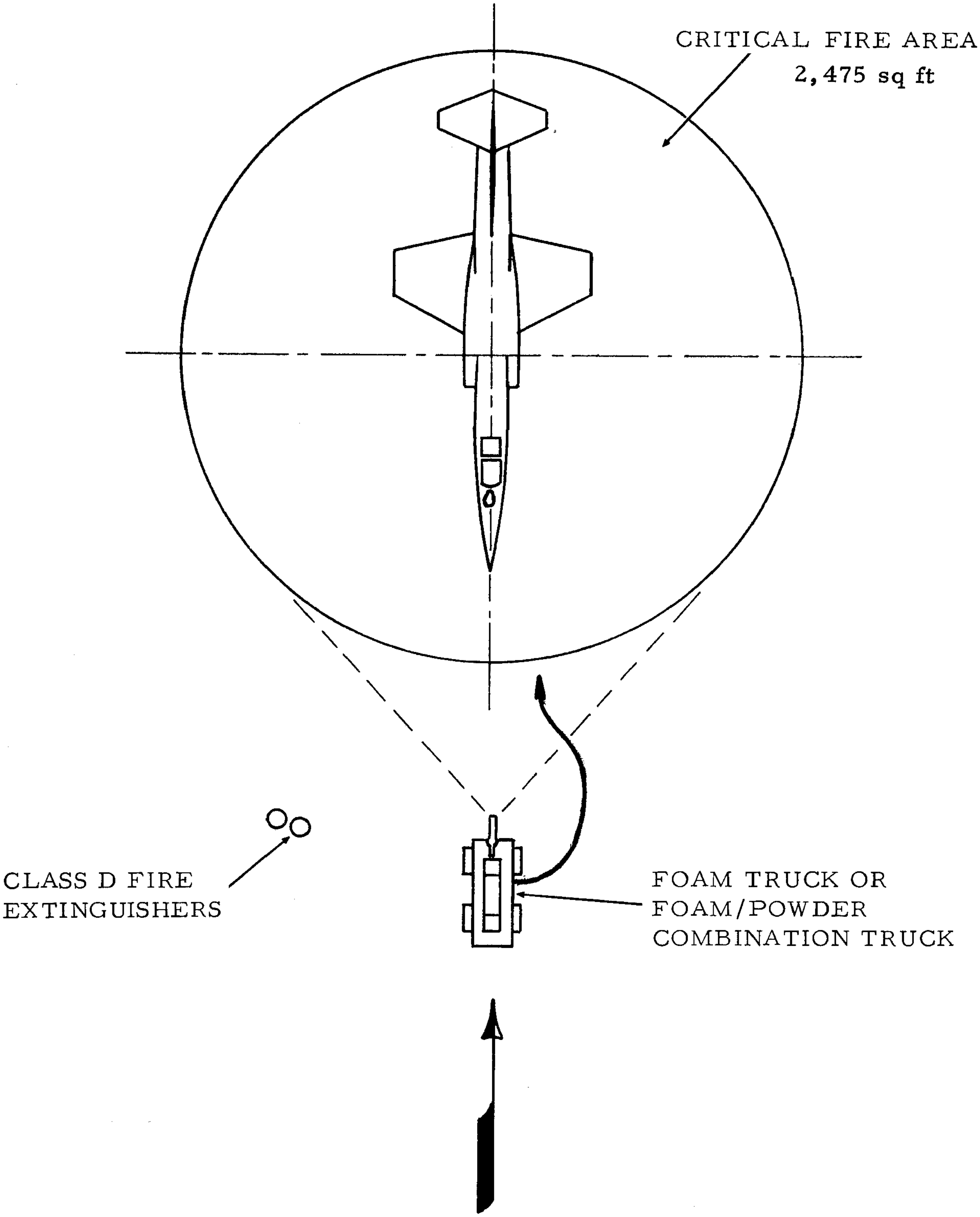


FIGURE 64 - DEPLOYMENT OF FIREFIGHTING EQUIPMENT TO PROTECT A F-104A AIRCRAFT WHEN THE WIND DIRECTION IS PARALLEL WITH THE FUSELAGE (NOT TO SCALE)

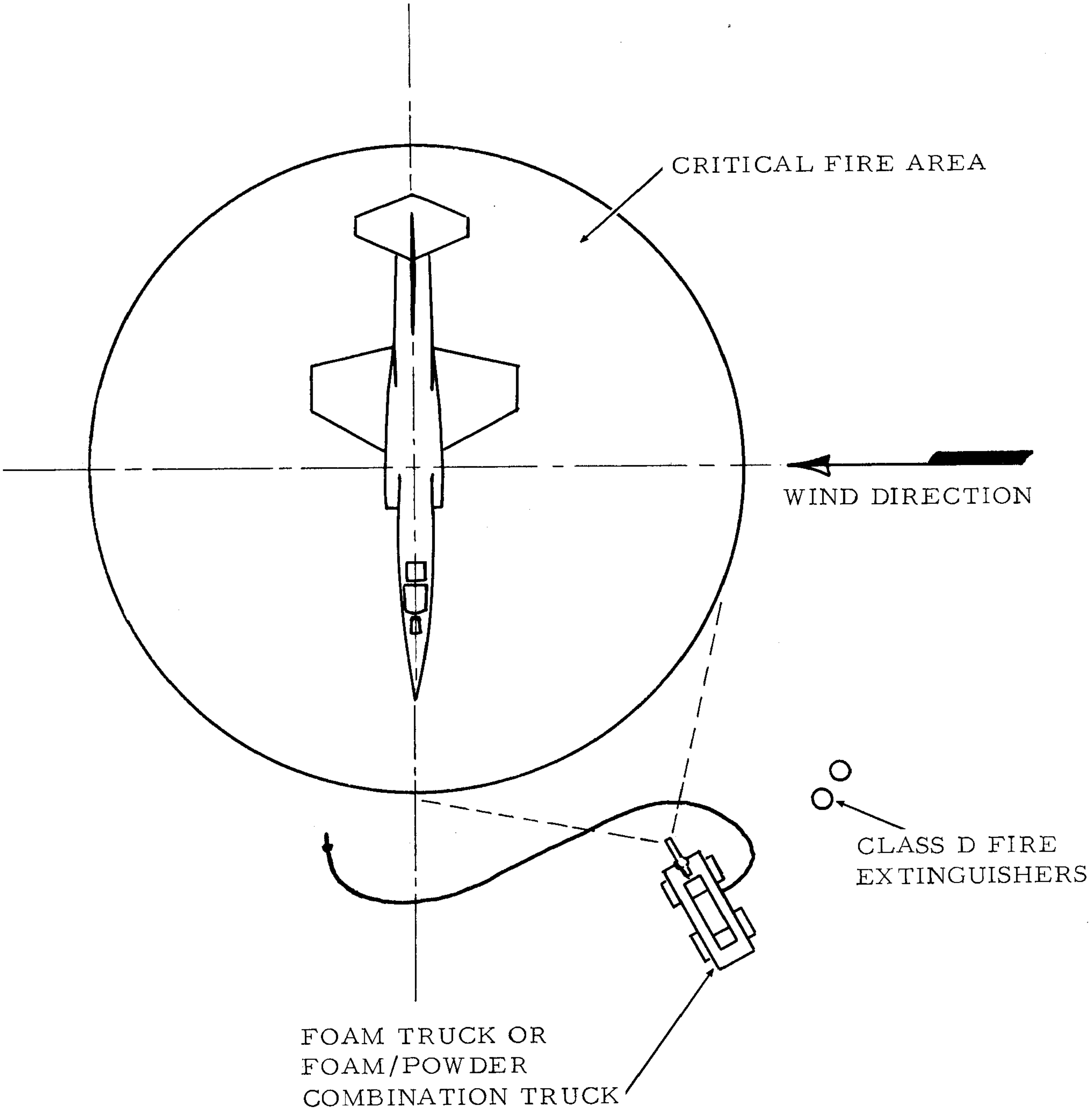


FIGURE 65 - DEPLOYMENT OF FIREFIGHTING EQUIPMENT TO PROTECT A F-104A AIRCRAFT WHEN THE WIND DIRECTION IS PERPENDICULAR TO THE FUSELAGE (NOT TO SCALE)

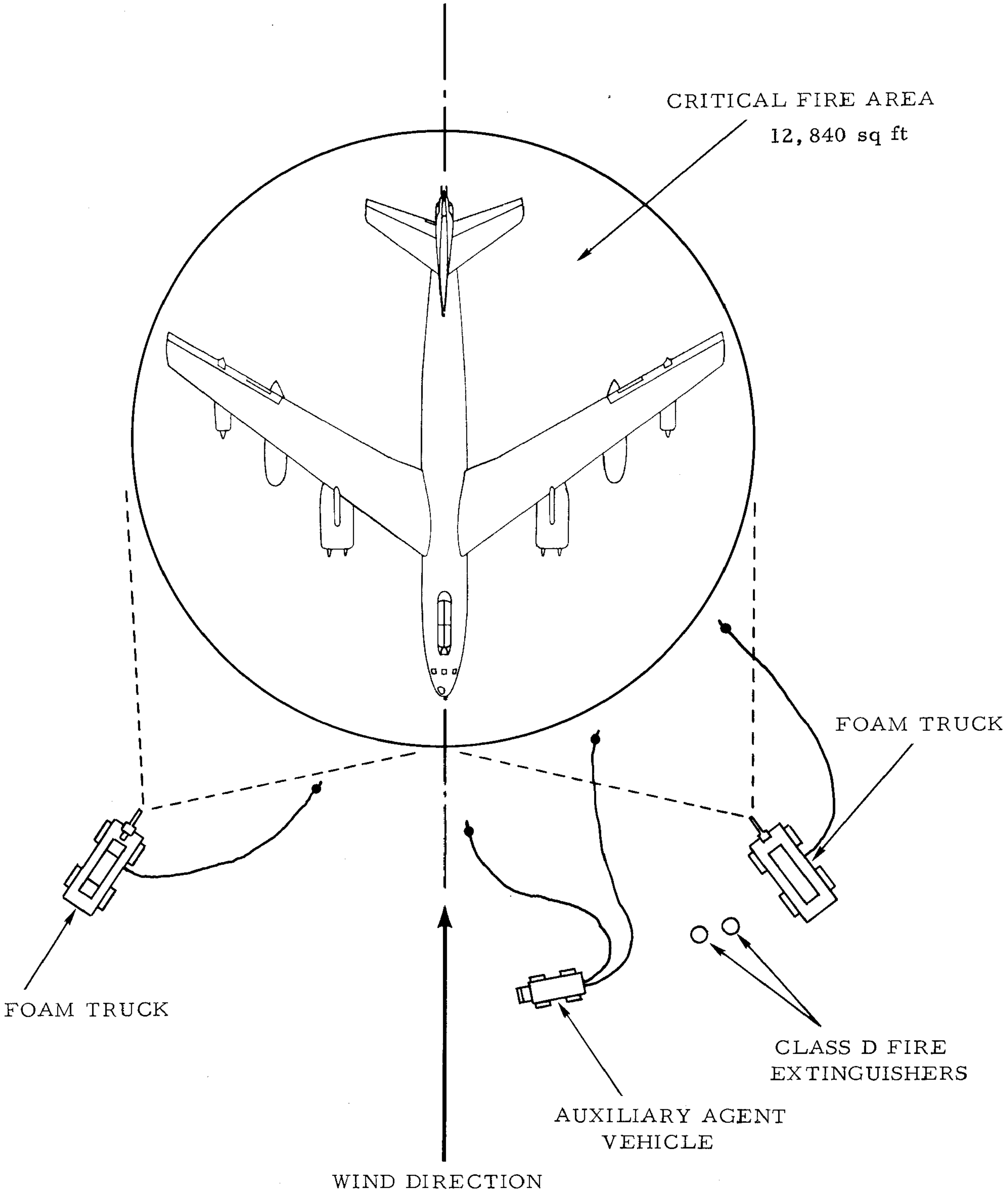


FIGURE 66 - DEPLOYMENT OF FIREFIGHTING EQUIPMENT TO PROTECT A B-47 AIRCRAFT WHEN THE WIND DIRECTION IS PARALLEL WITH THE FUSELAGE (NOT TO SCALE)

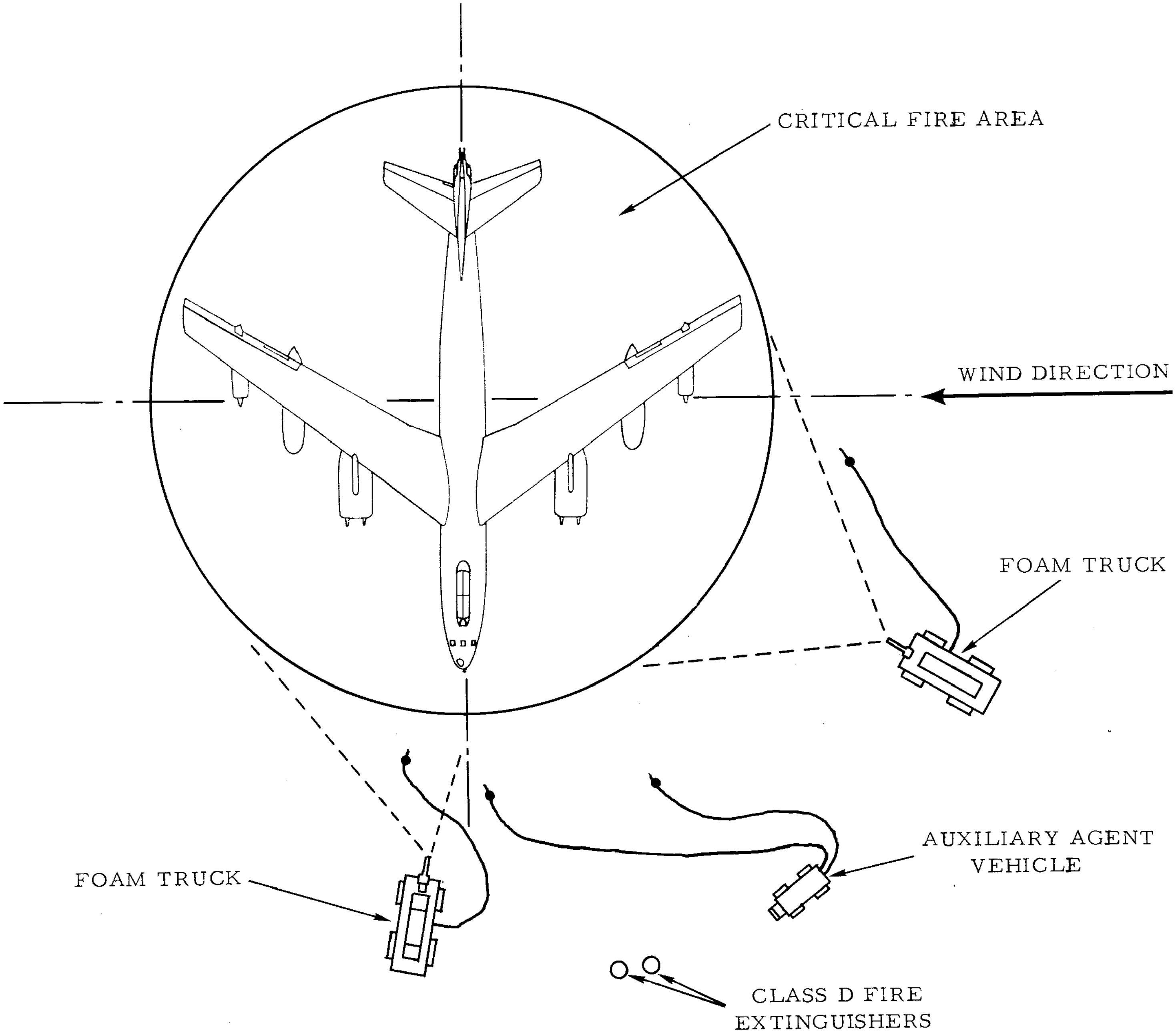


FIGURE 67 - DEPLOYMENT OF FIREFIGHTING EQUIPMENT TO PROTECT A B-47 AIRCRAFT WHEN THE WIND DIRECTION IS PERPENDICULAR TO THE FUSELAGE (NOT TO SCALE)

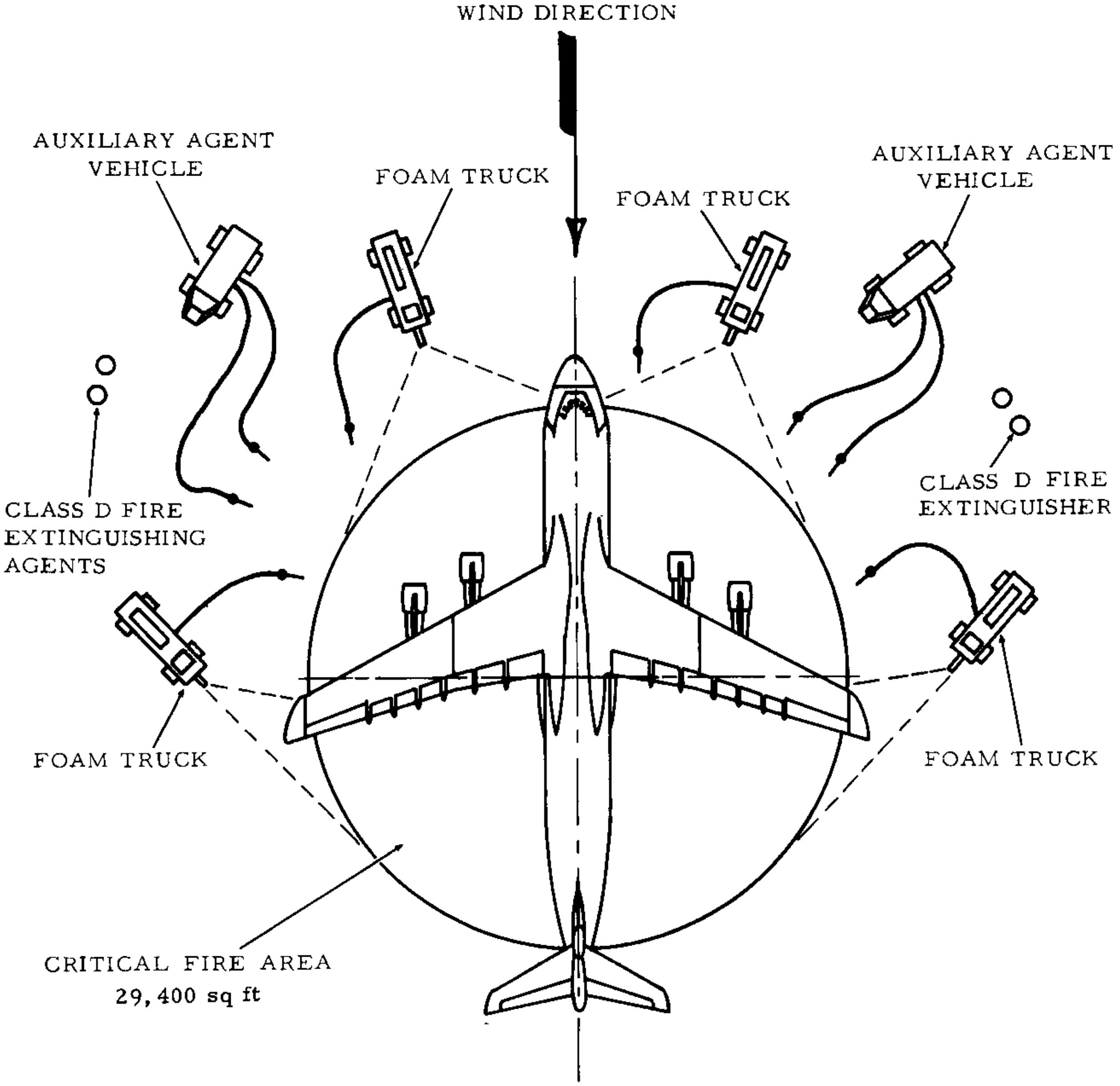


FIGURE 68 - DEPLOYMENT OF FIREFIGHTING EQUIPMENT TO PROTECT A C-5A AIRCRAFT WHEN THE WIND DIRECTION IS PARALLEL WITH THE FUSELAGE (NOT TO SCALE)

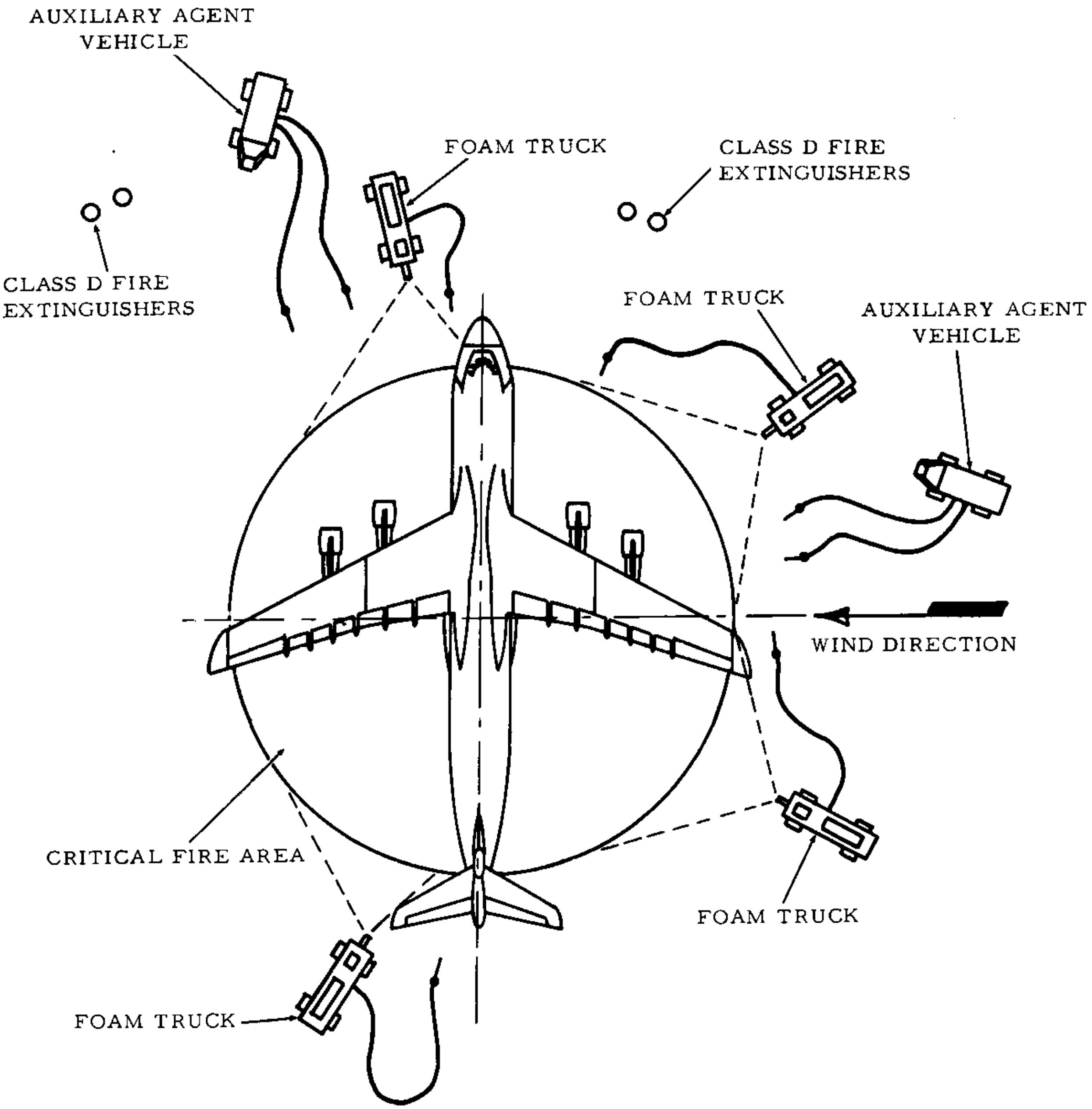


FIGURE 69 - DEPLOYMENT OF FIREFIGHTING EQUIPMENT TO PROTECT A C-5A AIRCRAFT WHEN THE WIND DIRECTION IS PERPENDICULAR TO THE FUSELAGE (NOT TO SCALE)

These idealized configurations are based upon the concept of dividing the total fire area into equal segments, where the terrain permits, which will enable each foam dispensing system to achieve an optimum solution application rate, i.e., approximately 0.20 gpm per sq ft for protein foam and 0.13 gpm per sq ft for AFFF. It is evident, of course, that in a fire situation of maximum severity any overlapping of foam patterns will reduce the overall firefighting effectiveness of the equipment and is to be avoided if practicable. Any delay in achieving the most rapid fire control time of which the equipment is capable is also self-defeating, in that the initial foam discharged is continually draining, which renders it progressively less stable and increasingly more vulnerable to disruption by wind.

The auxiliary agent equipment is shown deployed on the upwind side of the aircraft in support of the water-foam trucks where it can be dispensed most effectively, but it should be considered mobile and capable of rapid movement to other locations if required.

Summary of Results

The results obtained from the full-scale fire-modeling experiments, using B-47 Stratojet aircraft dispensing protein foam and AFFF as the primary firefighting agents are:

1. A comparison between the firefighting effectiveness of the different foam agents and dispensing systems used in the full-scale fire-modeling experiments (pool fires), and the results of the fire tests using B-47 aircraft, based upon equal fire areas, showed that the fire control times increased by a factor of 1 to 1.9 for AFFF and from 1.5 to 2.9 for protein foam.

2. Mechanical foams were subject to decomposition when applied with a solid stream on free-burning pool fires. The decomposition rate varied from two to three times greater for protein foam than for AFFF.

3. Foam dispensed in the form of a solid stream into large simulated fuel spills resulted in extensive splashing of the burning liquid and serious disruption of the established foam blanket.

4. The most effective means for applying foam on large spill fires involving two or more stationary vehicles was to position them so that each nozzle was capable of dispensing foam over an assigned area, which was at or near the optimum application rate for the system.

5. The most effective foam solution application rates were estimated to be from 0.12 to 0.14 gpm per sq ft for AFFF and from 0.18 to 0.22 gpm per sq ft for protein foam using the three different foam dispensing systems.

6. Severe Class A and Class D fires developed inside the aircraft fuselage and spread rapidly in those areas where the fuselage skin melted.

7. The magnitude of the potential ground fire hazard associated with an aircraft in an incident was determined as a function of the critical fire area around the aircraft.

Conclusions

Based upon the results of the full-scale fire-modeling experiments using B-47 Stratojet aircraft, it is concluded that:

1. The fire control times obtained with a given foam agent and dispensing system derived from simple pool-fire experiments may not be directly applicable, under all conditions, to actual aircraft accidents involving fire.

2. The most effective means of applying protein foam on a free-burning pool fire is with a dispersed foam stream.

3. Foam-dispensing nozzles used in crash firefighting should be capable of applying foam on fuel spills in a continuously variable manner from a solid stream to a fully dispersed pattern.

4. Foam should be dispensed on large fuel spill fires involving two or more crash-fire vehicles so that each nozzle is capable of applying foam over its assigned area at or near the optimum solution application rate determined for the system.

5. Class A and Class D fire-extinguishing agents should be provided to control and extinguish fires within the fuselage in the event of fire damage (melting) to the aircraft skin.

6. The quantity of Classes A, B, and D firefighting agents and the equipment necessary to protect an aircraft fuselage from fire damage should be based upon the critical fire area.

APPENDIX A

FIREFIGHTING AGENT AND/OR EQUIPMENT MANUFACTURERS

This section provides a list of firefighting agent and equipment manufacturers contacted during the laboratory investigation.

1. National Foam Systems Inc.
Union and Adams Sts.
West Chester, Pa. 18380

2. Mearl Chemical Corporation
220 Westfield Ave. West
Roselle Park, N. J.

3. Chemical Concentrates Corporation
432 Pennsylvania Ave.
Fort Washington, Pa. 19038

4. Bliss-Rockwood
38 Harlow St.
Worchester, Mass. 01605

5. The Ansul Company
Marinete, Wisconsin 54143

6. Cardinal Industries, Inc.
405 Oak Plaza Building
3707 Rawling St.
Dallas, Texas 75219

7. A. K. Peters Company
230 Park Ave.
New York, N.Y. 10017

8. Pyrene Manufacturing Company of Canada Limited
777 Dundas St. East
Toronto 8, Ontario

9. Morgan International Products Company
El Monte, California

10. General Dynamics
Fort Worth, Texas

11. Minnesota Mining and Manufacturing Company
2501 Hundson Road
St. Paul, Minnesota 55119

12. Fire Control Engineering Company
1402 E. Berry St.
Fort Worth, Texas 76119

13. Fyr-Fyter Company
Newark, New Jersey

14. Dow Chemical Company
Midland, Michigan

15. S. G. Stevens Company
3859 Lockwood Ave.
Toledo 12, Ohio

16. Charles A. Wagner Company
4455 N. 6th Street
Philadelphia, Pa. 19140

17. Walter Motor Truck Company
School Road
Voorheesville, New York 12186

18. American La France
3961 Baltimore Ave.
Philadelphia, Pa. 19104

19. Svenska Skumelocknings AB
Kungalv, Box 32
Kungalv, Sweden

20. Laurentian Concentrates Ltd.
1762 Carling Ave.
Ottawa 13, Ontario

21. Technidyne Incorporated
P. O. Box 553
West Chester, Pa. 19380

22. Cardox Division of Chemetron
Corp.
840 N. Michigan Avenue
Chicago, Illinois 60611

23. Nocor Chemical Company, Inc.
P. O. Box 2049
Morristown, N.J. 07960

24. Allied Chemical Co.
P. O. Box 70
Morristown N.J. 07960

25. Akron Brass Co.
1540 Spruce St.
Wooster, Ohio 44692

26. Mine Safety Appliance
Company
201 North Braddock Ave.
Pittsburg, Pa. 15208

27. ICI America, Inc.
151 South St.
Stanford, Conn. 06904

APPENDIX B

A METHOD FOR ESTIMATING THE EFFECT OF FOAM AGENTS ON PUMP BEARING GREASE

The following procedure was employed by one commercial laboratory to estimate the effect of AFFF and protein foam in the concentrated form and as a 6-percent solution on water pump bearing grease.

The test required the addition of 1 milliliter of the grease to 10 milliliter of the test fluid in a glass test tube. The container and contents were then agitated for 24 hours and stored at ambient room temperature for 34 days. The contents of the tube were then visually examined for signs of emulsification of the grease by the fluids and for any change in the test fluids.

APPENDIX C

THE THERMAL STABILITY OF MECHANICAL FOAM BLANKETS

This section contains a description of the test procedure and equipment employed to evaluate the relative thermal stability of mechanical foam blankets.

Test Method

The test method is a variation of the standard fire test procedure contained in the federal specification (Reference 6) of this report, and was made by introducing a suitable source of flames and radiant heat into the fire test tank after the fire had been extinguished.

Test Equipment

The basic equipment comprised the fire test tank and standard 6-gpm foam nozzle specified in Reference 6.

A means of introducing a source of intense thermal radiation into the center of the 10-ft by 10-ft by 3-ft steel tank was made by erecting a 4-ft by 4-ft by 3/8-in.-thick steel plate, in a horizontal position, 8 in. above a 17-in.-high section of a 55-gal steel drum.

An elevation view of the fire test bed is shown in Figure 3-1.

Fire Test Procedure

The 10-ft by 10-ft by 3-ft steel test tank was filled to a depth of 11 in. with water upon which 100 gal of JP-4 fuel was floated. The fuel was then ignited and given a preburn time of 60 sec. Foam was discharged onto the fire for a total time of 10 min, and the time to obtain fire control and extinguishment were recorded. Fire control was judged to be the time required for 90 percent of the fuel surface to be covered by foam. The fire extinguishment time was recorded as the total elapsed time from the start of foam application until all flames were extinguished within the tank. At the conclusion of the 10-min foam application time, 5 gal of JP-4 fuel was placed in the drum section in the center of the tank and ignited. The time required for the fuel outside the drum section to ignite was recorded as the reignition time and was considered to be a measure of the foam blanket stability.

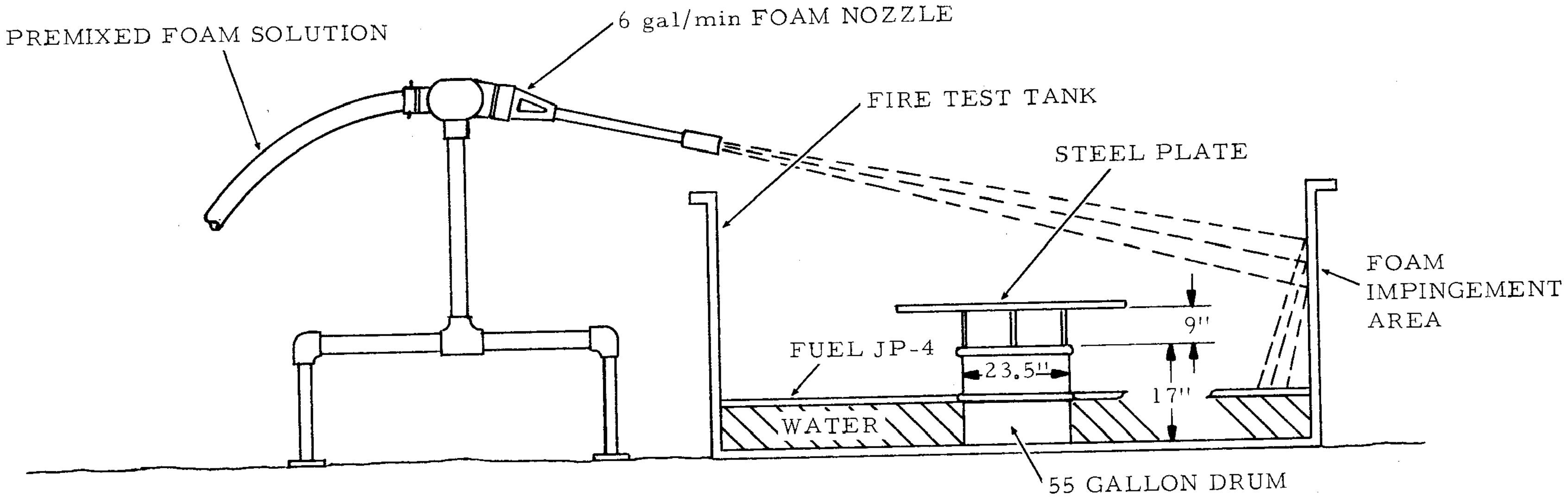


FIGURE 3-1 - ELEVATION VIEW OF THE FIRE TEST BED TO DETERMINE THE THERMAL STABILITY OF MECHANICAL FOAM BLANKETS (NOT TO SCALE)

APPENDIX D

THE EFFECT OF TERRAIN ON THE FIRE CONTROL AND EXTINGUISHMENT TIMES FOR JP-4 FUEL FIRES

This section contains a description of the test precedure and equipment employed in a determination of the effects of different terrains on the fire control and extinguishment of JP-4 fuel fires.

Test Method

This was a new test method, in which fire control and extinguishment tests were performed in 10-ft by 10-ft open pits. The terrains selected for evaluation were confined within this area by 12-in.-high earthen dikes.

Foam was dispensed from an air-aspirating nozzle positioned 10 ft from the dike, on the upwind side of the fire pit, so as to impinge on a steel backboard on the opposite side and flow back over the burning area to extinguish the fire.

Test Equipment and Foam Agents

The mechanical equipment comprised the small-scale 6-gpm mechanical foam nozzle described in Reference 6 mounted on a suitable monitor stand and a 4-ft by 4-ft steel backboard and stand.

The two types of foam agents employed in these experiments were AFFF (Manufacturer E-1, Lot No. 591) and protein foam manufactured in conformance with the requirements of Reference 6 (Manufacturer A). All foam liquids were premixed to produce a solution concentration of 6 percent by volume to assure uniformity.

Test Procedure

Three square pits 1-ft by 10-ft by 10-ft were constructed within the 200-ft-diameter fire test bed. Each pit was filled with a different material to simulate a particular naturally occurring surface structure. These included (1) a 3-in.-thick layer of traprock to simulate a rocky terrain; (2) a 3-in.-thick layer of fine sand; and (3) grass-covered sod studded symetrically, on 2-ft centers, with 16-pine boards, 2-in. by 2-in. by 24-in. high, to simulate a woodland area.

Each pit was saturated uniformly with 100 gal of JP-4 fuel just prior to ignition. The basis for comparison was the time required to control and extinguish a pit of similar size wherein the JP-4 fuel was floated on a water surface. A preburn time of 1 to 2 minutes was allowed before foam application was started, depending upon the type of terrain.

Foam was applied to the test pits by directing a solid stream from the upwind side of the fire so as to impinge on the center of a 4-ft by 4-ft steel backboard located on the downwind side of the pit. Foam was, therefore, required to flow back across the pit to effect fire extinguishment. The time necessary to obtain fire control and extinguishment was determined. Fire control was estimated to be the time required for 90 percent of the fire surface to be covered by foam. Extinguishment time was recorded as the total elapsed time until all flames were extinguished.

Sufficient premixed foam solution was available for approximately 15 min of foam discharge. Therefore, if the foam solution was exhausted before total fire extinguishment was obtained, only the time of total foam discharge was recorded.

APPENDIX E

PHYSICAL PROPERTIES OF THE VAPORIZING LIQUIDS

Chemical Name	Bromochloromethane	Bromochlorodifluoromethane	Dibromotetrafluoroethane
Halon Number	1011	1211	2402
Chemical Formula	CH_2BrCl	$CBrClF_2$	$CBrF_2$-$CBrF_2$
Molecular Weight	129.4	165.4	259.8
Boiling Point, °F	153.0	24.8	117.3
Freezing Point, °F	-125.4	-257.0	-166.8
Critical Temperature, °F	567.0	309.0	418.0
Critical Pressure, psia	953	595	500
Critical Density, lb per gal	5.75	5.94	6.58
Density at 70°F, lb per gal	16.1	15.25	18.0
Heat of Vaporization, at 760mm, Btu per lb	101.5	57.6	45.0

APPENDIX F

LABORATORY FOAM-POWDER COMPATIBILITY TEST

This test method is a modification of that required in Reference 11 to determine the compatibility between Purple-K powder and protein foam, and is concerned primarily with the addition of the important parameter of fuel to the system. Combinations of foams and dry chemical powders, meeting the requirements of the modified test, have shown an acceptable degree of compatibility in terms of foam blanket stability and depth in full-scale fire modeling experiments.

Test Procedure

A sample of the experimental foam solution is prepared by mixing 6 parts of the foam liquid concentrate with 94 parts by volume of fresh water at 70° ± 2°F. Two hundred milliliters (ml) of this solution is poured into the large bowl of a kitchen-mixer (Sunbeam Mixmaster Model 12C or equivalent) and beaten at a speed of 870 rpm for exactly 2 min. During the mixing process the bowl is made to rotate at approximately 1 rps. At the end of the 2-min foam-mixing cycle and with the mixer running, a 10-gram (g) ± 0.1 g sample of the test powder is sprinkled onto the surface of the foam in the bowl and allowed to mix for an additional 30 sec, after which a 15-ml sample of the test fuel (JP-4) is added and the mixing continued for another 30 seconds. The foam mixture remaining in the bowl is removed with the aid of a spatula into the standard foam container (Reference 9) and screeded-off level with the rim. The pan is then placed on a stand having a slope of 1 in. in 12 in. toward the front and constructed so that the top of the pan and the foam surface is 2 3/8 in. below a radiating metal surface. The heat source consists of a 1,000-watt electrical hotplate with a 7-in.-diameter face (Edwin L. Wiegard Co., Pittsburgh, Pa., Model ROPH-100 or equivalent) mounted upside down over a 6 1/2-in.-diameter hole in a 1/2-in.-thick piece of transite. The temperature of the hotplate face is maintained at 1,000°F by varying the current input with a Variac transformer. To determine this temperature, it is convenient to use a thermocouple embedded in the hotplate. As the pan containing the foam is inserted, a sheet of transite 8 in. sq and 1/2 in. thick is placed beneath the pan to insulate it from the hot stand.

A 100-ml graduated cylinder is placed under the draw-off tube of the foam container, and the liquid draining from the foam is measured at 30-sec intervals. From these data the time required to collect 25 ml of solution is determined.

The results of experiments performed in accordance with this modified procedure using a variety of foam and dry-chemical agents indicated that if the time required to collect 25 ml of foam solution was 2.5 min or more, an acceptable degree of compatibility would be obtained under conditions involving a high degree of turbulence of the burning fuel, foam, and dry-chemical powder.

APPENDIX G

AN EVALUATION OF THE U.S. AIR FORCE A/S32P-2 FIREFIGHTING TRUCK USING PROTEIN FOAM AND AFFF

Test Methods

The evaluation was conducted in two phases.

Phase 1: Foam quality and foam-distribution patterns were determined in accordance with the requirements of Reference 6 of this report for (1) 25-percent-solution drainage time, (2) foam expansion ratio, and (3) foam solution concentration.

Phase 2: Fire tests were conducted using AFFF (Manufacturer E-1) at the rate of 0.029 to 0.376 gpm per sq ft on Jet A fuel by maintaining a constant nozzle discharge rate and varying the fire size. This procedure was similar to that employed in tests conducted by the NRL at the Naval Air Station, Miramar, California, and reported in Reference 29 of this report.

Test Procedures

Foam Evaluation: The objective of these experiments was to obtain adequate data with regard to foam quality and foam ground patterns to establish the degree of correlation between the roof turret nozzle and bumper nozzle. All foam produced in these experiments was made by proportioning the foam liquid concentrate and water through the truck's foam system.

Roof Turret Nozzle: One barrel of the composite nozzle was evaluated for foam quality and range of foam discharge for the dispersed and solid-stream patterns at a nominal solution discharge rate of 500 gpm and a pressure of 250 psi. A protein foam agent (Manufacturer A) conforming to the federal specification was employed in these experiments to conserve the AFFF agent.

Bumper Nozzle: This nozzle was evaluated for foam quality and range of foam discharge for the dispersed and solid-stream patterns at a nominal solution discharge rate of 300 gpm and a pressure of 250 psi. Both protein foam and AFFF were employed in these experiments.

Prior to conducting the fire tests, the water rate of the bumper nozzle was evaluated and found to be 316 gpm; therefore, this value was used in all calculations.

Fire Test Bed: All fire tests were conducted in accordance with the general procedure established at NAFEC and presented in Reference 49 of this report. The only significant variation in the procedure was that in this series of tests, the solution application rate was varied by changing the fire-pool size instead of the equipment discharge rate. In the interest of effecting maximum economy in time and manpower, the tests were conducted in concentric pools with diameters of 32.7, 46.3, 82, and 117 ft, and by removing the intervening dike it was possible to change from one fire size to the next larger.

An obstacle comprising a cruciform configuration of nine 55-gal steel drums and a 3-dimensional fire was provided in the center of the fire pool. The 3-dimensional fire was sustained by directing a solid stream of Jet A fuel from a 1/4-in.-diameter stainless steel tube from a height of 3 ft into the top of a vented 5-gal steel pail containing a small quantity of magnesium metal chips. Uniform environmental burning conditions were maintained by allowing a 30 sec preburn time at maximum radiation intensity which was determined from the radiometer data before foam application was started.

A burnback test was conducted as part of each experiment by measuring the time required for the unextinguished 3-dimensional fire to progressively increase in size until a radiation intensity of 0.5 Btu per sq ft per sec was detected by any one of the four radiometers located around the pool perimeter. The radiometer distribution is presented schematically in Figure 7-1. Heat sensors A and B were elevated on steel poles 8 ft above ground level on the diameter at right angles to the wind direction and remained in position throughout the test. Radiometers C and D were 42 in. high and placed on the downwind side of the pool after fire control had been obtained, to monitor the increase in heat flux during the burnback cycle. Thermal data were recorded on two instruments equipped with event markers.

Visual analysis of the fire test performance was obtained with two cameras exposing 16 mm Kodachrome II color film and operating at 24 frames per sec. One additional motion picture camera was used to obtain documentary coverage of the overall firefighting operation from random locations. Black and white still pictures were also taken during various phases of the fire-extinguishing operation.

The experimental parameters are summarized in Table 7-I for each of the four fire sizes.

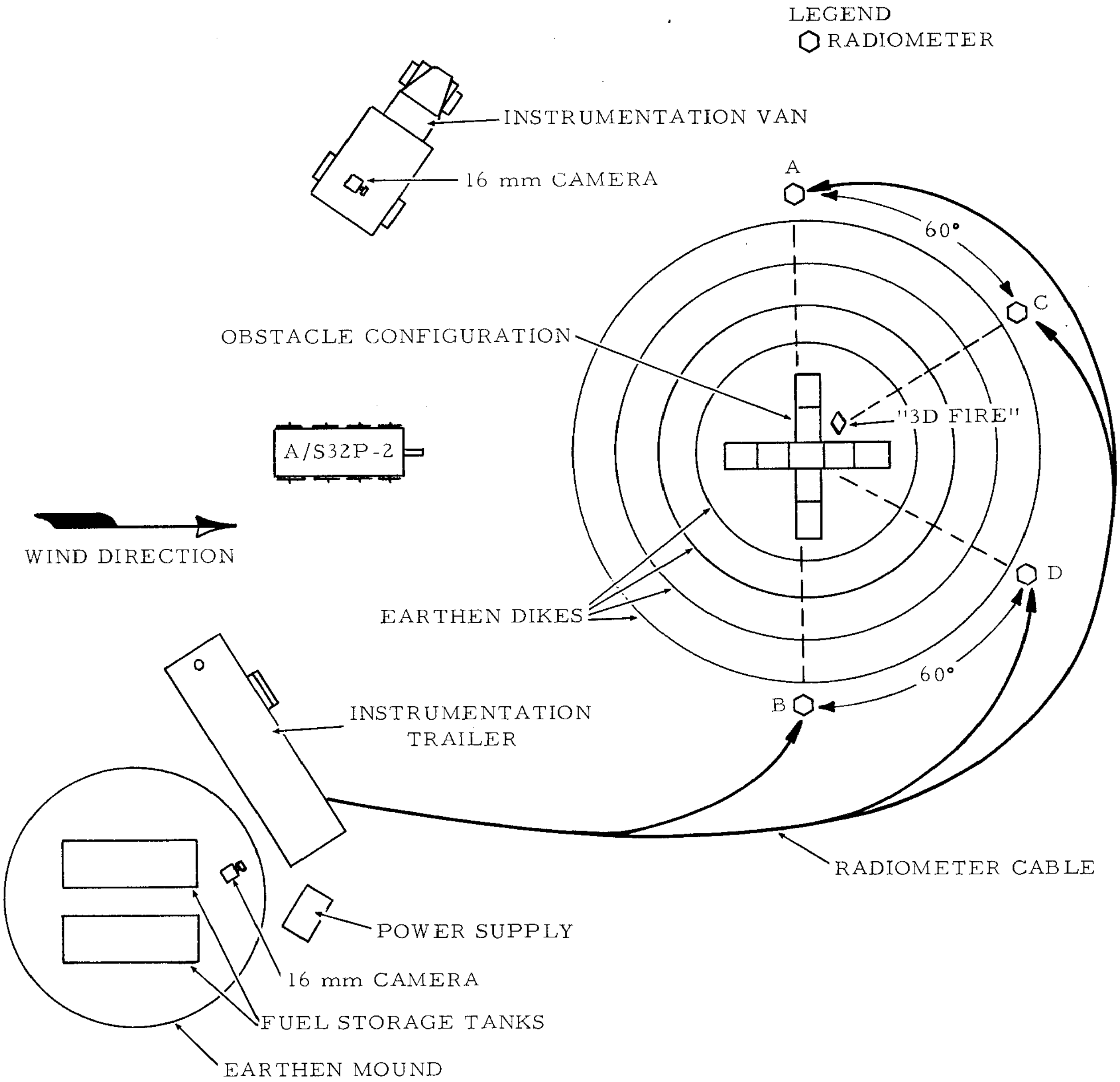


FIGURE 7-1 - PLAN VIEW OF THE FIRE TEST BED USED IN THE EVALUATION OF THE U.S. AIR FORCE A/S32P-2 TRUCK

TABLE 7-I

FIRE TEST PARAMETERS USING THE U.S. AIR FORCE A/S32P-2 TRUCK

Test	Diameter ft	Fire Area sq ft	Solution Discharge Rate gpm	Volume of JP-4 Fuel gal	Solution Application Rate gpm per sq ft
1	32.7	840	316	700	0.376
2	46.3	1,680	316	540	0.188
3	82.0	5,290	316	1,700	0.059
4	117.0	10,750	316	4,540	0.029

Test Results

Foam Quality Determinations: The results of the foam quality experiments are presented in Table 7-II in which each value is the average of three separate determinations.

TABLE 7-II

FOAM QUALITY DETERMINATIONS FOR PROTEIN FOAM AND AFFF DISPENSED BY THE U.S. AIR FORCE A/S32P-2 TRUCK

Vehicles	Foam Expansion Ratio	25-Percent (1) Drainage Time min	Solution Concentration percent
U.S. Air Force A/S32P-2 Roof Turret Nozzle (Protein Foam Mfr. A)	8.8:1	6.8	6.4
Bumper Nozzle (Protein Foam Mfr. A)	8.5:1	6.5	6.2
Bumper Nozzle (AFFF Mfr. E-1)	8.0:1	2.6	6.1
U.S. Navy MB-5 Vehicle (2) Roof Turrett Nozzle (AFFF Mfr. E-1)	8.4:1	3.0	5.5

(1) Conducted in accordance with Reference 6 of this report
(2) Data taken from NRL Report (Reference 29 of this report)

The results of the foam pattern tests using the bumper nozzle with protein foam and AFFF are presented schematically in Figure 7-2.

After the foam ground patterns had been established with the bumper nozzle, it was necessary to determine the optimum distance from the upwind rim of the fire pool to position the foam truck. This distance is of importance if severe plunging of the high-velocity foam stream and the resulting fuel turbulence is to be avoided during fire control and extinguishing. The results of a series of dry-run foam pattern tests performed on 40-ft-diameter pools indicated that the best foam distribution could be obtained with the bumper nozzle when the A/S32P-2 vehicle was positioned approximately 45 ft from the upwind rim of the fire pool.

Pool-Fire Tests: The environmental conditions on the two days of testing, as reported by the NAFEC Weather Bureau Airport Station, are summarized below:

Date	Test No.	Temperature °F	Wind Velocity mph
16 Jan 1968			
10:00 a.m.	1	19	25-32
17 Jan 1968			
10:00 a.m.	2 and 3	21	6
01:00 p.m.	4	29	9

The results of the pool-fire tests employing AFFF are presented in Table 7-III.

These data are also shown graphically in Figure 7-3, in which the foam solution application rate is plotted as a function of the fire control time for each test. The solid-line profiles show the fire control and extinguishment times obtained with AFFF dispensed by the A/S32P-2 vehicle, while the dashed curves were developed from the data obtained by the NRL (Reference 29 of this report) in tests conducted with the U.S. Navy MB-5 vehicle. These data are also presented graphically in Figure 7-4 in which the foam solution application rate is plotted as a function of the solution application density.

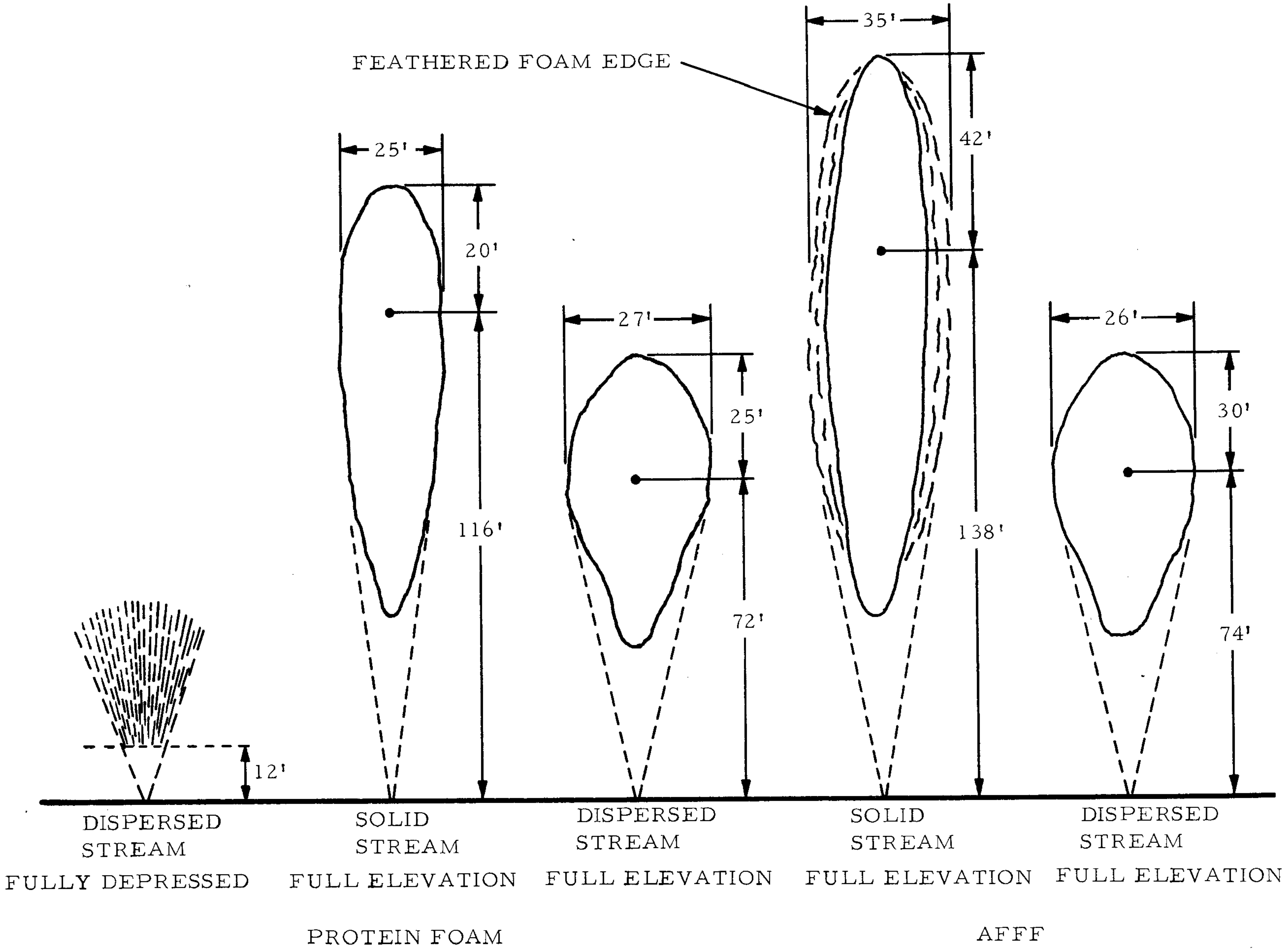


FIGURE 7-2 - FOAM-GROUND PATTERNS PRODUCED BY THE BUMPER NOZZLE ON THE U.S. AIR FORCE A/S32P-2 TRUCK

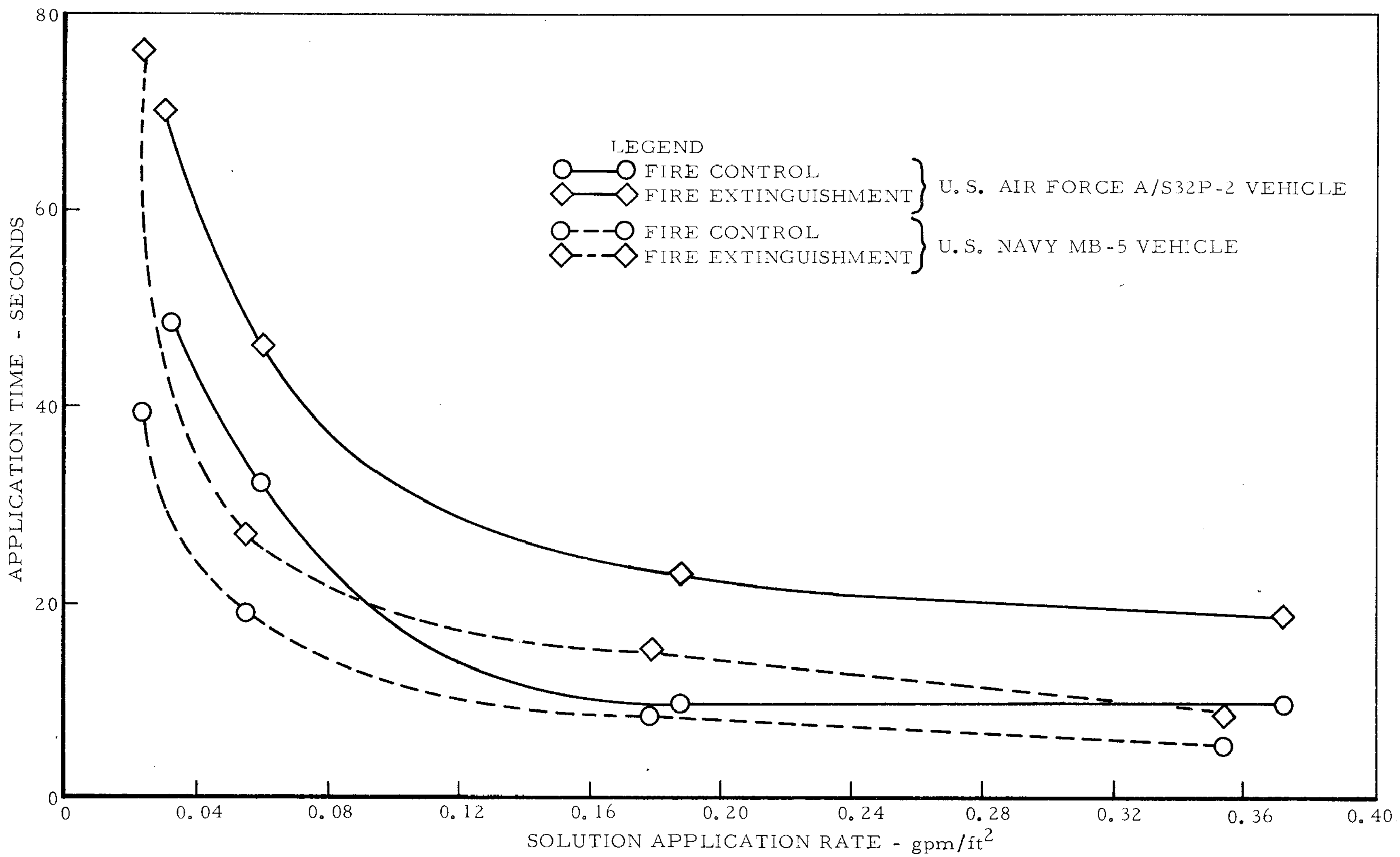


FIGURE 7-3 - FIRE CONTROL AND EXTINGUISHING TIMES AS A FUNCTION OF AFFF SOLUTION APPLICATION RATE ON JET A FUEL FIRES USING THE U.S. AIR FORCE A/S32P-2 AND U.S. NAVY MB-5 TRUCKS

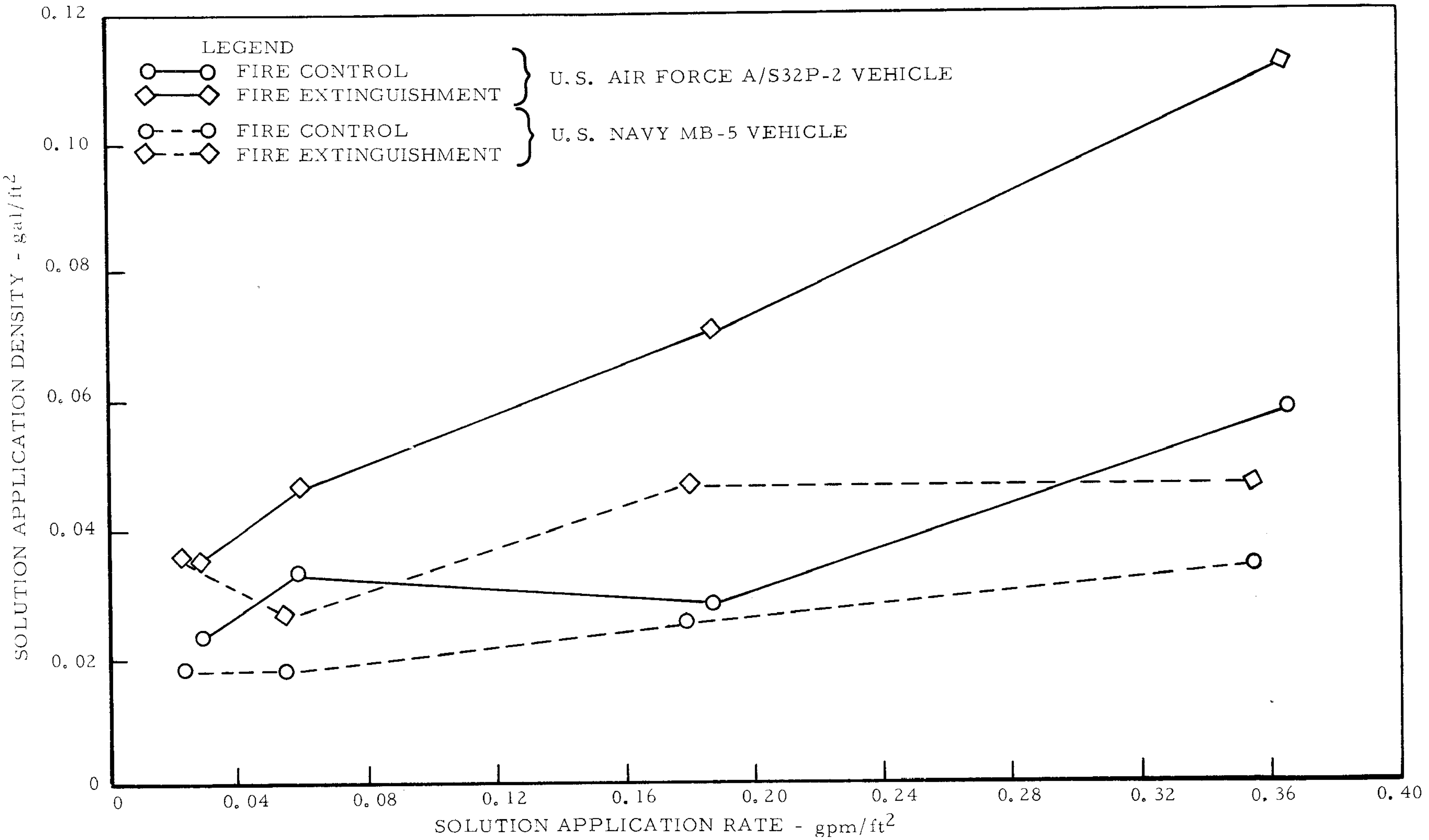


FIGURE 7-4 - AFFF SOLUTION APPLICATION SENSITY AS A FUNCTION OF THE SOLUTION APPLICATION RATE TO CONTROL AND EXTINGUISH JET A FUEL FIRES USING THE U.S. AIR FORCE A/S32P-2 AND U.S. NAVY MB-5 TRUCKS

TABLE 7-III

FIRE TEST RESULTS

Test No.	Solution Application (time/sec)		Solution Applied (gal)		Solution Application (density/gal/ft^2)		Burn Back Time Minutes
	Fire Control	Fire Extinguishment	Fire Control	Fire Extinguishment	Fire Control	Fire Extinguishment	
1	9.3	18	48.9	94.8	0.058	0.113	18.4
2	9	22.5	47.4	118.5	0.028	0.071	14.6
3	32	46	168.4	242.1	0.032	0.046	22.4
4	47	70	247.4	369.7	0.023	0.034	35.9

Three determinations of the AFFF solution concentration were made during the fire test program to monitor the foam liquid proportioning system with the following results:

Date of Test	AFFF Solution Concentration Percent by Volume
16 Jan 1968 (Sample taken after test 1)	7.0
17 Jan 1968 (Sample taken after test 2)	6.0
17 Jan 1968 (Sample taken after test 4)	5.8

APPENDIX H

A COMPARATIVE EVALUATION OF A MODIFIED U.S. AIR FORCE 0-11A FIREFIGHTING TRUCK DISPENSING CHEMICAL FOAM WITH A U.S. AIR FORCE A/S32P-2 FIREFIGHTING TRUCK DISPENSING MECHANICAL FOAM

Firefighting Vehicles

1. The chemical foam-dispensing equipment was a U.S. Air Force 0-11A crash, fire, and rescue truck which had been modified to dispense chemical foam. The vehicle had a capacity of 1,000 gal of "A" solution (aluminum sulfate) and 1,000 gal of "B" solution (sodium bicarbonate) which were proportioned in equal volumes and discharged simultaneously at a nominal solution rate of 500 gpm.

2. The mechanical protein-base foam was dispensed by the U.S. Air Force A/S32P-2 firefighting truck at a solution discharge rate of 500 gpm.

Firefighting Agents

1. The protein-base foam employed in these experiments was manufactured in conformance with the federal specification in Reference 6 of this report (Manufacturer A).

2. The two chemical agents required for the production of chemical foam in the modified 0-11A truck were proprietary compositions (Manufacturer B). The chemical required for the production of the "A" solution was procured under code No.FC-100-A-SML and for the "B" solution, under FC-100-A-SML. The concentration of both the "A" and "B" solutions was 1 lb of chemical for each gallon of water.

No particular difficulty was encountered in dissolving the "A" and "B" components used in the chemical foam truck. However, the suggestion offered by the manufacturer to dissolve the "B" component in a separate tank to avoid the accumlation of an objectionable quantity of sediment in the "B" compartment was followed.

3. The Purple-K dry-chemical powder used in the foam-powder compatibility tests was procured under a military specification (Reference 39 of this report).

Test Procedures

The test procedure was subdivided into three phases:

Phase 1 concerned the evaluation of mechanical and chemical foam in terms of (1) foam quality, (2) the foam discharge ground patterns, and (3) the compatibility of the foam with Purple-K powder.

Phase 2 concerned the evaluation of mechanical and chemical foam for fire control time on conventional water-base pool fires.

Phase 3 concerned the evaluation of mechanical and chemical foam in terms of fire control time on a traprock-base fire.

Test Methods

Phase 1 - Foam Quality Determinations: Foam quality and foam discharge patterns were determined in accordance with NFPA requirements (Reference 9 of this report). All tests with the O-11A vehicle were conducted with the component solutions heated to a temperature between 70° and 80°F. This was necessary to obtain adequate foam expansion because chemical foam formation is the result of a chemical reaction, the rate of which approximately doubles for each 10°C rise in temperature.

A comparative evaluation of the heat resistance of the mechanical and chemical foam was conducted in conformance with the requirements of the federal specification in Reference 50 of this report.

The compatibility of the chemical and protein-base foam with Purple-K was evaluated by modifying the heat-resistance test in Reference 50 by sprinkling 100 g of Purple-K powder on the foam blanket prior to igniting the fuel and comparing the burnback time with that obtained with the untreated foam blanket.

Phase 2 - Fire Tests: The large-scale fire tests were conducted in accordance with the general procedure employed at NAFEC, and the method is presented in detail in Reference 3 of this report. The only exception in the procedure was that, in the current series of tests, the solution application density on the fire was varied by changing the fire area instead of the nozzle discharge rate.

The tests were conducted in concentric pools of 50.5 ft, 72.75 ft, and 103 ft in diameter with 10-in.-high earthen dikes enclosing, in the center, a cruciform configuration of seven 55-gal steel drums and a 3-dimensional fire, that was sustained by directing a stream of JP-4 fuel from a 1/4-in.-diameter stainless steel tube onto the top of the center drum from a height of 3 ft. A plan view of the fire test bed is presented in Figure 8-1.

A burnback test was incorporated by measuring the time required for the unextinguished 3-dimensional fire to progressively increase in size and intensity until a heat flux of 0.5 Btu per sq ft per sec was detected by any one of the radiometers positioned around the pool perimeter. Radiometers "A" and "B" were elevated on steel poles 8 ft above ground level on the diameter at right angles to the wind direction. Thermal data were taken on a pen recorder equipped with an event marker.

Visual analysis of the fire tests was provided by two cameras exposing 16 mm Kodachrome II color film and operating at 24 frames per sec.

Phase 3 - Effect of Terrain on Fire Control Time: To determine the effect of terrain upon the fire control time employing both protein foam and chemical foam, two tests were conducted on the 50.5-ft-diameter fire pit in which a 4-in. to 5-in.-thick layer of 3/8-in. traprock was substituted for the water-base pool fire. In these experiments, sufficient JP-4 was used to bring the fuel level flush with the surface of the traprock. Previous tests performed on this terrain indicated that after a 30-sec preburn time, the surface exposed was entirely traprock.

Results:

1. The quality of foam produced by the O-11A and the A/S32P-2 vehicles in terms of the foam-expansion ratio and 25-percent-drainage time is presented in Table 8-I.

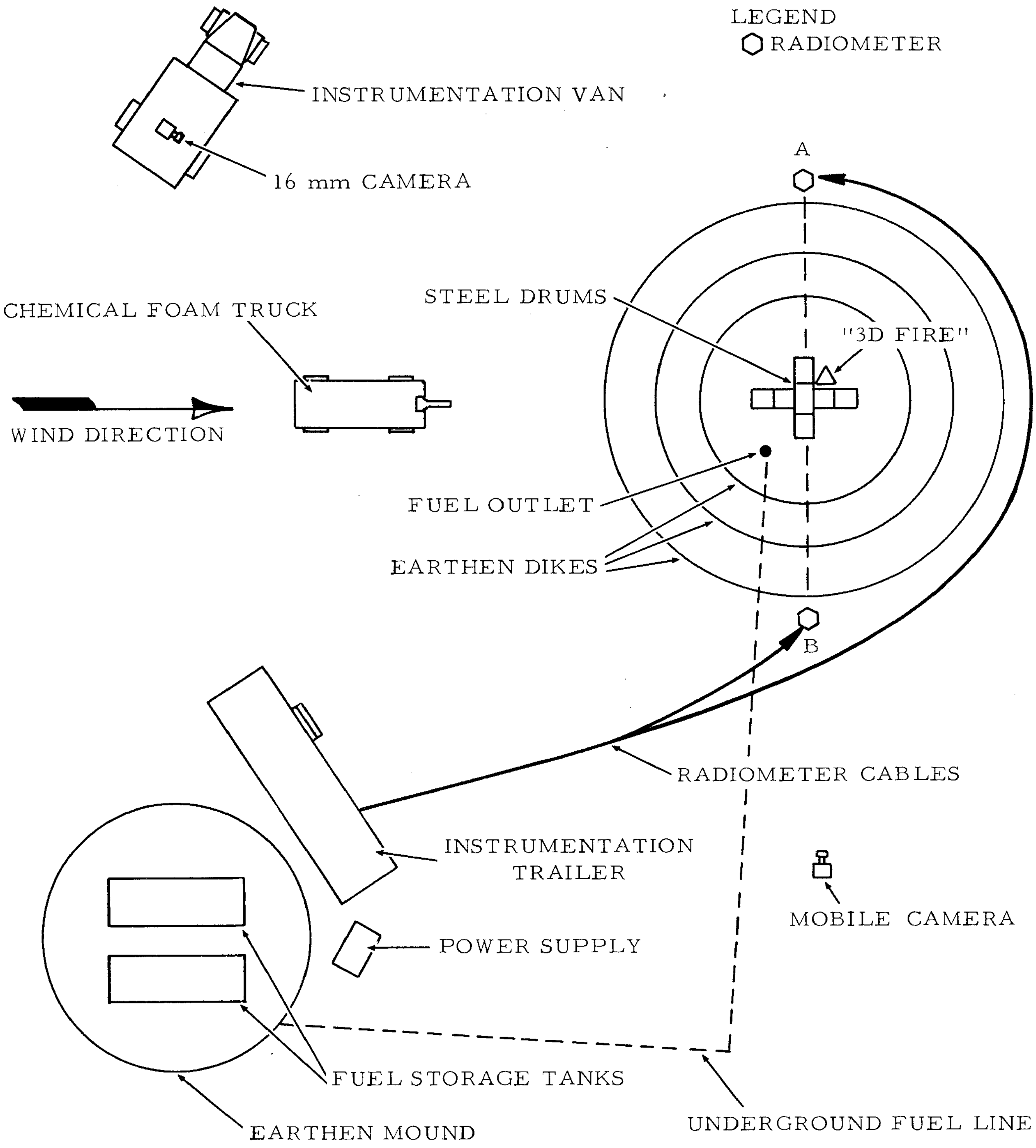


FIGURE 8-1 - PLAN VIEW OF THE FIRE TEST BED USED IN THE EVALUATION OF THE MODIFIED U.S. AIR FORCE 0-11A AND THE U.S. AIR FORCE A/S32P-2 FIREFIGHTING TRUCKS

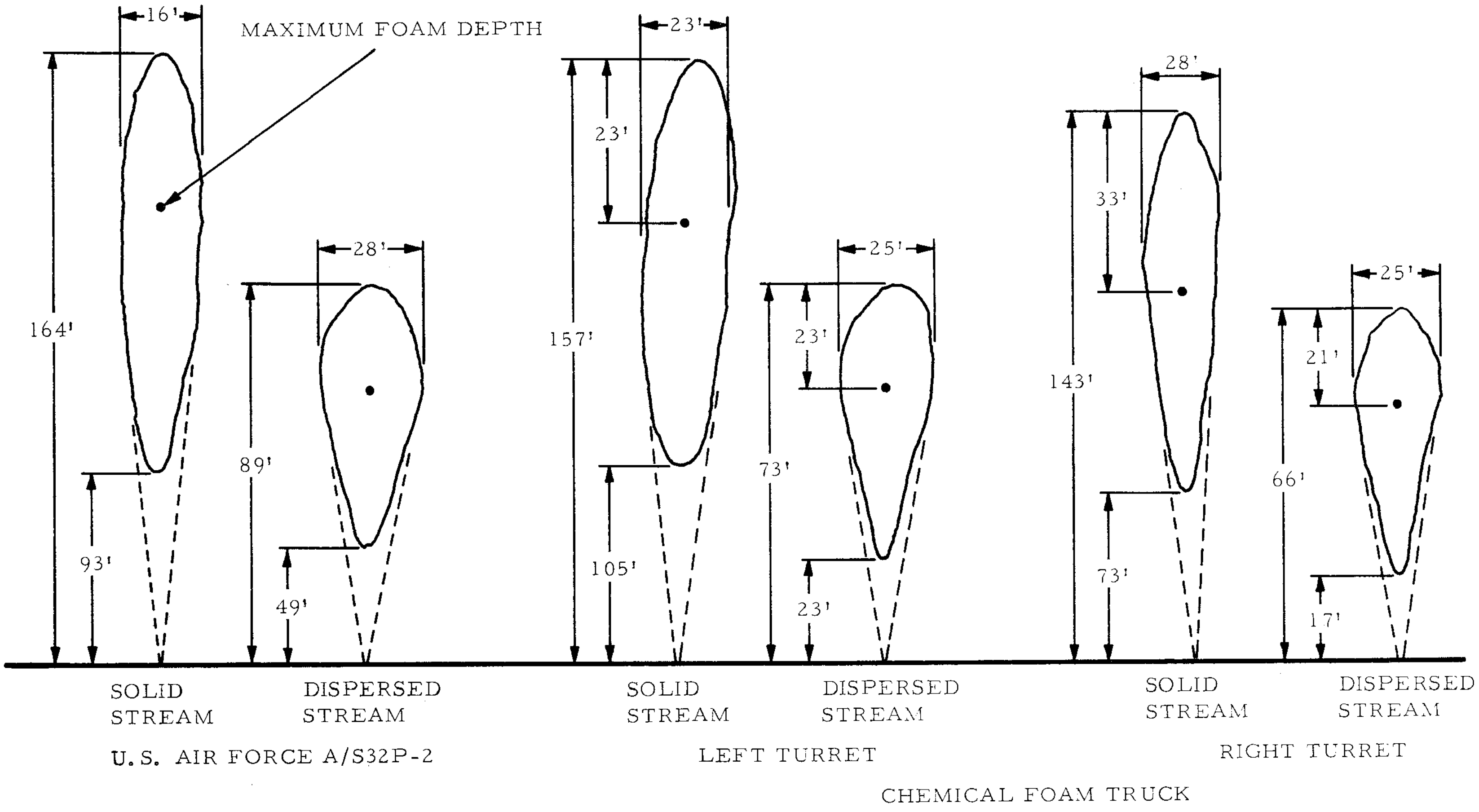


FIGURE 8-2 - FOAM DISTRIBUTION PATTERNS PRODUCED BY THE MODIFIED 0-11A CHEMICAL FOAM TRUCK AND THE U.S. AIR FORCE A/S32P-2 TRUCK

TABLE 8-III

COMPATIBILITY OF CHEMICAL AND PROTEIN FOAMS WITH PURPLE-K POWDER

	Foam Blanket Remaining After a 4-Minute Burn Time Percent	Total Time to Burn Off Foam Blanket Min
Protein Foam	0	3.9
Chemical Foam	70-75	20.2

4. The results of the pool-fire tests employing the U.S. Air Force A/S32P-2 truck are presented in Table 8-IV under Tests Numbered P-2, P-3, and P-4, and for the 0-11A vehicle in Table 8-V under Tests Numbered C-2, C-3, and C-4. These data are presented graphically in Figure 8-3, where fire control time is plotted as a function of the solution application rate.

5. The results of the fire tests conducted on traprock-base fires employing protein foam are presented in Table 8-IV under Test Number P-1 and for chemical foam in Table 8-V under Test Number C-1. These data are also plotted as single points in Figure 8-3 for comparison with the profiles developed from the pool-fire tests.

TABLE 8-IV

FIRE TEST RESULTS EMPLOYING THE U.S. AIR FORCE A/S32P-2 TRUCK ON WATER BASE POOL FIRES AND TRAPROCK BASE FIRES

Test No.	Fire Type	Fire Diameter	Preburn Time	Fuel JP-4	Wind Velocity	Fire Control	Fire Ext.	Burn-back Time	Solution Application Rate
		ft	sec	gal	mph	sec	sec	min: sec	gpm per sq ft
P-1	Trap-rock	50.5	32	900	10-12	36	73	7:00	0.25
P-2	Pool	50.5	32	700	8	20	33	3:24	0.25
P-3	Pool	72.75	27	2120	13	42	52	1:28	0.12
P-4	Pool	103.0	63	3200	12	48	62	2:19	0.06

NOTE: Solution discharge rate: 500 gpm

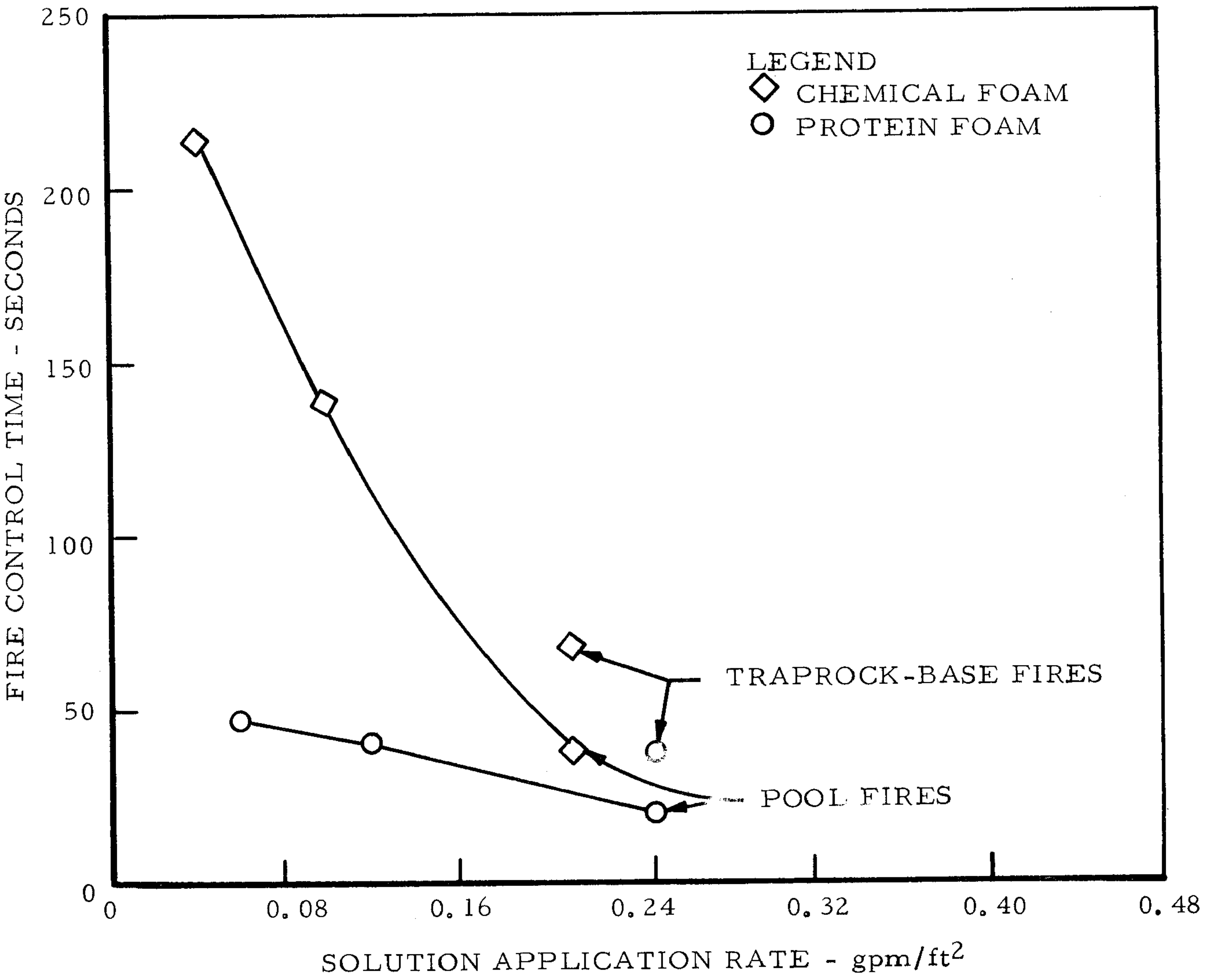


FIGURE 8-3 - FIRE CONTROL TIME AS A FUNCTION OF THE SOLUTION APPLICATION RATE FOR PROTEIN AND CHEMICAL FOAMS ON POOL FIRES AND ON TRAPROCK-BASE FIRES

TABLE 8-V

FIRE RESULTS EMPLOYING THE MODIFIED 0-11A CHEMICAL FOAM TRUCK

Test No.	Fire Type	Fire Diameter ft	Preburn Time sec	Fuel Jp-4 gal	Wind Velocity mph	Fire Control sec	Fire Ext. sec	Burn-back Time min: sec	Solution Application Rate gpm per sq ft
C-1	Traprock	50.5	29	700	6-8	67	71	6:11	0.21
C-2	Pool	50.5	32	700	10	38	71	9:23	0.21
C-3	Pool	72.75	35	1250	8	139	166	19:53	0.10
C-4	Pool	103.0	28	3320	10	213	231	1:26	0.05

NOTE: Solution discharge rate: 423 gpm

APPENDIX I

AN EVALUATION OF THE U.S. AIR FORCE FIRE SUPPRESSION KIT (FSK) AND THE EFFECT OF HELICOPTER ROTOR-WASH ON PILOT RESCUE TIME

Equipment and Fire-Extinguishing Agents

1. One manned H-43B helicopter.

2. One U.S. Air Force Fire Suppression Kit No. 5590436. The general configuration of these units was extracted from Reference 51 of this report and is as follows:

    a. Total gross weight 1,000 lb (approximately).

    b. Water capacity 78.5 gal.

    c. Foam concentrate tank 5 gal.

    d. Air pressurizing tank 3,000 lb per sq in.

    e. Solution discharge time 45 to 55 sec, fully open.

    f. Solution discharge rate 85 to 105 gpm.

    g. Foam nozzle hose length 150 ft.

3. The firefighting agents employed in these experiments were procured under the following specifications:

    a. The protein foam was manufactured to conform with the federal specification (Reference 6 of this report).

    b. The AFFF (Manufacturer E-1) was manufactured in conformance with the military specification (Reference 19 of this report).

    c. The CB was manufactured in conformance with the military specification (Reference 46).

    d. The fluoroprotein foam was the type evaluated and described in Reference 8 of this report.

Evaluation of the Fire Suppression Kit: Prior to conducting the fire tests, the FSK was evaluated for foam quality and performance in terms of the foam-expansion ratio, 25-percent drainage time, and foam-ground patterns employing each agent individually and in combination with CB. The results of the agent evaluation experiments are presented in Table 9-I, and the foam-ground patterns are shown in Figure 9-1.

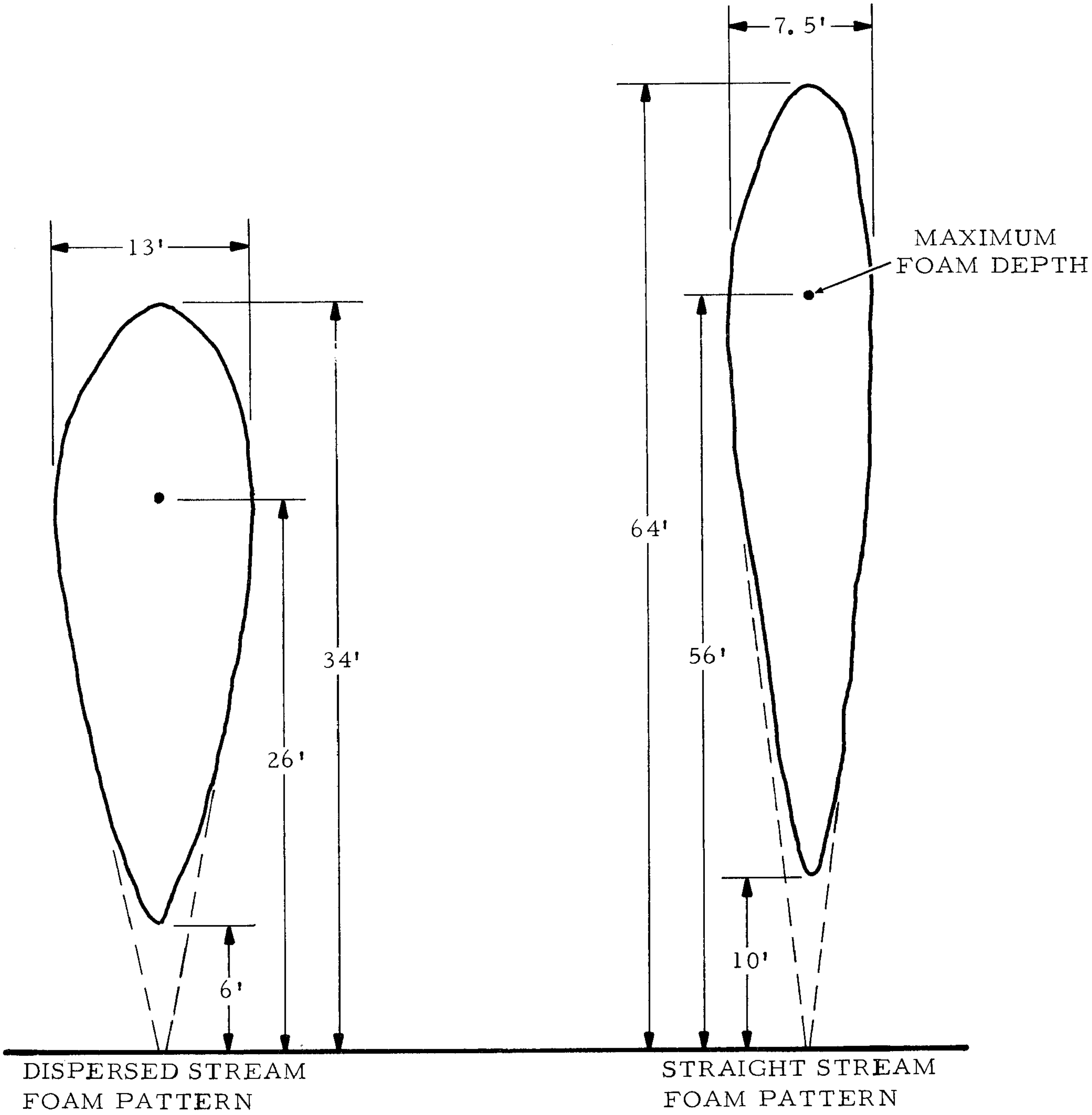


FIGURE 9-1 - PROTEIN FOAM DISTRIBUTION PATTERNS OBTAINED WITH THE FSK. SIMILAR PATTERNS WERE OBTAINED USING AFFF

TABLE 9-I

THE QUALITY OF FOAM PRODUCED WITH THE FSK USING AFFF AND PROTEIN FOAM SINGLY AND IN COMBINATION WITH CB

Agent System	Foam 25-Percent Drainage Time Min	Foam Expansion Ratio
AFFF alone	2.72	8.2:1
AFFF and CB	2.67	7.9:1
Protein foam alone	12.33	13:1
Protein foam and CB	8.11	10.2:1

Test-Fire Bed

Water-Base Pool-Fire Tests: The first series of pool-fire tests was conducted in a circular diked area 50.5 ft in diameter containing sufficient water to present a smooth surface and prevent "islands" from intruding through the fuel surface.

The fire-pool was charged with 700 gal of JP-4 fuel which provided an application density of 0.35 gal per sq ft. A cruciform cluster of seven 55-gal steel drums was used as an obstacle and heat sink in support of the 3-dimensional fire which was sustained by a spray of JP-4 fuel from a 1/4-in.-diameter stainless-steel tube.

The instrumentation employed in monitoring the fire test performance is shown in Figure 9-2. Heat sensors were located at the pool perimeter on the diameter and at right angles to the wind direction. Thermal data were recorded on instruments within a specially prepared trailer. Motion pictures of each test were taken for data analysis from locations on top of a van and at ground level.

Traprock-Base Fire Tests: After the completion of the pool-fire tests, a second series of tests was performed in which the water was drained from the pit and replaced by a 5- to 6-in.-deep layer of 3/8-in. traprock. In these tests,

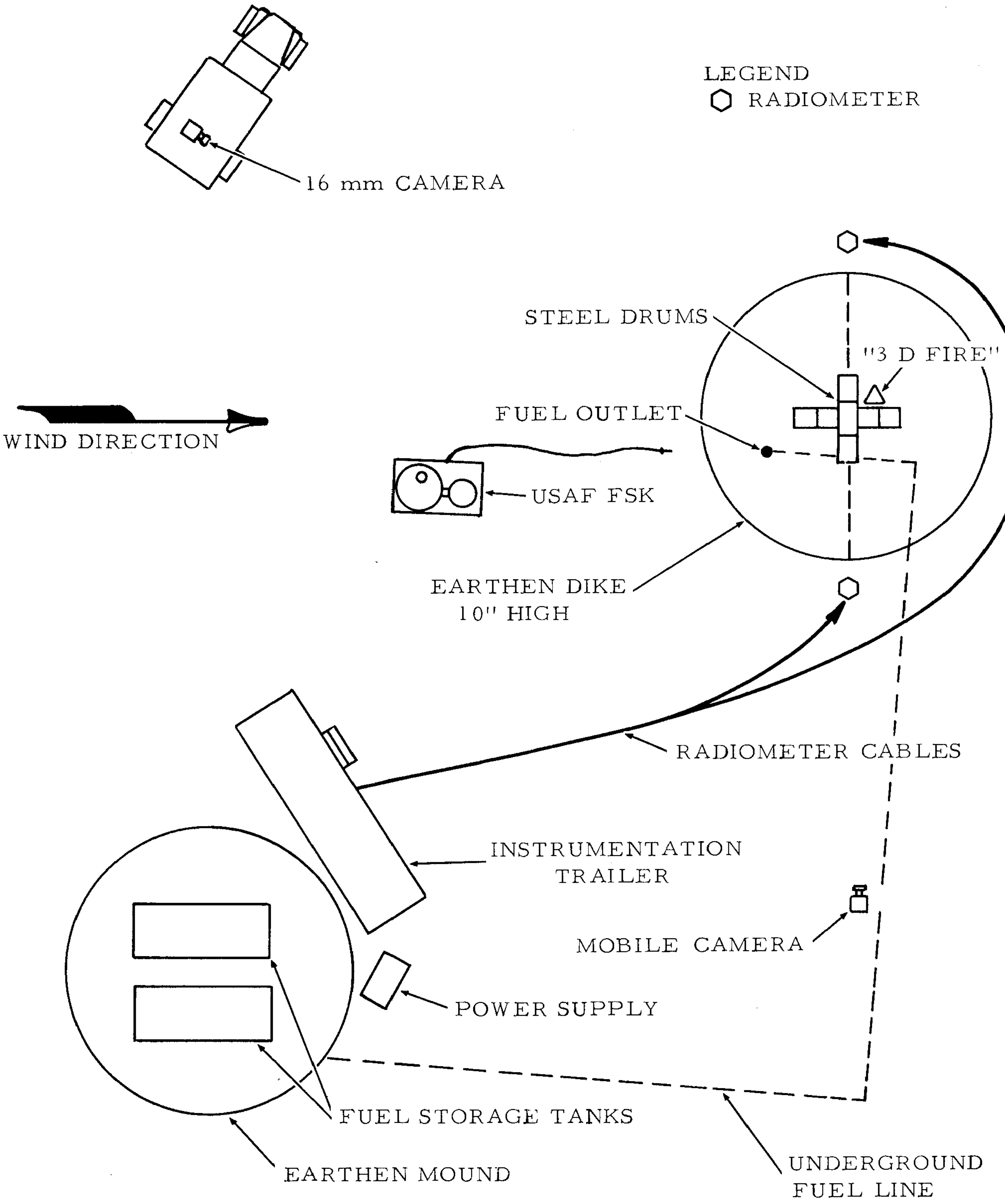


FIGURE 9-2 - PLAN VIEW OF THE FIRE TEST BED SHOWING THE RADIOMETER AND CAMERA LOCATIONS sufficient JP-4 fuel was employed to bring the fuel level flush with the surface of the traprock. Preliminary experiments conducted on this environment indicated that after a 30-sec preburn time, the surface exposed to foam application was composed almost entirely of traprock.

Fire Test Procedure

AFFF Pool-Fire Tests: Fire control times were determined for AFFF discharged alone and in combination with CB on 50.5-ft-diameter JP-4 fuel fires. This fire size provided a foam solution application rate of approximately 0.05 gpm per sq ft. The fire control time was defined in these experiments as the elapsed time between the initiation of the extinguishing operation to that time when the heat flux, as measured by the radiometers, was reduced to 0.2 Btu per sq ft per sec.

The sequential discharge of CB and AFFF was accomplished by substituting 5 gal of CB for an equal volume of water in the water compartment of the FSK. Under these conditions, the water insoluble CB, with a density of 1.93 gpm, sank to the bottom of the spherical water tank and was discharged first over a period of 2.9 to3.5 sec, together with a small quantity of AFFF concentrate. This initial discharge was followed immediately by the remainder of the AFFF solution.

The anticipated effect of this sequential discharge was to produce a more rapid flame "knockdown" and a shorter fire control time.

Protein Foam Pool-Fire Tests: Identical tests were performed with protein foam, both singly and in combination with CB, as were conducted with AFFF.

Traprock-Base Fire Tests: Tests identical with those described in Items 1 and 2 above were performed on traprock-base fires.

All of the tests conducted under this phase of the effort were performed by NAFEC personnel.

Test Results

AFFF Water-Base Pool-Fire Tests: The results of the three tests performed with AFFF under pool-fire conditions are presented in Table 9-II, tests numbered A-3, A-4, and A-5.

TABLE 9 - II

RESULTS OF TESTS PERFORMED WITH THE FSK USING AFFF AND PROTEIN FOAM SINGLY AND IN COMBINATION WITH CB

Test Number	Agent(s) Employed	Foam Solution Used gal	Solution Discharge Time sec	Solution Discharge Rate gpm	Solution Application Density gal per sq ft	CB gal	Solution Application Rate gpm per sq ft	Fire Control Time sec	Minimum Heat Flux Btu per sq ft per sec	Fire Preburn Time sec
					JP-4 POOL FIRES					
A-1	Protein Foam	83.5	59	85.2	0.042	-	0.0424	No Control	0.68	55
A-2	Protein Foam and CB	78.5	41	115.0	0.039	5	0.0569	No Control	0.89	50
A-3	AFFF	83.5	51	98.2	0.042	-	0.048	45	0.02	58
A-4	AFFF and CB	78.5	49	96.0	0.039	5	0.0476	45	0.02	66
A-5	AFFF and CB	78.5	49	96.0	0.039	5	0.0476	45	0.02	57
				JP-4 TRAPROCK-BASE FIRES						
B-1	Protein Foam	83.5	59	85.2	0.042	-	0.042	Inconclusive	Radiometer out	-
B-2	Protein Foam	83.5	55	90.7	0.042	-	0.045	No Control	0.77	84
B-3	Protein Foam and CB	78.5	43	114.9	0.039	5	0.057	No Control	0.36	59
B-4	AFFF	83.5	51	98.2	0.042	-	0.048	44	0.02	67
B-5	AFFF and CB	78.5	44	107.0	0.039	5	0.053	No Control	0.56	57

These data show that in all experiments, the fire was brought under control within 45 sec and that no increase in efficiency, in terms of the fire control time, was obtained when AFFF and CB were employed in combination over AFFF applied singly. However, it was observed that the visibility through the flames was greatly improved during the first brief discharge of the CB, which provided the firefighter with a view of the terrain over which he would be required to proceed to reach his objective.

Protein Foam, Water-Base Pool-Fire Tests: The results of the evaluation of protein foam, alone and in combination with CB, are presented in Table 9-II under Tests Nos. A-1 and A-2, respectively. The minimum heat flux obtained during the protein foam discharge was 0.68 Btu per sq ft per sec. These results are consistent with the data presented in Table 9-II, where it may be noted that the foam-expansion ratio and 25-percent-drainage time is significantly lower for protein foam and CB in combination than for protein foam alone.

Traprock-Base Fire Tests: The results of fire tests performed on traprock-base fires using the same FSK and agents as employed for the pool fires are presented in Table 9-II, Tests Nos. B-1 through B-5. These data indicate that the traprock-base fires were, in general, more difficult to control than the pool fires. The only successful test in terms of fire control time was B-4 in which AFFF was used alone.

Simulated Pilot Rescue Mission From an F-86 Aircraft Fuselage

Discussion : One test was performed with the completely instrumented F-86 fuselage on the 50.5-ft-diameter traprock-base fire using the FSK with AFFF alone. A plan of the fire test environment and position of the F-86 fuselage is presented in Figure 9-3.

The objective of this test was to determine the time required to establish a fire-free path to the cockpit of the fuselage and total time it could be secured by the FSK without the assistance of the helicopter rotor-wash.

The fuselage was instrumented with 5 radiometers and 10 thermocouples positioned as shown in Figure 9-3.

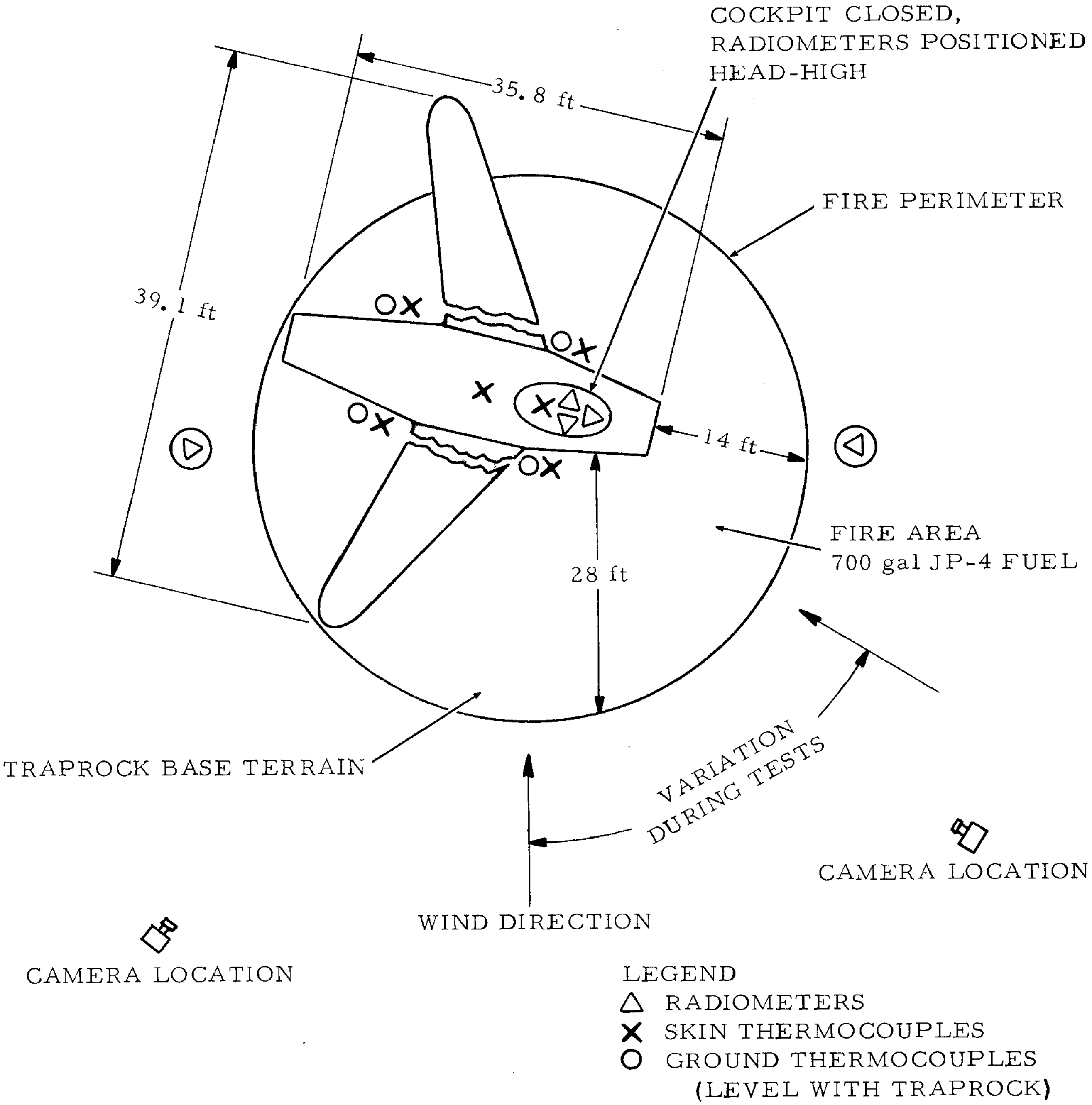


FIGURE 9-3 - FIRE TEST BED USING THE F-86 AIRCRAFT

The heat flux, to which the firefighting team was exposed while securing a rescue path to the cockpit of the F-86 aircraft was monitored by a radiometer and thermocouple mounted on a 4-ft-long pole and carried by a NAFEC technician. This device also measured the radiant energy to which the pilot would be exposed during evacuation from the cockpit and out through the rescue path.

The simulated pilot rescue mission conducted under this phase of the effort was performed by a U.S. Air Force firefighting team which was composed of a foam handline operator and a rescue technician trained in medical first-aid practices.

Results: The instrumentation data obtained during the single test conducted on the fully instrumented F-86 fuselage are presented in Figures 9-4 through 9-9. The thermal energy to which the firefighting team was exposed during the simulated pilot rescue mission is shown by the data profiles presented in Figures 9-4 and 9-5. The pilot rescue time is shown on each curve and was defined as the total elapsed time from the instant foam application was started to that time when the firefighting crew reached the cockpit of the aircraft. From Figure 9-4, in which temperature is plotted as a function of thermal exposure time, it is evident that during the AFFF application the temperature was comparatively low. However, from the curve presented in Figure 9-5, where heat flux is plotted as a function of time, it is evident that the thermal radiation reached a very dangerous level during this same period. A practical estimation of the intensity of thermal radiation may be made by considering the fact that approximately 0.10 Btu per sq ft per sec is delivered by the sun, at sea level, during the summer in the temperate zones and that exposure to 0.2 Btu per sq ft per sec for periods in excess of 30 sec will cause severe pain in humans.

In Figure 9-6, the fuselage skin temperature is plotted as a function of the time after ignition. The data show that all sections of the fuselage skin failed (melted) in less than 40 sec.

The environmental conditions within the cockpit to which the pilot would be exposed during a spill fire of maximum severity are presented in Figures 9-7 and 9-8. From Figure 9-7, in which heat flux is plotted as a function of time after fuel ignition, it will be noted that a dangerous level of radiation developed within 10 to 20 sec after fuel ignition. While from Figure 9-8, it is apparent that the actual air temperature was relatively low during this same period. Therefore, to assure protection from this high-thermal radiation, all portions of the body must be covered.

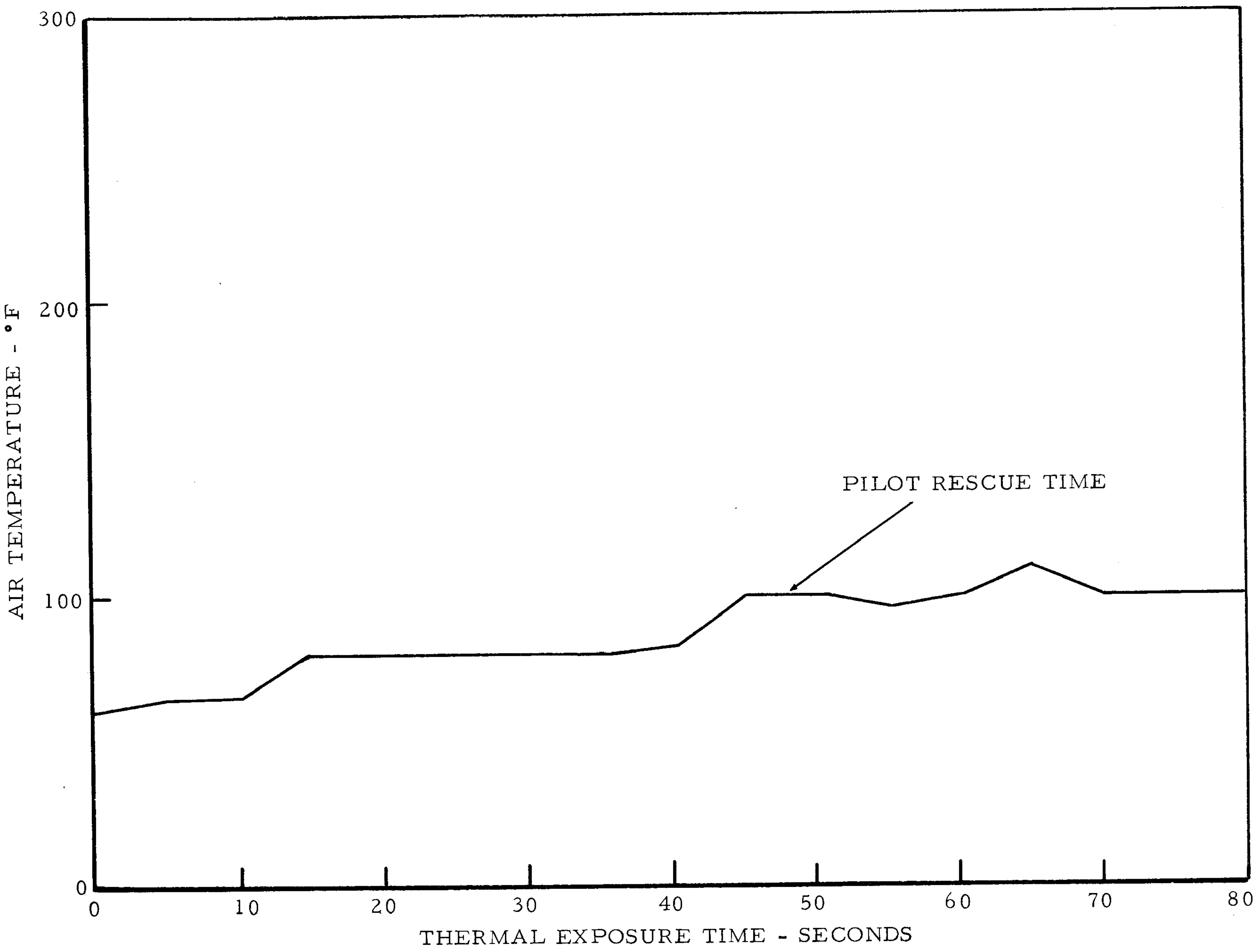


FIGURE 9-4 - AIR TEMPERATURE IN THE RESCUE PATH VS FIRE EXPOSURE TIME DURING AFFF APPLICATION

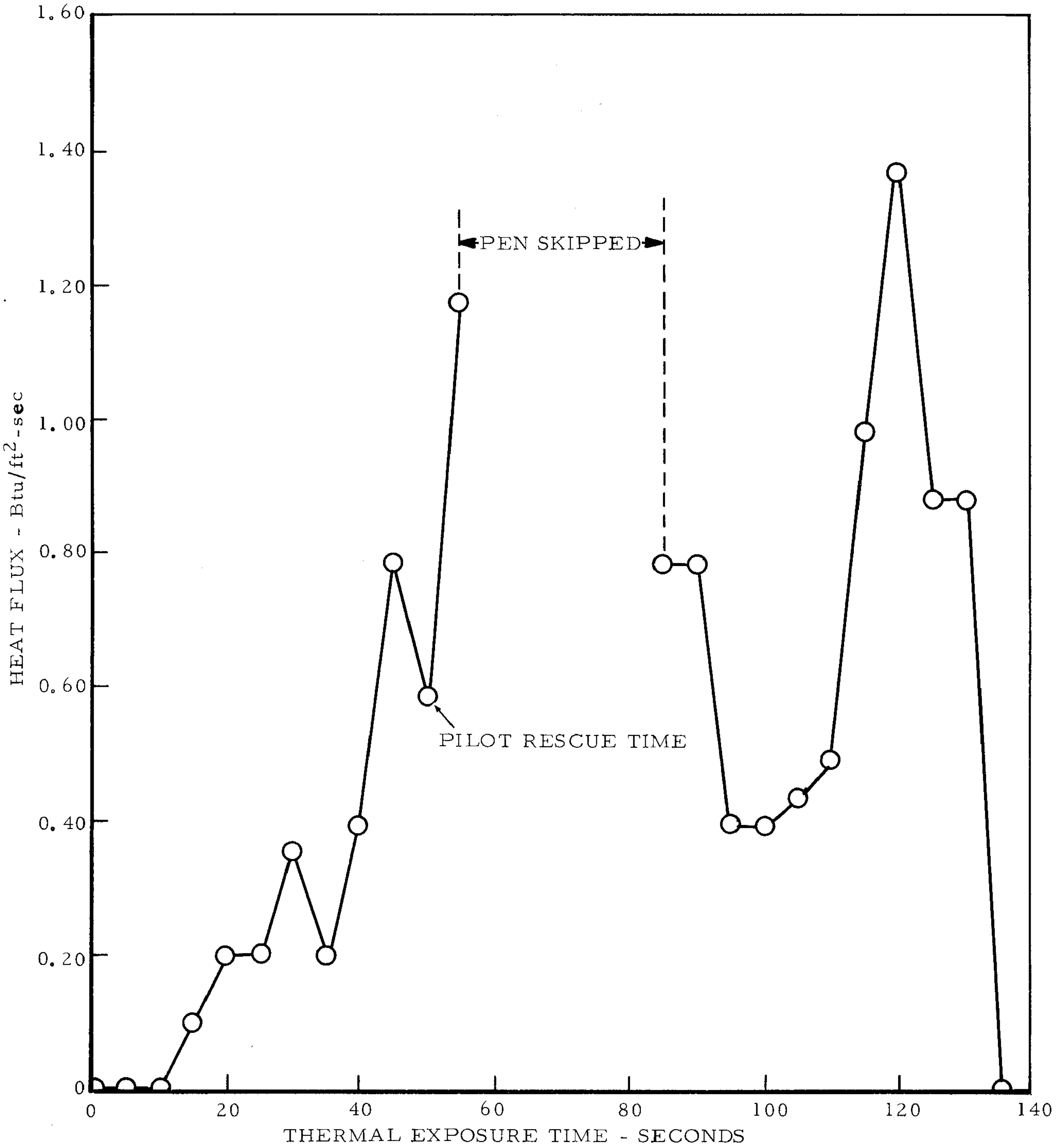


FIGURE 9-5 - RADIANT HEAT FLUX IN THE RESCUE PATH VS FIRE EXPOSURE TIME DURING AFFF APPLICATION

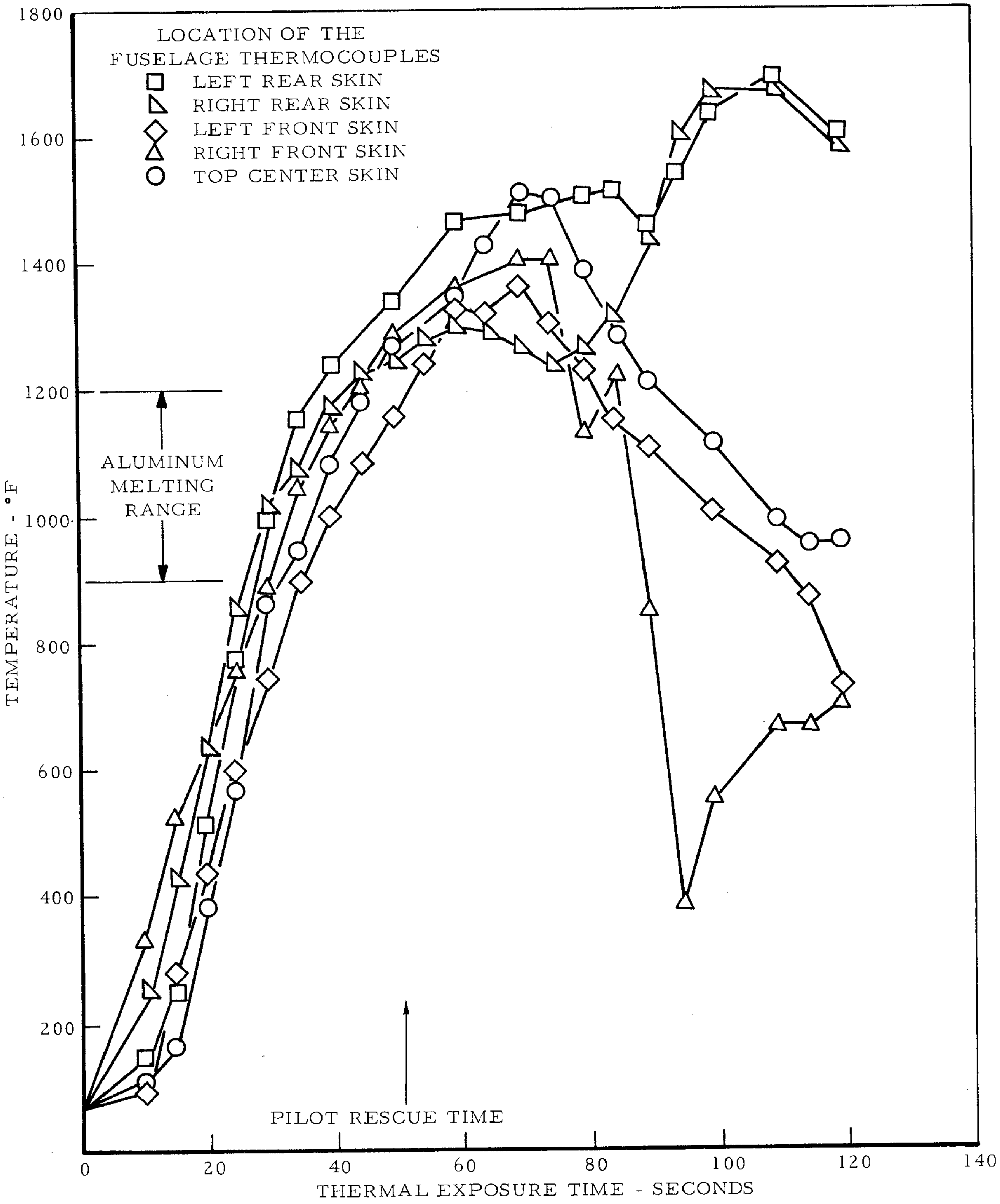


FIGURE 9-6 - FUSELAGE SKIN TEMPERATURE VS EXPOSURE TIME AFTER FUEL IGNITION

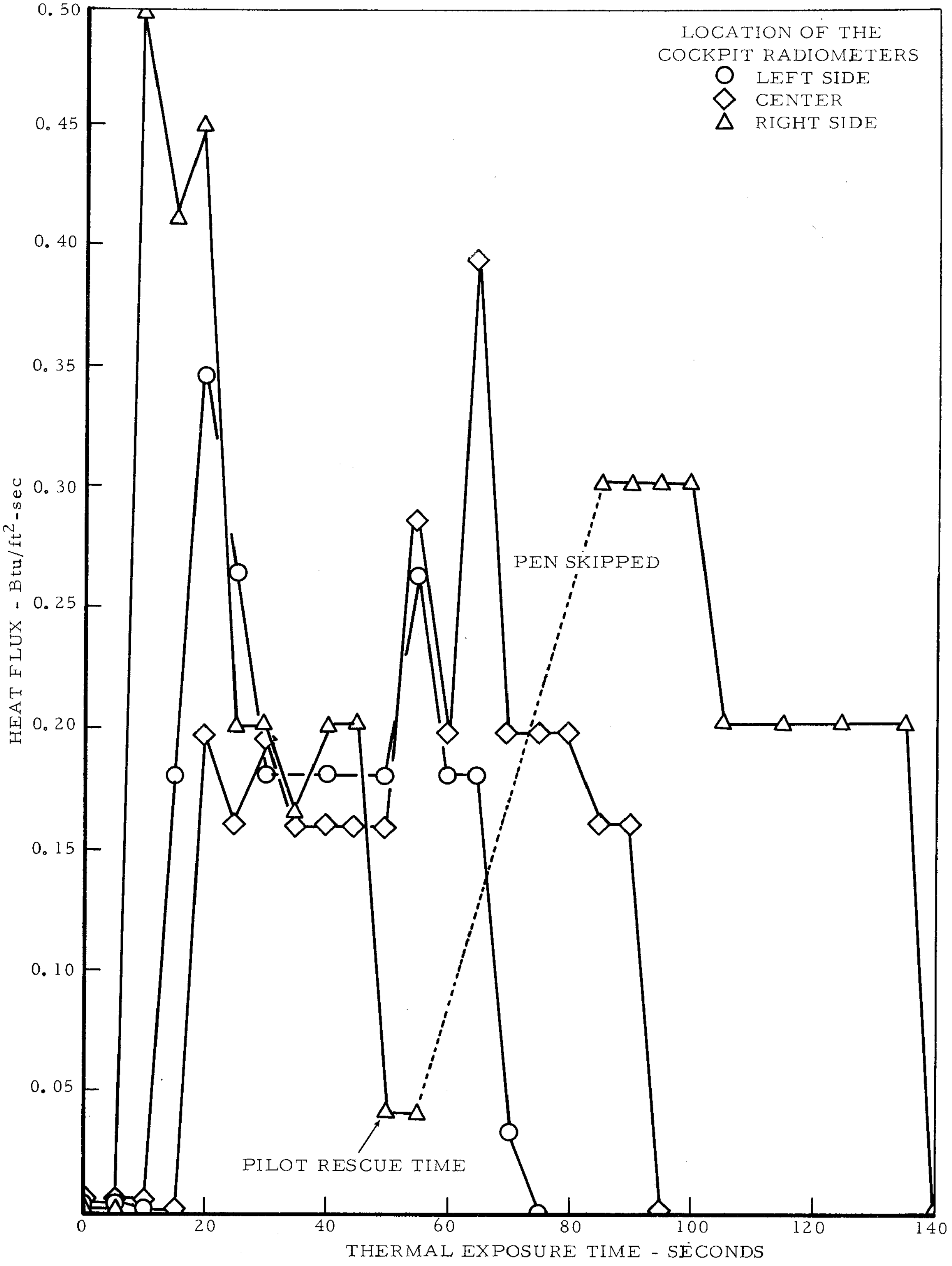


FIGURE 9-7 - RADIANT HEAT FLUX VS EXPOSURE TIME IN THE AIRCRAFT COCKPIT AFTER FUEL IGNITION

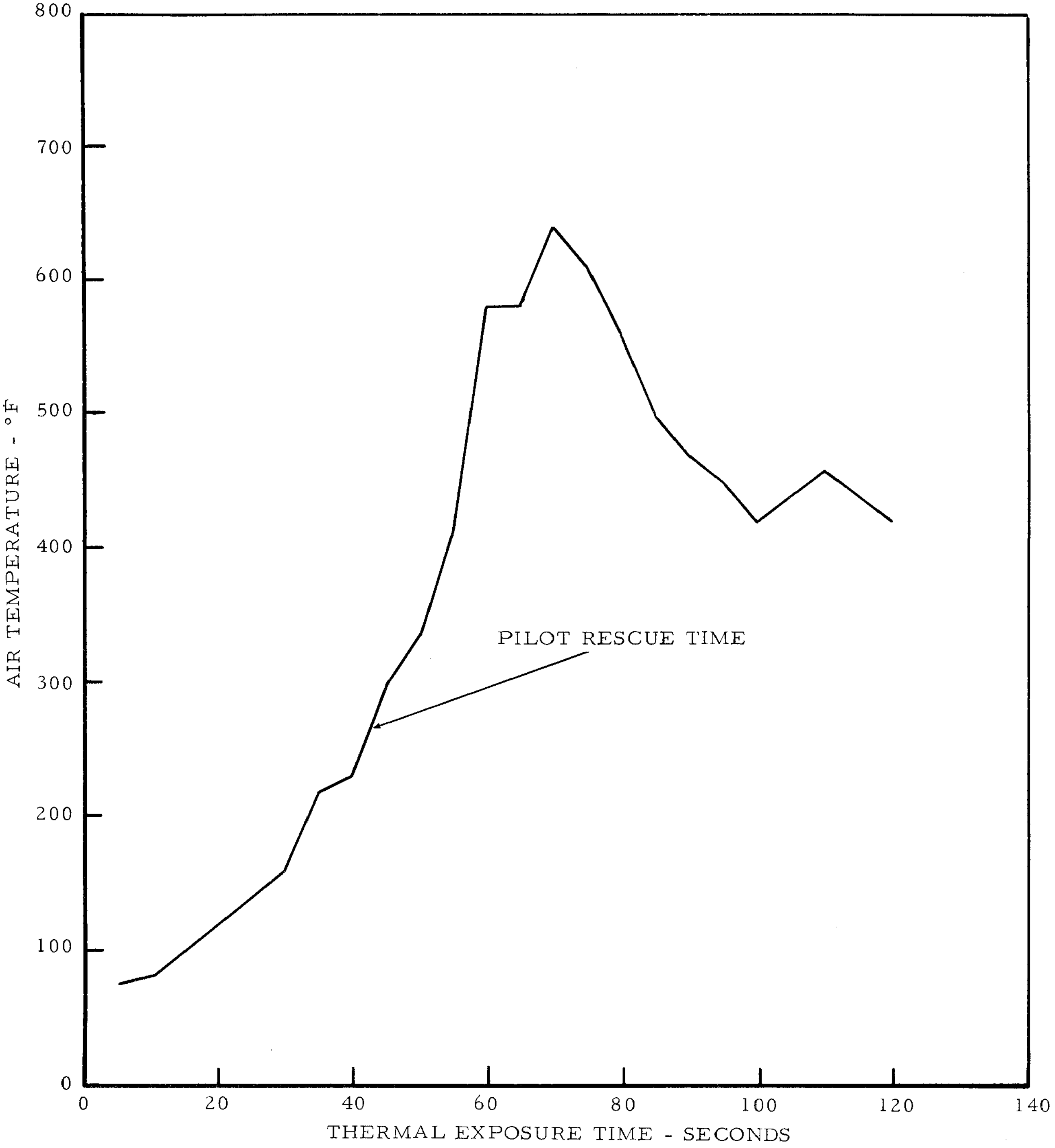


FIGURE 9-8 - AIR TEMPERATURE VS EXPOSURE TIME IN THE AIRCRAFT COCKPIT AFTER FUEL IGNITION

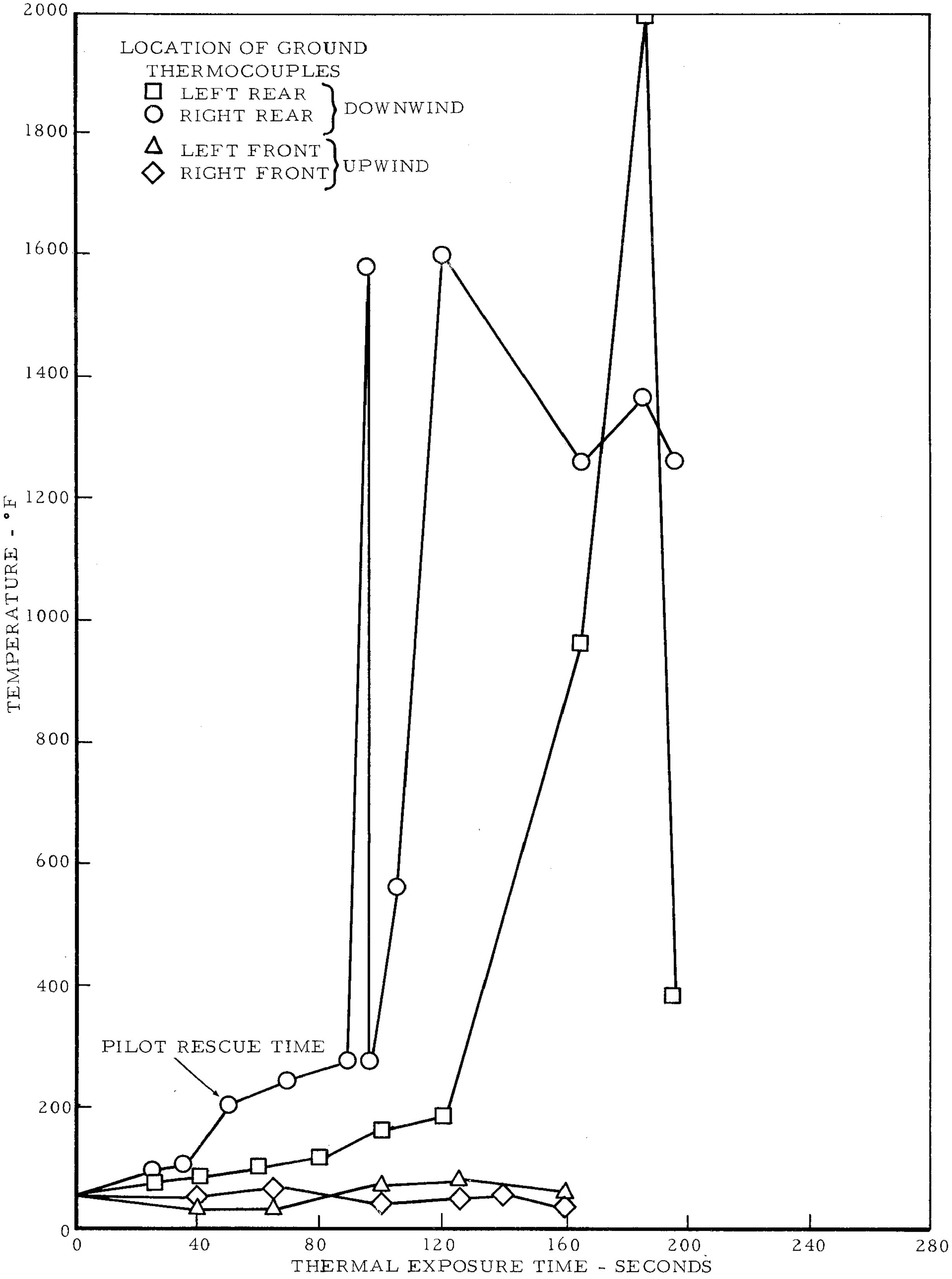


FIGURE 9-9 - TRAPROCK SURFACE TEMPERATURE VS EXPOSURE TIME AFTER FUEL IGNITION

The temperature at the surface of the traprock at various positions around the fuselage are presented in Figure 9-9. The curves show that the rise in temperature was very gradual at all stations during the first 90 sec after full ignition. It is also evident that an effective cooling foam blanket was established upwind in the vicinity of the cockpit where the rescue path was being established, while downwind around the tail section, the temperature rose rapidly, showing the surface effect produced by a fire burning completely out of control.

Effectiveness of the H-43B Helicopter Rotor-Wash in Maintaining a Fire-Free Rescue Path During FSK Discharge

Discussion: This series of tests was conducted using the test bed shown in Figure 9-10. In these experiments the helicopter rotor-wash was employed to control the direction of the fire plume, and to assist in maintaining a fire-free path to the fuselage. The effect of the helicopter rotor-wash on the fire plume is shown in Figure 9-11 for Test D-1. The fire-rescue techniques used by the helicoper pilot and rescue team were in accordance with those presented in Reference 51 of this report.

During the rescue mission, the heat flux and air temperature to which the rescue team was exposed were monitored by a NAFEC technician carrying a radiometer and thermocouple mounted on a short pole and carried approximately head high, as in the previous experiments.

In all of these tactical rescue missions, the foam discharge was made at the discretion of the operator whose objective was to open and maintain a fire rescue path to the cockpit of the fuselage for as long as possible. Therefore, the total time during which the fire rescue path was secured was a measure of the firefighting efficiency of the agent system and the application techniques employed.

All tests conducted under this phase of the effort were performed by the U.S. Air Force firefighting personnel.

Results: The results of the five fire tests are presented in Figures 9-12 through 9-15. In Figure 9-12, the air temperature, which was measured by the portable thermocouple and radiometer monitoring system, is plotted as a function of the

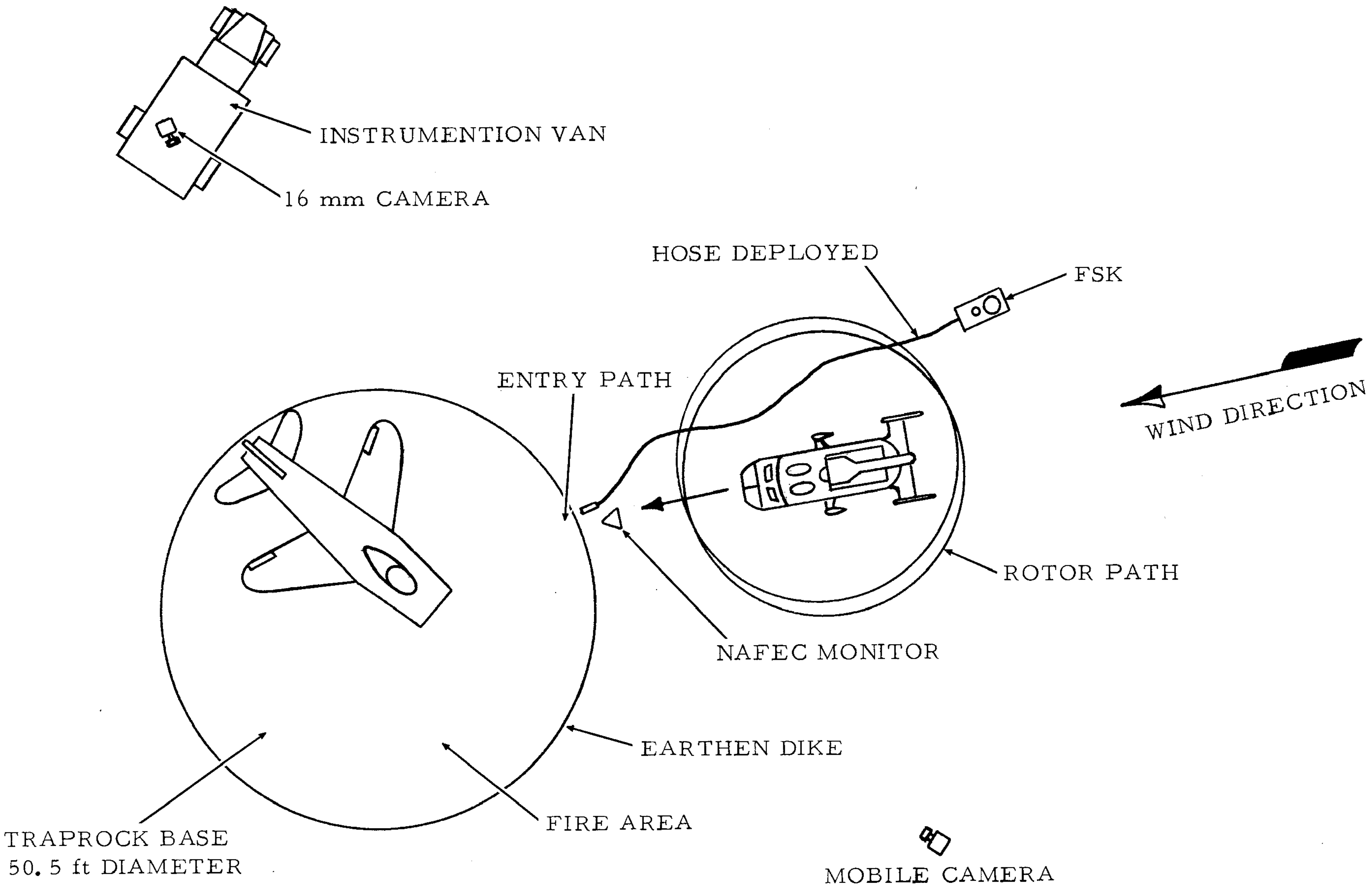


FIGURE 9-10 - FIRE TEST BED SHOWING THE HELICOPTER APPROACH PATH

(a) FIRE CONFIGURATION 1 SECOND BEFORE THE START OF FOAM DISCHARGE

(b) FIRE CONFIGURATION 12 SECONDS AFTER THE START OF FOAM DISCHARGE

FIGURE 9-11 - HELICOPTER ROTOR-WASH USED IN SUPPORT OF THE FSK

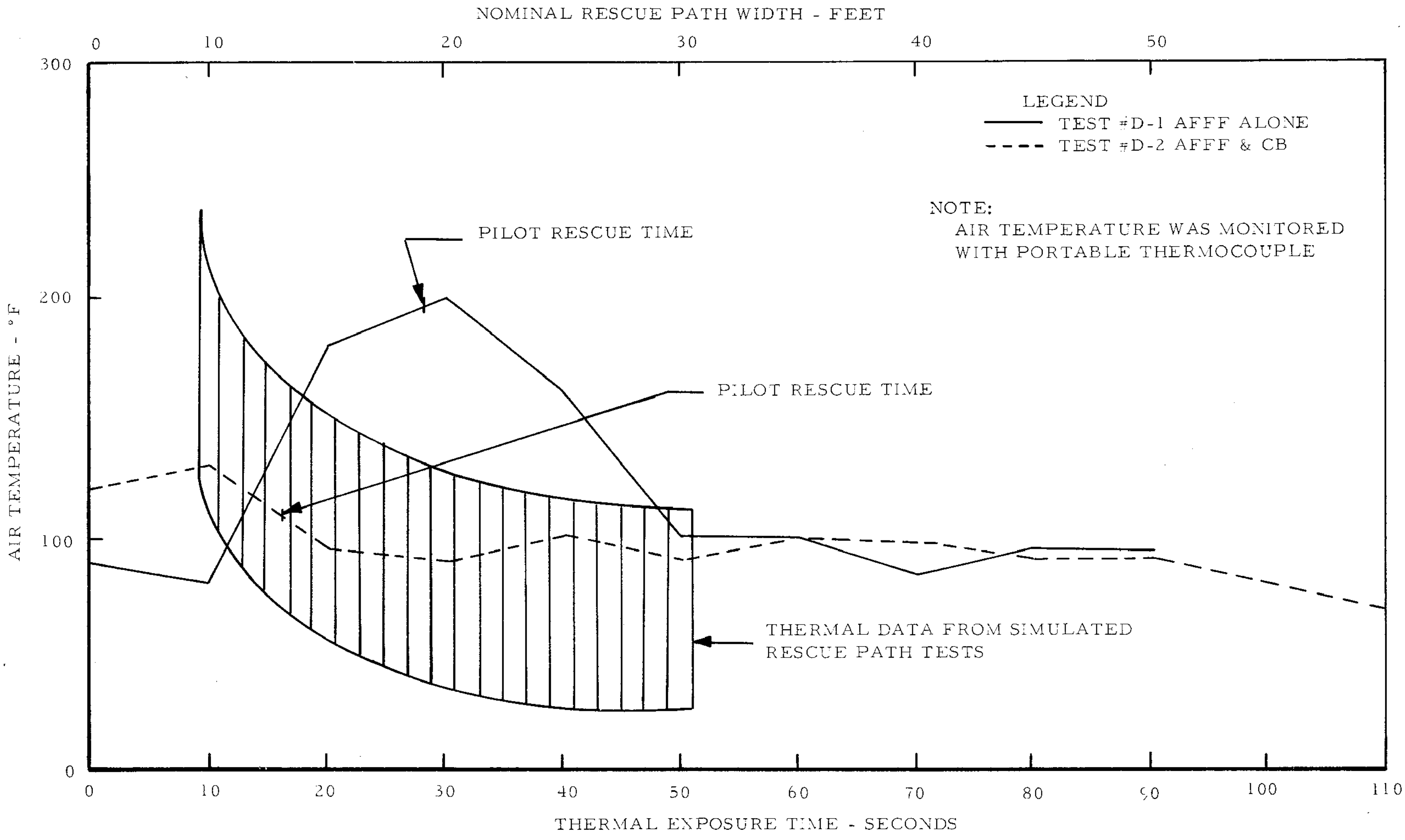


FIGURE 9-12 - AIR TEMPERATURE IN THE RESCUE PATH
VS EXPOSURE TIME DURING THE DISCHARGE OF
AFFF SINGLY AND IN COMBINATION WITH CB

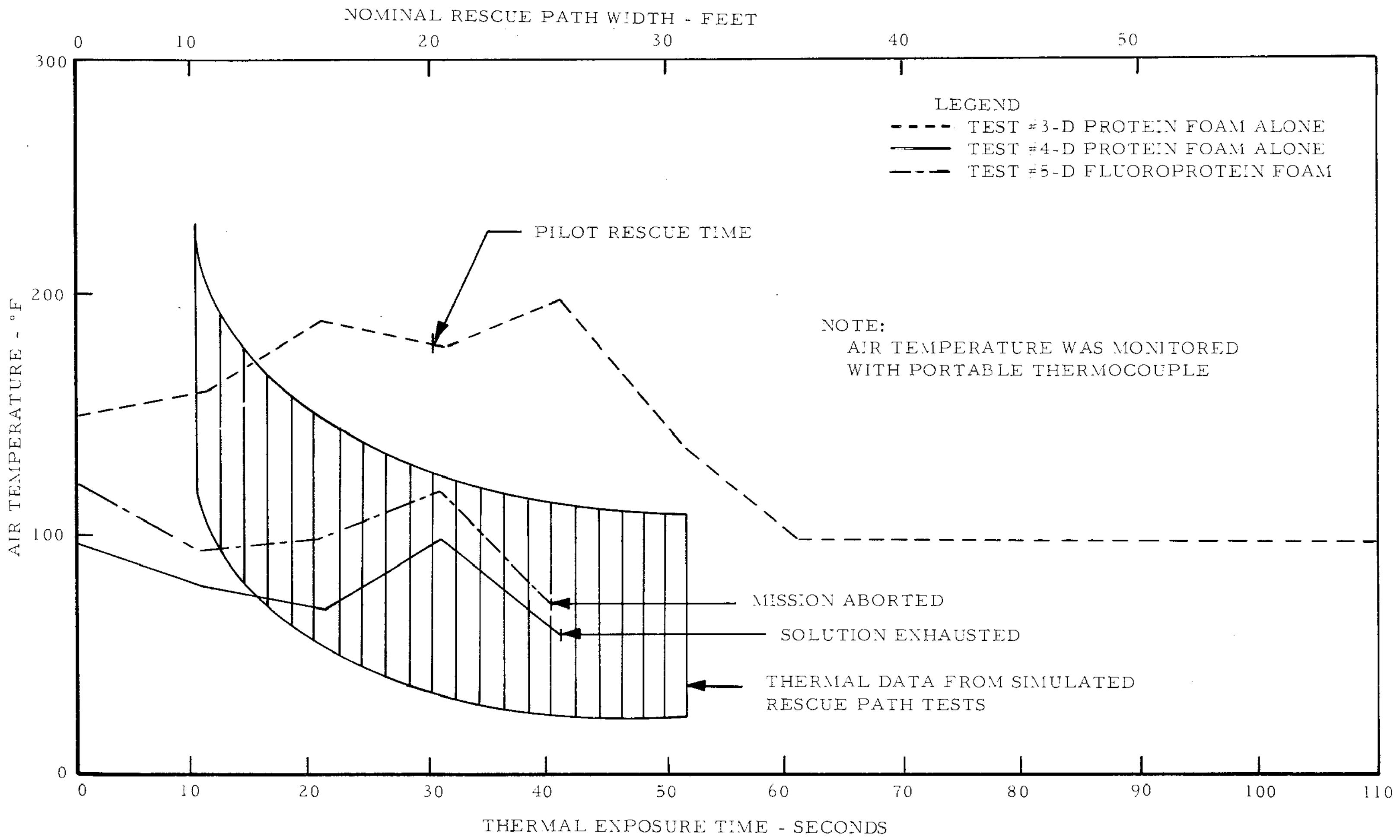


FIGURE 9-13 - AIR TEMPERATURE IN THE RESCUE PATH VS EXPOSURE TIME DURING THE DISCHARGE OF PROTEIN FOAM AND FLUOROPROTEIN FOAM

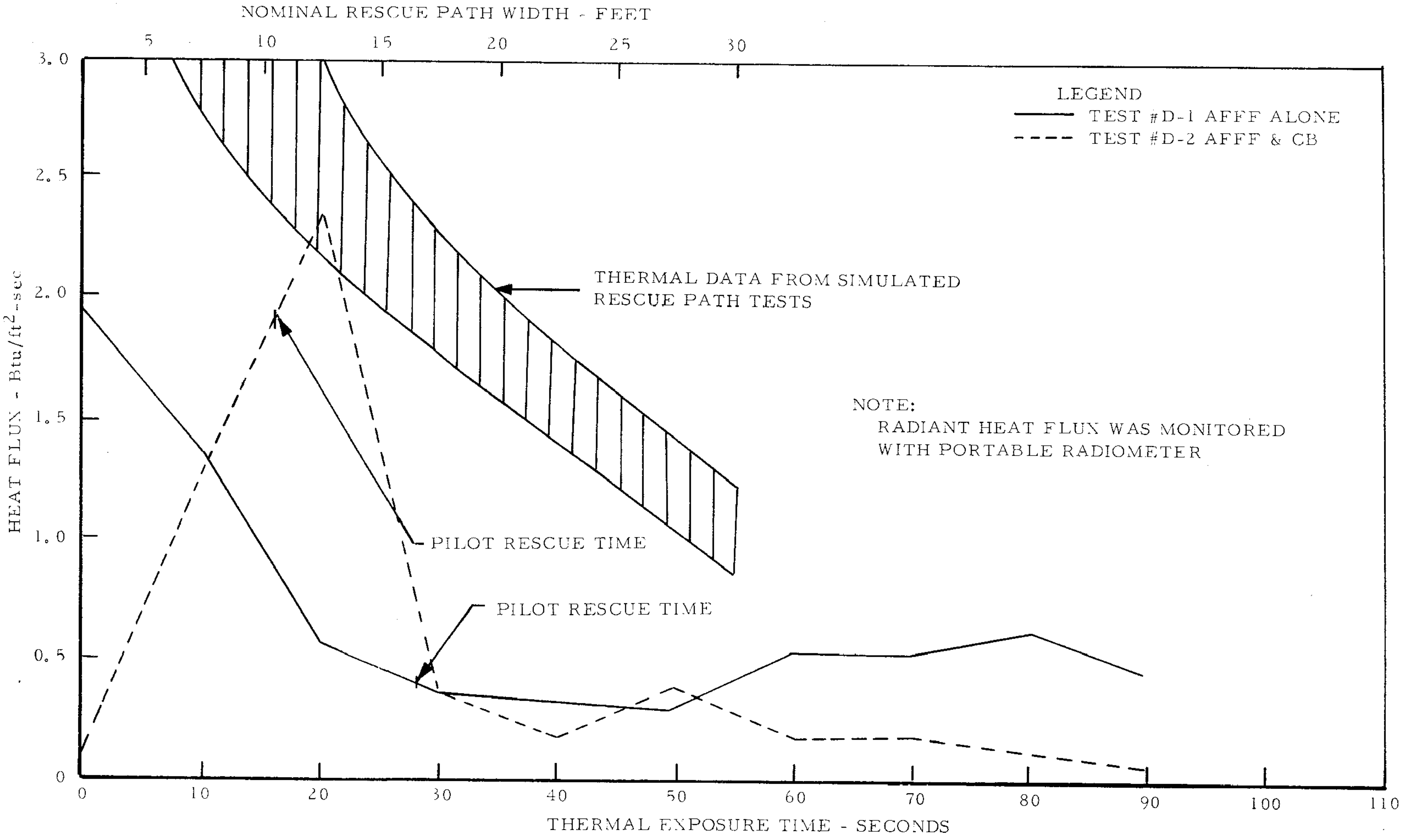


FIGURE 9-14 - RADIANT HEAT FLUX IN THE RESCUE PATH VS EXPOSURE TIME DURING THE DISCHARGE OF AFFF SINGLY AND IN COMBINATION WITH CB

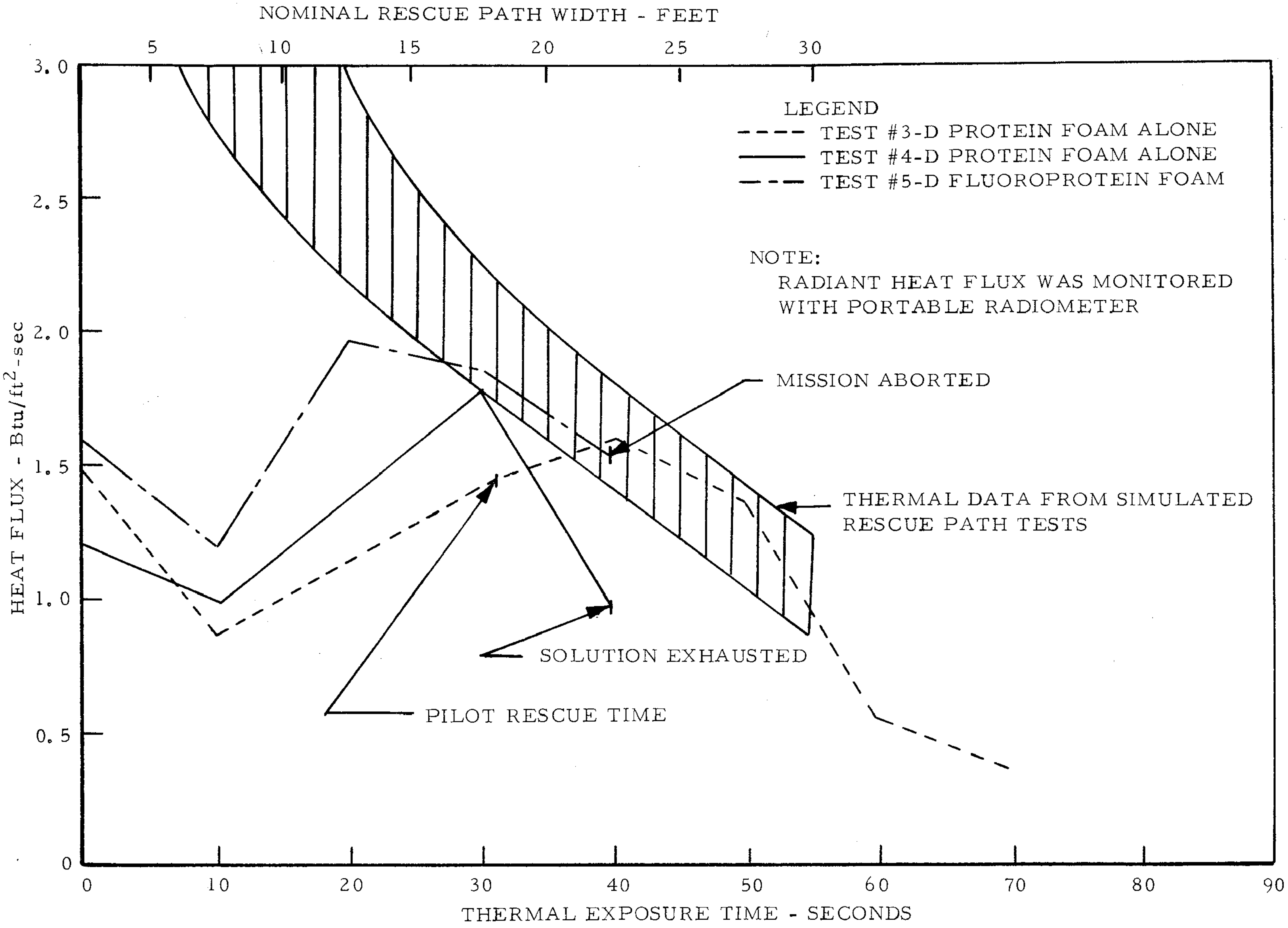


FIGURE 9-15 - RADIANT HEAT FLUX IN THE RESCUE PATH VS EXPOSURE TIME DURING THE DISCHARGE OF PROTEIN FOAM AND FLUOROPROTEIN FOAM time during which the rescue team discharged AFFF alone and in combination with CB from the FSK while proceeding toward the cockpit of the F-86 fuselage. The superimposed envelope (Reference 2 of this report) shows the variation in the environmental air temperature as a function of the rescue path width when assisted by helicopeter rotor-wash. The length of these curves is also a measure of the total time during which the foam solution was discharged after the 60-sec preburn time.

In all of the tactical rescue missions, foam was discharged at the discretion of the nozzle operator and only as required to maintain a fire-free rescue path. Therefore, the total time of foam discharge is a measure of the firefighting efficiency of the agent and technique employed.

The curve shown in Figure 9-12, for Test No. D-2, in which AFFF and CB were discharged in combination from the FSK shows that a consistently lower environmental temperature was maintained over a longer period of time than that obtained when protein foam was discharged either singly or in combination with CB.

The results of two tests employing protein foam, and one test using a fluoroprotein foam are presented graphically in Figure 9-13. The data curve for Test No. D-3, in which protein foam was employed, indicates that the pilot rescue time was approximately 31 sec and the total time, during which the foam was intermittently discharged to maintain a fire-free path, was 70 sec. Tests Nos. D-4 and D-5 were unsuccessful in terms of a completed pilot rescue mission, because the rescue path could not be cleared of fire sufficiently to permit safe progress to the aircraft fuselage.

In Test No. D-4, employing protein foam, the solution was exhausted before a well-defined fire-free rescue path was established, while in Test No. D-5, the mission had to be aborted because of a major flashback caused by the instability of the fluoroprotein foam blanket.

The curves presented in Figures 9-14 and 9-15 show the heat flux as a function of the thermal exposure time for Tests Nos. D-1 through D-5. The superimposed envelope shows the heat flux to which a fire rescue team would be exposed for different widths of rescue paths employing the H-43B helicopter rotor-wash (Reference 2).

An estimation of the overall fire hazard, to which the rescue team was exposed during the simulated rescue mission, may be made from a consideration of the air temperature data presented in Figures 9-12 and 9-13, and the radiation data presented in Figures 9-14 and 9-15 for any particular time during the rescue operation.

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13. ABSTRACT

An analysis of aircraft crash firefighting systems was made through a survey of known and newly developed agents, both blanketing and auxiliary, and of dispensing equipment. Laboratory studies were conducted to ascertain the most acceptable agents and equipment for use in performing full-scale firefighting tests. Experiments were performed principally upon those agents which were manufactured in conformance with a Federal or Military specification or were listed and approved by a recognized testing laboratory. Full advantage was taken to avoid duplication of effort by accepting all published data which was considered reliable by reason of its source. Large-scale fire tests were conducted only with those agents considered worthy of additional testing. Full-scale tactical firefighting experiments were performed with medium size aircraft (B-47 Stratojet Bombers) to determine the effectiveness of each fire fighting agent and the validity of the techniques and agent application rates employed.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Aircraft Ground Crash Fires						
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Fire Extinguishers						
Suppression Equipment						
Suppression of Aircraft Fires						