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Equivalency Evaluation of Firefighting Agents and Minimum Requirements at U.S. Air Force Airfields

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G. GEYER

October 1982

Final Report

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Technical Center
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An evaluation of selected aircraft firefighting agents was made both blanketing and auxiliary and of dispensing equipment. Laboratory studies and outdoor fire tests were conducted to ascertain the fire extinguishing equivalency of the auxiliary agents and to determine the most acceptable agents and equipment for use in performing large-scale firefighting tests.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

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

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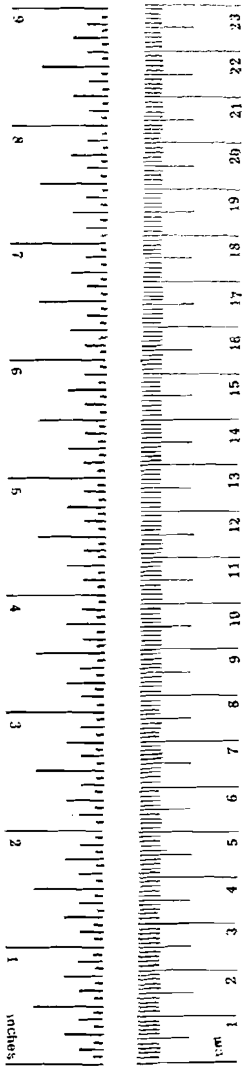
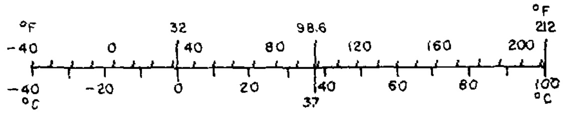
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This report was prepared at the Federal Aviation Administration (FAA) Technical Center by the Fire Safety Branch of the Aircraft Safety Development Division, Atlantic City Airport, New Jersey 08405, under project number 910-003-200 for the Engineering and Services Laboratory, Air Force Engineering and Services Center (AFESC), Tyndall Air Force Base, Florida, 32403 under project order number DTC-9-38.

Mr. Joseph L. Walker was project manager for AFESC.

This report summarizes the work accomplished between January 1979 and March 1982.

The authors wish to express their appreciation to Senior Master Sergeant George E. Laird and members of the 177th Air National Guard Fire Department stationed at the FAA Technical Center, Atlantic City Airport, Atlantic City, N. J., for their excellent cooperation and assistance in performing segments of both the small- and large-scale fire modeling experiments utilizing their equipment. The cooperation of the Delaware Air National Guard at the Greater Wilmington Airport is also gratefully acknowledged for demonstrating the response characteristics of their A/S 32P-2 vehicle under Chief of Fire, Lawrence G. Keller. Appreciation is additionally extended to Ruhl Chemie, Friedrichsdorf, West Germany, for their sustained interest and support in providing a variety of dry chemical powders not available domestically or previously evaluated by either the United States (U.S.) Air Force or the FAA Technical Center.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Services (NTIS). At NTIS it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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EXECUTIVE SUMMARY

This document presents the results of laboratory experiments and large-scale fire test which establish the fire extinguishing equivalency between the dry chemical powders and Halon 1211 as auxiliary agents. The primary firefighting agents comprised the 3- and 6-percent aqueous-film-forming-foams which were (AFFF) evaluated individually and in combination with the auxiliary agents on medium- and large-scale JP-4 fuel fires.

The principal dispensing equipment for the primary firefighting agents was the United States Air Force's A/S 32 P-4 and P-2 vehicles. The equivalency between the auxiliary agents was established mainly from fire tests performed with the United States Air Force's A/S P-13 vehicle.

The experimental results demonstrated the effectiveness of the AFFF agents in controlling and extinguishing large free-burning JP-4 pool fires at the rate of 0.05 gallons per minute per square foot, within sixty and ninety seconds, respectively. The auxiliary agents Purple K powder, or equivalent (Karate Massiv, Mounex) and Halon 1211 were effective in extinguishing specific 3-dimensional JP-4 fuel fires and as mopup agents for the extinguishment of shielded or concealed fires.

Minimum quantities of firefighting agents and dispensing equipment were developed for the protection of small, medium, and large military aircraft at United States Air Force airfields. The 3-percent type AFFF agent is recommended for use because of its logistics advantage in that it requires only one-half of the storage volume and weight of the 6-percent type agent. Purple K powder is recommended as one auxiliary agent along with Halon 1211 for the Air Forces' P-13 vehicle because of its fire extinguishing effectiveness, moderate cost, and availability.

INTRODUCTION

OBJECTIVES.

The project objectives were to establish the firefighting equivalency between dry-chemical powder (DCP) and a liquid vaporizing agent (Halon 1211) both singly and in combination with aqueous film forming foam (AFFF) and to conduct large-scale fire modeling tests using this information to establish minimum requirements at United States (U.S.) Air Force airfields.

BACKGROUND.

Aircraft possess a broad spectrum of potential fire and explosion hazards, but the principal threat is associated with the preponderance of hydrocarbon fuel. However, attention must also be directed toward other potential fire hazards such as lubricating oils, hydraulic fluids, electrical equipment, interior cabin furnishings, flammable metals and a diversity of cargo. Additionally, a rather wide variety of potential ignition sources are also existent such as hot engine surfaces, hot brakes, and electrical and friction sparks. Therefore, to achieve an effective fire protection capability requires a critical assessment of the means whereby these combustible fules and ignition sources can be isolated from one another through aircraft design, and the incorporation of appropriate fire monitoring and suppression techniques to circumvent fires in these high risk situations. However, these factors were not of major concern under this effort, but rather the extinguishment of the aviation fuel fires ignited by these agencies.

Substantial technical data has been developed and reported in the literature (references 1, 2, and 3) concerning the firefighting effectiveness of the individual agents commonly employed at civil and military airports during aircraft incident/accident situations. This information generally does not address the complex interrelationship between the firefighting agents brought to bear on the fire and the minimum requirements to obtain optimum fire control and extinguishing times. Therefore, this study was required to optimize aircraft fire extinguishing systems in terms of the types of agents, total quantities, and discharge rates which are commensurate with the requirement to provide a reasonable degree of protection of life and property.

A preliminary assessment of the firefighting capability of the Aircraft Ground Fire Suppression and Rescue Services (AGFSRS) to achieve these goals would be based upon their possessing adequate equipment and agents to obtain fire control in 60 seconds after arrival at the accident site and extinguishment within 90 seconds.

To accomplish these objectives, a knowledge of the firefighting equivalency between the ancillary agents (dry chemical powder and halocarbon) and the principal agent (foam) is required. Concerned organizations have promulgated advisory and regulatory data which varies significantly as a possible consequence of inadequate supporting evidence concerning the firefighting effectiveness of the available agents and dispensing systems.

Under Federal Aviation Regulations (FAR Part 139.49) concerning the substitution of dry chemical powders, the ratio of 2.8 pounds per gallon of water may be substituted for up to 30 percent of the water specified for protein foam, thereby providing a 1 to 2.98 ratio of powder-to-foam solution on a weight basis.

The chemical agents are categorized as either homogeneous or heterogeneous, depending upon whether they are dispensed as liquids (vapors or gas) or powdered solids. Their principal function upon entering the flame plume is to interact with the free radicals produced during the combustion process, thereby causing flame extinction.

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 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 inhibitors is believed responsible for the high-extinguishing efficiency of these agents. The only homogeneous extinguishing agent evaluated in this effort was bromochlorodifluoromethane (Halon 1211).

The potential heterogeneous flame inhibitors comprise a vast number of powdered salts. Of all the salts available, only those of the alkali metals and ammonia 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 adsorbing surface where the active species can combine, or the salt may pyrolyze to provide the active chain-breaking moieties necessary to inhibit the combustion process. A third method whereby flaming combustion can be inhibited is by reducing the flame temperature through the application of powder or a suitable halocarbon such as carbon tetrafluoride (reference 6). Laboratory experiments have indicated that all chemically inert inorganic powders of suitable particle size and distribution may act as flame inhibitors. However, their effectiveness is of a lower order of magnitude than that obtained with chemically reactive powders. A survey and bibliography of some current theories germane to flame inhibition by chemical means are presented in reference 5.

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, potassium chloride, and potassium sulfate. During this long development period, the performance characteristics of the various dry chemical agents on small fires has been assigned to matched combinations of powders and equipment by the Underwriters' Laboratories Inc. (UL) and others. This procedure has been found necessary since the effectiveness of these units is strongly dependent upon the chemical composition of the powder and its physical characteristics, as well as the nozzle configuration, discharge rate, throw range, internal pressure and the means of pressurization.

Some typical fire performance data developed by several manufacturers for their particular brand of dry chemical powders dispensed from a variety of portable extinguishers are presented in figure 1. These profiles illustrate the relative extinguishing effectiveness of several different powder compositions on standardized UL type fires. In these UL tests, Monnex™ is identified as the most effective agent followed closely by Purple K powder (PKP), while sodium bicarbonate dry chemical is the least effective of the three agents. The new potassium sulfate base dry chemical which was evaluated during this effort is not included among these data since this agent is not currently manufactured in the United States.

TABLE 1. DRY CHEMICAL POWDER MANUFACTURERS AND PRODUCTS

AGENT MANUFACTURER AND PRODUCT	CHEMICAL COMPOSITION
Ruhl-Chemie	
BCE Karate™	Potassium Sulfate
Karate Massiv™	Potassium Sulfate (modified)
BCE-101-K™	Potassium Bicarabonate
ABCDE Troplar™	Monoammonium Phosphate
Total Foerftner	
Totalit Super™	Potassium Sulfate
ICI Americas	
Monnex™	Urea/Potassium Bicarbonate
The Ansul Company	
Purple K Powder	Potassium Bicarbonate
"Regular" Dry Chemical	Sodium Bicarbonate
Pyro Chemicals Inc.	
Super K™	Potassium Chloride

™ - Are known trade names, the others are generic.

TABLE 2. EQUIVALENCY RANKING OF DRY CHEMICAL POWDERS USING AVIATION GASOLINE, JP-4 AND JET A FUELS

GROUP 1

	Threshold Powder Weight (grams)			
	Fuels			
	Av. Gas	JP-4	Jet A	Increase
Monnex (urea potassium bicarbonate)	0.7	0.7	1.9	2.71
Purple K (potassium bicarbonate)	0.7	0.9	2.4	3.00
BCE-101-K (potassium bicarbonate)*	0.8	1.0	2.4	2.66
Karate Massiv (potassium sulfate)*	1.2	1.0	3.7	3.36
Super K (potassium chloride)	1.6	1.4	3.6	2.40
			Average	2.83

GROUP 2

	Av. Gas	JP-4	Jet A	Increase
ABCDE Tropolar (monoammonium phosphate)*	1.7	2.5	3.0	1.43
Totalit Super (potassium sulfate)*	-	2.7	-	-
BCE Karate (potassium sulfate)*	3.6	3.1	5.1	1.52
Regular Dry Chemical (sodium bicarbonate)	5.4	4.5	6.6	1.33
			Average	1.43

*Produced in Federal Republic of Germany

FOAM-POWDER COMPATIBILITY DETERMINATIONS. The firefighting performance of all dry chemical powders may be regarded to be of the "go" or "no-go" type. That is, the fire will be either completely extinguished and the environment allowed to cool below the flashpoint of the fuel, or the fire will reflash. Therefore, their principal use in combatting complex three-dimensional fuel spill fires is as auxiliary or complementary agents in conjunction with one or more of the foam-blanketing agents.

The increasing use of dry chemical powders as auxiliary agents in aircraft accidents requires a knowledge of the compatibility of these agents with different foams. The results of large-scale fire tests performed at the FAA Technical Center (reference 1) with incompatible powder-foam combinations resulted in an almost complete cancellation of the firefighting effectiveness of both agents, and fire control was never obtained. To be successful, the dry chemical powders used in either a combined agent attack or as mop-up agents should demonstrate a reasonable degree of compatibility with the foam.

The compatibility between dry chemical powders and different foams is usually one of degree rather than an absolute value. Therefore, laboratory tests designed to evaluate this property must be correlated with the results obtained using the same agents under simulated full-scale crash fire conditions. The laboratory test outlined in appendix C contains the four parameters existent in all aircraft fire situations in which foam and powder are employed (i.e., fuel, heat, foam, and dry chemical powder). However, not all current laboratory foam powder compatibility tests incorporate these four critical parameters. The purpose of employing the procedure in appendix C, which the materials are intimately mixed and exposed to intense thermal radiation, was an attempt to simulate the most severe conditions which might be realized under actual crash firefighting conditions to avoid the ambiguity sometimes associated with interpreting the results of tests representative of some unknown intermediate degree of fire severity, such as those which omit the effects of heat and/or fuel on compatibility.

The results of experiments performed in accordance with this procedure using a variety of foam and dry chemical agents, indicated that if the time required to collect 25 milliliters (ml) of foam solution was 2.0 minutes 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 in crash-fire situations.

The results obtained using the procedure contained in appendix C and two different AFFF agents with five different dry chemical powders are presented in table 3. These data indicate that all combinations of AFFF and dry chemical powder, when mixed in the presence of JP-4 fuel, meet the minimum solution drainage time requirements established in the test procedure. In general, the presence of fuel in the system tends to produce a slight decrease in the foam solution drainage time, with both FC-206 and FC-203.

The foam solution drainage times developed in table 3 provide adequate laboratory data for assessing the foam blanket stability of each combination of agents under conditions of severe turbulation encountered during a combined agent attack on large free-burning pool fires. These experiments are considered significant in that they serve to confirm and emphasize the fact that the compatibility between powder, foam, and fuel is one of degree and, therefore, worthy of consideration when establishing full-scale firefighting procedures and training techniques. A

However, at all ambient temperatures above -72 degrees F (-57.8 degrees centigrade) a greater percentage of Halon 1211 will exist in the liquid phase than Halon 1301. Halons 2402 and 1011 will normally be in the liquid state when discharged, although they may be rapidly volatilized within the fire environment.

Because of their relatively low boiling points, Halon 1301 and Halon 1211 must be stored in pressure vessels and transferred from one container to another under closed conditions. This fact may tend to cause greater logistic problems where large quantities of these agents are handled than did CB.

FIRE EXTINGUISHING CHARACTERISTICS OF HALON 1211. Halon 1211 is a chemical extinguishant in that it extinguishes fires by interrupting the combustion process by sequestering certain free radicals within the flame plume. The high temperature environment causes partial decomposition of the halocarbon thereby releasing free halogen radicals and other active fragments which react with the active species essential for maintaining flaming combustion. It is particularly effective against flammable liquid fires, and demonstrates some effectiveness in extinguishing most solid combustibles, and is safe for use around electrical equipment. Halon 1211 should never be employed against fires of the alkali metals such as lithium, potassium, sodium or other active metals such as magnesium and titanium.

Surface fires associated with burning solids may be readily extinguished by Halon 1211. However, if burning persists and has become established below the surface of a fibrous or particulate material, extinguishment may be difficult or impossible with a limited amount of agent. Under these conditions, the burning rates may be retarded or the fire actually extinguished if a sufficiently high concentration of halocarbon can be maintained over an adequate cooling period. However, it may not always be practicable to maintain the conditions necessary for extinguishment and the halocarbon could continue to pyrolyze, which might lead to the development of an unacceptable atmosphere within a confined or unventilated compartment. A concentration of 5 percent of Halon 1211 is usually sufficient to extinguish fires involving paper or wood. However, deep seated fires in bulk quantities of paper, wood, wool, crumpled cardboard, crumpled paper, and layered paper which were allowed to burn from 17 seconds to 10 minutes for the various materials could not be extinguished by a 5 percent concentration of Halon 1211 (reference 9).

U.S. AIR FORCE A/S 32P-13 FIREFIGHTING RAMP VEHICLE

VEHICLE DESCRIPTION.

The A/S 32P-13 vehicle is a mobile, completely self-contained firefighting unit with the capability of dispensing dry chemical powder or Halon 1211, either selectively or in combination. However, since each extinguisher system is completely independent of the other, two firefighters are required to dispense the agents simultaneously.

The dry chemical powder unit is mounted on the front portion of the vehicle bed and is comprised of a 350-pound-capacity dry chemical tank, a 250-cubic-foot capacity expellant cylinder(s) (nitrogen or dry air), a pressure reducing valve, flow control valves and piping, two pressure gauges, and 100 feet of expellant hose fitted with a powder nozzle mounted on a reel. The dry chemical (Purple K)

TABLE 4. DISCHARGE RATES OF THE DRY CHEMICAL POWDERS BY THE A/S 32P-13 VEHICLE

Powder Discharge Time (s)	Monnex Powder (lb)	Monnex Discharge Rate (lb/s)	Purple K Powder (lb)	Purple K Discharge Rate (lb/s)	BCE Karate Powder (lb)	BCE Karate Discharge Rate (lb/s)
15	100	6.67	115	7.67	100	6.67
30	100	6.67	130	8.67	135	9.00
45	55	3.67	98	6.53	105	7.00
60	0	0	37	2.47	45	3.00
TOTAL	255		380		385	

Previous experiments (reference 10) conducted with Purple K and Monnex showed that the approximate threshold discharge rate was 6.0 pounds per second for these agents on 35-foot-diameter fires. Therefore, the profiles in figure 3 suggest that the maximum effective discharge time for Monnex and Purple K would be 33.4 and 46.5 seconds respectively and 48.8 seconds for BCE Karate. However, this equipment performance data alone cannot be used as a measure of the fire extinguishing effectiveness of these agents since it does not take cognizance of the very wide variations in their chemical reactivity (i.e., TPW table 2).

The results of subsequent experiments conducted with the A/S 32P-13 vehicle employing Purple K, Monnex and a modified BCE Karate (Karate Massiv) on 33-foot-diameter JP-4 fuel fires corroborated 6.0 pounds per second as the threshold discharge rate for this fire size.

To assess the equivalency between the auxiliary agents and AFFF, it was necessary to reduce the flow rate of the A/S 32P-13 dry powder nozzle in several of the large-scale (855 ft square) fire tests to 3 pounds per second. This was accomplished by machining aluminum sleeves which could be inserted in the barrel of the nozzle, thereby reducing the flow rate of each dry chemical to the required value. The powder nozzle configuration and two sleeves are shown in figure 4.

EFFECTIVE POWDER THROW RANGE. The effective powder throw range of the A/S 32P-13 vehicle was assessed by discharging Purple K, Karate Massiv, and Monnex over the 3-dimensional fire grid shown in figure 5. The objective was to establish the maximum range at which the specific powder density was adequate for flame extinction using each candidate agent. The test bed comprised a ground configuration of 52 1-foot-square fire pans and 32 aerial fire cans suspended at two horizontal levels (16 each per level) 3 and 6 feet above the ground. The powder was discharged from a fixed nozzle located 35.5 feet from the first ground fire pan and positioned 32 inches above and parallel with the ground. The photograph presented in figure 6 shows Purple K and Halon 1211 being discharged simultaneously from the A/S 32P-13 equipment over the fire test bed.

of Halon 1211 may be adequate to extinguish very small Class B fires at distances up to 60 feet under ideal outdoor conditions, but that the maximum effective throw range for the control of large outdoor JP-4 fuel fires is 33 feet or less. Since one of the principal uses for the halon system is in the extinguishment of aircraft engine fires, a maximum effective throw range of approximately 33 feet is considered adequate, based upon two times the engine height of the Lockheed C5A aircraft.

EFFECTIVENESS OF THE SIMULTANEOUS DISCHARGE OF HALON 1211 AND DRY CHEMICAL POWDER. The A/S 32P-13 vehicle is provided with both dry chemical powder and Halon 1211 which are available to combat the same class of fires either individually or in combination. The choice as to which agent should be used on a particular fire, or if a combination would be more effective, rests with the senior firefighter present at the fire site. Adequate guidance material has been developed (appendix E) for the selection and use of each agent individually, but no information has been provided concerning the effectiveness or use of the simultaneous discharge of these agents on Class B fires. Therefore, a series of experiments was performed to determine if the fire extinguishing effectiveness of the simultaneous discharge of dry chemical powders and Halon 1211 was an additive function or if there was any evidence of synergism. This objective was accomplished by discharging Halon 1211 in combination with Purple K powder over the 3-dimensional fire test bed from adjacent nozzles. The results of this test are presented diagrammatically in figure 11 and show that two 1-square-foot ground fire pans and one aerial fire can (3-foot level) were extinguished. However, in contrast, figure 7 shows that Purple K alone extinguished 10 1-square-foot ground fire pans and 6 lower fire cans (3-foot level), while figure 10 shows that Halon 1211 extinguished 2 1-square-foot ground fire pans and 3 lower fire cans. Therefore, it is evident that under these experimental conditions the fire extinguishing effectiveness of the dual agent application was below that obtained using either agent individually.

One interpretation of these anomalous results concerns the relative reactivity of the moieties produced by Halon 1211 during pyrolysis in the fire plume and the free radicals which are responsible for flame propagation. The fire test results suggest that the reactive moieties produced by Halon 1211 are preferentially adsorbed on the surface of the powder particles, thereby, precluding the adsorption of the O, H, and OH radicals which are present in the flame plume and responsible for the continuation of flaming combustion.

Since this phenomenon appeared not to have been previously reported in the literature, additional experiments were conducted to further investigate the interaction between the homogeneous and heterogeneous agents using a different dry chemical powder. In selecting a candidate agent for the experiments, consideration was given to the chemical composition of each dry powder. Since potassium bicarbonate, which is common to both Purple K and Monnex, has basic properties, it would be expected to react more readily with the acidic moieties produced during the pyrolysis of Halon 1211 than either a neutral or acidic salt. Therefore, the neutral salt potassium sulfate (Karate Massiv) was chosen as the experimental powder.

To minimize any untoward physical effects resulting from the relative nozzle positions two configurations were evaluated. In the first experiment (figure 12) the halon nozzle was mounted above the powder nozzle and in the second experiment (figure 13) the relative nozzle positions were reversed. The results of these experiments are summarized in table 6, which also includes data for each agent individually for comparison. The experimental results show that the discharge of Karate Massiv alone provided a longer effective throw range than either nozzle configuration employing Karate Massiv and Halon 1211, simultaneously.

Although the adverse interaction between the homogeneous and heterogeneous agents is evident from these experiments, there is no conclusive evidence as to whether or not the interference is chemical or physical in nature. However, the magnitude of the interaction was less pronounced between the Halon 1211 and Karate Massiv than between Halon 1211 and Purple K powder, which may in part be attributable to variations in their reactivity with the dissociated Halon 1211 moieties, resulting from differences in their basic chemical composition.

EFFECTIVE THROW RANGE OF AQUEROUS-FILM-FORMING-FOAM (AFFF) AND DRY CHEMICAL POWDER. Rapid intervention vechicles (RIV's) specified for use by the crash-fire-rescue services, frequently provide foam and dry chemical powder capabilities. This combination of agents has been determined (reference 10) to be effective against complex aircraft fires involving 2-dimensional Class B fires as well as 3-dimensional flowing fuel fires. Since both powder and foam may be available at any given fire site, there exists the distinct possibility that they may be discharged simultaneously under certain circumstances. Accordingly, tests were conducted to assess the influence of a foam stream upon the integrity of the dry chemical power discharge from the A/S 32P-13 vehicle, in the 3-dimensional mode.

Two experiments were performed in which AFFF (FC-206) was discharged at a solution rate of 25 gallons per minute (3.48 pounds per second) from the Fire Boss™ unit (reference 10) in combination with Purple K (6.7 pounds per second) and Karate Massiv (4.9 pounds per second) from adjacent nozzles positioned as indicated in figures 14 and 15. From figure 14, the adverse effects of the overlapping foam and powder streams are apparent. The Purple K powder, which alone (figure 7) was capable of extinguishing 10 ground pans and 6 aerial cans, was reduced to zero ground pans outside the foam ground pattern and four cans at the 3-foot level. One reason for the reduced effectiveness of the Purple K is attributed to the dilution of the powder concentration in the flame plume through turbulation produced by the foam stream, to a valve below the specific density required for fire extinguishment. By contrast, the overall fire extinguishing effectiveness of the simultaneous discharge of Karate Massiv and AFFF (figure 15) was essentially equivalent to Karate Massiv alone (figure 8) in terms of the number of fire cans and pans extinguished. The reason for the disparity between the performance of Purple K and Karate Massiv is not apparent. However, the differences in the physical characteristics between Karate Massiv and Purple K powder are probably more significant in maintaining the integrity and fire extinguishing effectiveness of the powder stream during the simultaneous discharge with AFFF than is the chemical reactivity (table 2) of the agents. Therefore, these experiments demonstrate the requirement to maintain the integrity of the powder stream either at or above the specific powder density (TPW) required for fire extinguishment in order to obtain the maximum throw range and effectiveness.

EFFECTIVE THROW RANGE OF AFFF AND HALON 1211. Less emphasis has been placed upon the development and use of a "clean" dual agent system employing AFFF and Halon 1211 for extinguishing concurrent engine nacelle and ground fires, than in the development of the various foam and dry chemical powder systems. Notwithstanding, Halon 1211 and AFFF are usually available at aircraft accident sites and it is reasonable to anticipate that they will be discharged simultaneously during an attempt to extinguish complex 3-dimensional (flowing) fuel fires both in and around aircraft engines. Therefore, one test was conducted in which Halon 1211 was

TABLE 7. FIRE EXTINGUISHING EFFECTIVENESS OF HALON 1211 AND DRY CHEMICAL POWDER DISCHARGED SIMULTANEOUSLY

Nozzle Position	Ground Pans Extinguished	Maximum Range ft	Aerial Cans Extinguished (3 ft)	(6ft level)	Total	Maximum Range (ft)
		Discharged Simultaneously				
Halon 1211 (top) Karate Massiv (bottom)	6	62.5	6	3	9	83.5
Karate Massiv (top) Halon 1211 (bottom)	5	48.5	6	0	6	79.0
		Single Agent Discharge				
Karate Massiv	19	83.5	12	6	18	90.0
Halon 1211	12	42.0	3	0	3	60.0

The results of the throw range experiments employing dry chemical powder and Halon 1211 in combination with AFFF indicate that the effectiveness of the auxiliary agents may be adversely affected by the AFFF stream when they are discharged from adjacent nozzles. This interaction is physical, since there is no chemical reaction between AFFF and dry chemical powders (reference 7) or Halon 1211. Therefore, care should be exercised when dispensing AFFF in combination with the auxiliary agents to maintain the integrity of the auxiliary agent stream by avoiding mutual impingement insofar as practicable.

THREE-DIMENSIONAL FIRE EXTINGUISHING TESTS.

INCLINED PLANE EXPERIMENTS. One fire condition common to many aircraft accidents involves the flow of fuel from ruptured fuel tanks over sloping terrain or down an incline. This condition was simulated by constructing a trough of concrete 5 feet wide and 20 feet long with a catch basin at its base 5 feet long and 10 feet wide. The JP-4 fuel was discharged through five holes in a horizontal pipe positioned across the top of the incline as indicated in figure 17. The flow of fuel was variable and fire extinguishing experiments were performed with AFFF, dry chemical powders, and Halon 1211 at fuel (JP-4) flow rates of 6 and 12 gallons per minute.

The objective of the flowing-fuel fire tests was to extinguish the fire as rapidly as possible using the smallest quantity of agent following a 30-second preburn period. The method of attack was to apply the agent from the upwind side of the test bed with a side-to-side swinging motion of the nozzle and as close to the base of the fire as possible. The initial attempts to extinguish this fire at close range, employing the full discharge capacity of the A/S 32P-13 vehicle demonstrated a propensity to blast the burning fuel off the incline and distribute it over a wide area. Subsequent experiments showed that the most effective technique for combating this type of fire required the firefighter to (1) approach from the upwind side, (2) start the discharge from approximately 25 feet from the flame front, and (3) to apply the agent in modified bursts of several seconds each while swinging the nozzle from side-to-side over the fire area. The fire extinguishing times

TABLE 8. FIREFIGHTING EFFECTIVENESS OF THE AUXILIARY AGENTS ON THE INCLINED PLANE FIRE TEST BED USING THE A/S 32P-13 VEHICLE JP-4 FUEL FLOW RATE 12 GAL/MIN

Firefighting Agents	Discharge Pressure (lbf/in^2)	Agent Discharge Rate (lb/s)	Application Area Incline and Catch Basin (ft^2)	Application Density (lb/ft^2)	Agent Discharge Time (S)	Weight Of Agent Used (lb)	Fire Exting. Time (S)
Purple K	235	6.4	150	0.26	6.0	38	6.0
Karate Massiv	235	6.3	150	0.23	5.5	35	5.5
Monnex	235	6.7	150	0.19	4.1	28	4.1
Halon 1211	235	4.9	150	0.34	10.4	51	10.4
JP-4 FUEL FLOW RATE 6 GAL/MIN							
Purple K	235	6.4	150	0.18	4.2	27	4.2
Karate Massiv	235	6.3	150	0.21	5.0	32	5.0
Monnex	235	6.7	150	0.15	3.3	22	3.3

TABLE 9. EFFECT OF POWDER DISCHARGE RATE ON FIRE EXTINGUISHING TIME EMPLOYING THE A/S 32P-13 VEHICLE AND KARATE MASSIV ON THE INCLINED PLANE FIRE TEST BED JP-4 FUEL FLOW RATE 12 GAL/MIN

Firefighting Agents	Discharge Pressure (lbf/in^2)	Agent Discharge Rate (lb/s)	Application Area Incline and Catch Basin (ft^2)	Application Density (lb/ft^2)	Agent Discharge Time (S)	Weight Of Agent Used (lb)	Fire Exting. Time (S)
Karate Massiv	235	9.33	100				
Test 1				0.28	3.5	32.7	3.0
Test 2				0.28	3.3	30.8	3.0
Test 3				0.24	2.6	24.3	2.6
Karate	235	2.20	100	0.33	14.8	32.6	14.0
JP-4 FUEL FLOW RATE 6 GAL/MIN							
Purple K	235	6.4	150	0.18	4.2	27	4.2
Karate Massiv	235	6.3	150	0.21	5.0	32	5.0
Monnex	235	6.7	150	0.15	3.3	22	3.3

TABLE 10. FIREFIGHTING EFFECTIVENESS OF AFFF ON THE INCLINED PLANE FIRE TEST BED JP-4 FUEL FLOW RATE 12 GAL/MIN

Firefighting Agents	Discharge Pressure (lbf/in^2)	Agent Discharge Rate (lb/s)	Application Area (ft^2)	Application Density (lb/ft^2)	Agent Discharge Time (S)	Weight Of Agent Used (lb)	Fire Exting. Time (S)
AFF	235	3.48	150	1.63	70	244	70
JP-FUEL FLOW RATE 6 GAL/MIN							
AFF	235	3.48	150	0.93	40	139	40

TABLE 11. FIREFIGHTING EFFECTIVENESS OF PURPLE K POWDER AND HALON 1211 ON A SIMULATED JET ENGINE FIRE EMPLOYING THE A/S32P-13 VEHICLE

Firefighting Agents	Discharge Pressure (lbf/in^2)	Agent Discharge Rate (lb/s)	Application Area Ground Fuel Catch Pan (ft^2)	Application Density On Fuel Catch Pan (lb/ft^2)	Agent Discharge Time (S)	Weight Of Agent Used (lb)	Fire Exting. Time (S)
Purple K	235	6.4	32	1.8	9	57.6	9
Halon 1211	235	4.9	32	2.9	19	93.1	19

slowly rose until a maximum radiation level was reached and maintained for a minimum of 20 seconds prior to the start of agent discharge. This period of maximum radiation intensity before agent application is defined as the preburn time (in this case, 20 seconds). Fire control 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, was reduced to 0.20 British thermal units (Btu)/ft^2- s. In these experiments, both the fire control and extinguishing times were recorded as major test parameters defining fire performance. However, the fire control time was more consistently reproducible in repetitive tests than the fire extinguishing time.

TESTS PERFORMED WITH THE A/S 32P-13 VEHICLE.

The firefighting effectiveness of the A/S 32P-13 vehicle was assessed by conducting a series of experiments on 33-foot-diameter (855-square-foot) JP-4 pool fires. The experiments were performed by discharging the agent(s) in a continuous stream starting 20 feet from the upwind rim of the fire pit. The application technique required the nozzle to be held approximately 3 feet above ground level and the agent applied over the burning fuel surface using a sweeping side-to-side motion. This technique was adapted to minimize the effects of the high surge in radiant energy on the firefighter, which always accompanies the initial discharge of dry chemical powder on large free-burning pool fires.

The results of fire tests conducted with four dry chemical powders and Halon 1211 and one experiment employing the simultaneous discharge of Purple K and Halon 1211 are summarized in table 12. A comparison of the fire control times achieved by the single agent discharges shows a range from 12.8 seconds for Karate Massiv to 30 seconds for Halon 1211. In these standardized tests, fire control times provide significant comparative data; however, the length of the fire control time may also be important in terms of the final outcome of an actual fire rescue mission, since it could provide the delaying action required for support vehicle response.

In this series of experiments, Purple K was the only dry chemical to extinguish the fire (19.7 seconds); while Karate Massiv provided one of the most rapid knockdown times (8.0 seconds), the shortest fire control time (12.8 seconds), and the longest control time (34.4 seconds) of all agents tested. Halon 1211 and BCE Karate were included in these experiments to provide additional background information (since BCE Karate had the second highest TPW 3.1 grams). It is noteworthy in this regard, that Halon 1211 performed somewhat better than BCE Karate in that it did control the fire within 30 seconds while BCE Karate did not.

The fire test results obtained using the simultaneous discharge of Halon 1211 and Purple K were unexpected in that it required over twice as long to extinguish the fire using the dual discharge as it did for Purple K alone. However, these data corroborate, in effect, the data developed for the combined agent discharge range experiments (table 6).

From the results of these fire extinguishing experiments, it is evident that:

1. Purple K was the only dry-chemical powder tested that extinguished the 855-square-foot JP-4 fuel fire.

2. Karate Massiv provided the longest fire control period of the agents tested.

3. Halon 1211 is less effective than Purple K, Karate Massiv, or Monnex in combating large (33-foot-diameter) JP-4 fuel fires.

4. The simultaneous discharge of Purple K and Halon 1211 from adjacent nozzles drastically reduced the firefighting effectiveness of the A/S 32P-13 vehicle.

FIRE EXTINGUISHING EFFECTIVENESS OF HALON 1211, AND DRY CHEMICAL POWDER IN COMBINATION WITH AFFF.

A second series of experiments was conducted to determine the relative firefighting effectiveness of three dry powders and Halon 1211 when they are discharged in combination with AFFF on the 33-foot-diameter (855-square-foot) JP-4 fuel fire. The agent dispensing equipment comprised the powder and Halon systems on the A/S 32P-13 vehicle and the AFFF system on the twinned-agent-unit (TAU) described in reference 10. An initial frame of reference was established by performing experiments in which the AFFF was discharged on the 855-square-foot JP-4 pool fire at the rates of 25 (0.029 gal/min-ft^2) and 50 (0.058 gal/min-ft^2) gallons per minute, employing standard application techniques. The fire control and extinguishing times obtained are presented in table 13 and show that when the solution rate was doubled the extinguishing time was reduced by 3.2 seconds. This resulted in a saving of 2.66 gallons of AFFF solution over that which would have been anticipated by doubling the discharge rate. When Purple K and Monnex were discharged, in combination with AFFF on an approximately equal basis by weight, the fire extinguishing time approximated that obtained for AFFF at the 50-gallon-per-minute rate. In these experiments the simultaneous discharge of Purple K and AFFF demonstrated an appreciable advantage over the Monnex - AFFF combination.

Because of the wide divergence in the fire control and extinguishing times obtained with the Karate - AFFF combination over those previously obtained, an analysis of the AFFF agent was conducted. From an evaluation of the foam expansion ratio, foam-powder compatibility, and aqueous film spread rate, it was concluded that this agent (from the qualified products list (QPL)) was borderline or below the averages associated with the current AFFF agents. Therefore, the results of this experiment were disregarded.

The results of one experiment, in which Halon 1211 was discharged in combination with AFFF (FC-206) at a combined agent weight of 8.38 pounds per second on 855-square-foot pool fires (table 13), achieved fire control and extinguishment in 10.8 and 19.2 seconds, respectively. This approximates the fire control and extinguishing times of 11.2 and 18.0 seconds, respectively, obtained with FC-206 discharge at 6.96 pounds per second (50 gallons per minute). However, the combined discharged rate of the Halon 1211 and AFFF was 1.42 pounds per second greater than for the AFFF agent alone. Therefore, in these experiments, Halon 1211 was less effective than an equal weight of AFFF in extinguishing the 855 square foot fire.

A comparison of the effectiveness of the combined agent discharge using Purple K and Monnex with FC-206 shows that the fire control and extinguishing times approximate those obtained for AFFF applied singly at 50 gallons per minute. Accordingly, these data indicate that dry chemical powders (table 2, group 1) and AFFF (FC-206) are approximately equivalent on a weight basis, with Purple K demonstrating a somewhat superior performance over Monnex in these experiments.

SUMMARY OF THE TEST DATA.

A review of the test data developed for the three candidate dry chemical powders using four different test procedures is presented in table 14. The ranking factors assigned to each agent under a particular test method have no significance other than to represent the numerical order in which they responded to that particular procedure from 1 (most effective) through 3 (least effective). This subjective assessment of the overall performance of Monnex, Purple K, and Karate Massiv, is based upon numerical ranking from the most to least effective. However, based upon the large-scale pool fire experiments, the ranking order for the three agents from the most to least effective would be Purple K, Karate Massiv, and Monnex. The underlying factors effecting this ranking are the TPW and the effective throw range. Successful fire extinguishment by dry chemical powder requires that the TPW required for extinction be delivered, in quantity, to the most remote boundaries of the fire. Accordingly, Purple K posseses an equal balance of these fundamental requirements. According to table 13, Monnex is indicated as having the lowest TPW and the shortest throw range while Karate Massiv has the highest TPW and the longest throw range. Therefore, Monnex and Karate Massiv each have one vital shortcoming which reduces the overall powder effectiveness.

TABLE 14. DRY CHEMICAL POWDER RANKING ORDER

Test Procedures	Monnex	Purple K	Karate Massiv
TPW	1	2	3
Throw Range	3	2	1
Flowing Fuel Fire (Rate 12 gpm/6 gpm)	1 (1/1)	2 (3/2)	2 (2/3)
Large-Scale Fire Tests	3	1	2
Totals	10	12	13

ESTIMATE OF THE MINIMUM DRY CHEMICAL POWDER REQUIREMENTS OF THE AGFSRS.

The firefighting strategy developed in this effort and in reference 2 requires that 90 percent of a given spill-fire area be brought under control with foam in 60 seconds and extinguished within 90 seconds. This procedure requires reasonable solution discharge rates which can readily be accomplished by current AGFSRS foam vehicles. However, in implementing this procedure, it is evident that during the last 30 seconds (extinguishing phase) of discharge, foam is being applied at excessively high densities which is uneconomical in terms of time and material. This condition may, in part, be overcome by reducing the foam discharge rate which is usually accompanied by a reduction in the throw range. Additionally, the last 10 percent of the fire area may be remote from the dispensing vehicle or "shadowed" by the aircraft or some other obstruction. Accordingly, the most effective means

TABLE 15. ESTIMATED POWDER REQUIREMENTS TO EXTINGUISH 10-PERCENT OF THE PRACTICAL CRITICAL FIRE AREA FOR SMALL, MEDIUM, AND LARGE AIRCRAFT

Aircraft Size	Pratical Critical Area (PCA) ft^2	Powder Area (10% PCA) ft^2	Equivalent PCA Fire Diameter Range-ft	Powder* Application Density lbs/ft^2	Minimum Powder For Extinguishment lbs	Threshold Powder Rate lbs/s
Small						
F-4	2058	205	16.2	0.154	31.7	6.7
C-140	1906	190	15.6	0.154	29.3	6.7
Medium						
VC-137	11514	1151	38.3	0.154	177.3	13.4
C-141	10716	1071	36.9	0.154	164.9	13.4
Large						
C-5	20554	2055	51.2	0.154	316.5	13.4
B-747	18798	1879	48.9	0.154	289.4	13.4

*Based upon Purple K on 33-ft diameter fires hazards associated with the neat Halon 1211 and those resulting from the thermal decomposition of the agent. According to NFPA No. 12B, the maximum concentration of Halon 1211 to which humans may be briefly exposed is a homogeneous mixture of air containing 4 percent (by volume) of the halocarbon. The respiration of this atmosphere for a period of 60 seconds may produce undesirable symptoms such as dizziness, disorientation, nausea, etc., in some individuals. In recognition of this fact the Underwriters' Laboratories Inc. (Standard 1093) limits the use of Halon 1211 to that quantity of agent which will result in a concentration of 2 percent in confined habitable compartments.

However, it is evident that during discharge the localized concentration of Halon 1211 in the immediate vicinity of the fire may exceed 5 to 6 percent by volume, which is generally required to extinguish deep-seated Class A materials fires. However, the neat agent tends to diffuse rapidly as a consequence of its high discharge velocity and the thermal convective currents developed within the fire environment.

During the course of fire extinguishment with Halon 1211 a portion of the neat agent is always pyrolyzed, yielding principally carbon monoxide and the halogen acid gases. The total quantity decomposed is dependent upon its discharge rate (environmental concentration), the fire size, class of combustibles involved, and the residence time of the agent in the flame plume or in contact with surfaces heated in excess of 900° F.

The approximate limiting quantities of Halon 1211 which may be discharged in small, medium, and large aircraft fuselages that will yield a homogeneous concentration of 2 percent by volume are illustrated by the data presented in table 16. However, it is evident that the local discharge of Halon 1211 during fire extinguishment in confined compartments may exceed the UL design limit of 2 percent, thereby, creating a potential serious environmental hazard to those occupants who are unprotected by adequate respiratory equipment. The actual local concentration developed by the halocarbon discharge will vary as a function of the discharge rate and duration of application. Based upon the data in table 16, it is evident that the Halon 1211 capacity of one A/S 32P-13 vehicle (507 pounds) exceeds that required to produce a concentration of 2 percent in large aircraft.

AIRCRAFT GROUND FIRE SUPPRESSION AND RESCUE SERVICES AT U.S. AIR FORCE AIRFIELDS

The objective of the aircraft ground fire suppression and rescue services (AGFSRS) are to protect life and property from the devastating effects of aircraft fuel spill fires. These goals are achieved through the prevention, control, and extinguishment of fires, thereby, providing safe personnel evacuation routes from disabled and/or burning aircraft. Typical aircraft emergencies requiring AGFSRS intervention at airfields range from small fuel-spill fires, which may occur during aircraft servicing and maintenance operations, to the devastating fires associated with major accidents.

Numerous large-scale fire tests existent 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 effects of the intense thermal environment 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 13 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 the total aircraft in a severe accident involving fire, should be based upon the need to maintain fuselage integrity insofar as practicable. In this regard, the distinction which is sometimes made between the ground firefighting requirements of tactical military and civil aircraft is occasionally overemphasized. The military currently operate a number of different transports which are common commercial aircraft with specialized internal configurations. Therefore, the ground firefighting requirements for military and civil aircraft within this category are assumed to be similar.

The essential differences which influence the firefighting techniques employed with military and civil aircraft are those associated with the presence of armament and specialized material, which may be aboard at the time of the accident and the problems associated with the crew's release from their ejection seats or making a forcible 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 forcible entry into the cockpit, if required. The height of the cockpit aboveground 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/crew rescue. Therefore, it is unrealistic to rely primarily on the crash crew to evacuate the aircrew within the time available after their arrival at the accident site. The rescue crew must now depend more heavily on effective firefighting, where previously they might have relied on speed of action to minimize personnel exposure to the fire environment. As a consequence of the extreme vulnerability of the aluminum aircraft skin to fire damage, a rapid response to the accident site by the AGFSRS is required if flame penetration into the aircraft fuselage is to be prevented.

FIRE RESPONSE CHARACTERISTISC OF THREE AGFSRS VEHICLES.

SEGMENTED TIME TRIAL METHODOLOGY. As a consequence of the importance of rapid fire intervention by the crash fire rescue (CFR) services in aircraft accidents, an analysis of the potential response time of three principal firefighting vehicles within the AGFSRS was performed. This information is germane in estimating the adequacy of fire protection, since accident experience has shown that there is a point in time, during major aircraft accidents involving large fuel spill fires, beyond which no amount of equipment was capable of significantly altering the devastating course of events (reference 13).

The vehicle response times were evaluated in accordance with the methodology developed in reference 10, in which a series of segmented time trials was conducted with the A/S 32P-13 and P-4 vehicles on the airport at the FAA Technical Center shown in figure 25. An additional test was performed with the A/S 32P-2 vehicle at the Greater Wilmington Airport by the Delaware Air National Guard.

TABLE 17. ESTIMATED RESPONSE TIME OF THE US AIR FORCE A/S 32P-13 VEHICLE

Start From Station	Speed mi/n	Distance Traveled ft	Time S
Acceleration	0-55	640	15.4
Cruise	55	620	7.8
Deceleration	55-30	122	2.5
90° Turn	30-23	120	3.0
Acceleration	23-55	550	11.0
Cruise	55	140	1.5
Deceleration	55-40	90	2.0
45° Turn	40-20	124	2.8
Acceleration	30-55	510	9.5
Cruise	55	830	10.4
Deceleration	55-0	145	4.0
Totals		3,891	69.9

TABLE 18. ESTIMATED RESPONSE TIME OF THE US AIR FORCE A/S 32P-4 VEHICLE

Start From Station	Speed mi/n	Distance Traveled ft	Time S
Acceleration	0-45	1400	35.0
Cruise	---	---	---
Deceleration	45-30	125	2.0
90° Turn	30-20	120	3.0
Acceleration	20-38	625	19.0
Cruise	---	---	---
Deceleration	None		
45° Turn	38-26	125	3.0
Acceleration	26-45	1000	23.0
Cruise	---	---	---
Deceleration	45-0	665	5.0
Totals		4,060	90.0

to represent the average, maximum, or minimum spill fire size associated with a particular aircraft. The theoretical critical fire area was determined at the FAA Technical Center by experimental means during a project jointly sponsored by the U.S. Air Force and the FAA. During the second meeting of the International Civil Aviation Organizations Rescue and Fire Fighting Panel (RFFP II) in June 1972, one state presented statistical evidence, based upon civil aircraft accident experience worldwide, which indicated that the actual critical fire area was approximately two-thirds of the theoretical critical fire area. This area was subsequently adopted by the ICAO, NFPA, AND FAA for calculating the magnitude of the potential fire hazard associated with various size aircraft. Since the practical critical fire area is based solely upon the melting time of the aluminum skin and the size of the aircraft (fuselage length and width) the concept of a critical fire area is equally adaptable to military and civil aircraft.

The theoretical critical (TC) fire area and practical critical (PC) fire area are determined by means of the following equations:

(1) Theoretical critical fire area (TC):
$TC = L(W+100)$ Where the length of the aircraft is more than 65 feet
$TC = L(W+40)$ Where the length of the aircraft is less than 65 feet
(2) Practical critical fire area (PC):
$PC = 2/3TC$
where:
L = length of the aircraft fuselage (feet)
W = width of the fuselage (feet)

The information presented in table 20 lists the theoretical and practical critical fire areas for selected military aircraft along with their maximum fuel load, fuel density and burning time within the practical critical area and the number of occupants. An assessment of some of these hazards to life and property are indicated in figure 36 in which the number of aircraft occupants is plotted as a function of the fuel-spill density within the practical critical area, along with the fuel burning time. These data assume the instantaneous release of the total fuel load over the practical critical area which could only occur during takeoff. All landing accidents would involve a lower fuel density and a shorter burning period. However, since the melting time of the aluminum aircraft skin may be 1 minute or less, all but the smallest aircraft would be subject to destruction by fire without the rapid intervention of the AGFSRS. From the data presented in figure 36, it is evident that a broad spectrum of hazardous conditions may develop within the U.S. Air Force aircraft inventory. The wide-bodied aircraft such as the B-747, DC-10, and L-1011, with their high occupant densities, large fuselages and high fuel loads, pose a maximum challenge to the capabilities of the AGFSRS. The B-52 is unique among the large aircraft in that it has a low occupant density (7 crew) for its size, the largest fuel spill density and burning time, and in addition it may contain a variety of armament which is subject to detonation within 2.5 to 8 minutes after fire exposure. The fighter aircraft are generally small and characterized by low occupant densities, high fuel capacity, and a variety of armament. The medium size aircraft are characterized by a relatively wide range in occupant density, long fuel burning times (10 to 30 minutes), and the presence of a variety of armament.

From the information presented in table 19 and figure 36, it is apparent that there is no direct relationship between the size of a military aircraft and the number of occupants nor is there any meaningful relationship between the fuselage length and the fuel spill density and burning time as evidenced by the data in figure 37. Therefore, the minimum AGFSRS foam vehicle requirements for any given aircraft set were based upon the one having the largest practical critical fire area, with a minimum fuel burning time of 3 minutes.

The literature contains an abundance of information concerning the potential hazards associated with major aircraft accidents and various means for combating these disasters. In one study, a mathematical model was developed (reference 15) based upon several accident scenarios which predicted the fire control and extinguishing times using different firefighting agents and techniques. Reports are existent in which minimum fire protection requirements were developed for military airfields and civil airports (references 2 and 16) and from practical fire tests such as those presented in references 3 and 17. Based upon these and similar efforts, both regulatory and advisory documentation has been developed and promulgated by various concerned organizations including the FAA (references 18 and 19), National Fire Protection Association (reference 20), and the International Civil Aviation Organization (reference 21), as compliance and/or guidance material for airport operators.

Figure 38 presents graphically the level of fire protection for airports based upon the water requirements to extinguish the practical critical fire area associated with the critical aircraft. These profiles show some disparities in the allocations of extinguishing agents by various agencies throughout the world for equivalent size aircraft. This is particularly true for those airports serving the smaller aircraft. The water allowance to produce AFFF for protecting U.S. Air Force aircraft (TA-010) is also included in figure 38.

The profile (figure 38) identified as "Experimental" shows the water requirement for FAA indexed airports based upon an experimental foam solution application rate of 0.05 gal/min-ft^2 which was adequate for controlling an aviation fuel fire in 60 seconds and extinguishment in 90 seconds.

FULL-SCALE FIRE MODELING EXPERIMENTS

The principal objective of this phase of the effort was to develop baseline information concerning the firefighting effectiveness of AFFF when it is employed in AGFSRS equipment on large (10,028 ft^2 and 20,554 ft^2) JP-4 fuel fires containing an obstacle. Previous experiments conducted with both air-aspirating and nonair-aspirating nozzles of equal capacity on the same fire configuration (reference 7) demonstrated that the nonair-aspirating equipment provided a small but uniform advantage over the air-aspirating equipment in terms of their fire control and extinguishing times (figure 39). Therefore, it was concluded that the data developed during these experiments is valid for both types of equipment.

The literature contains a large quantity of test data concerning the fire control and extinguishing times obtained for different foam agents and dispensing equipment. This information is frequently presented as shown in figure 39. These profiles are useful for comparing the relative fire extinguishing effectiveness of

The overall fire test environment is pictorially and schematically presented in figure 41. An obstacle representing the presence of an aircraft fuselage was positioned in the center of the earthen diked fire pit with its centerline parallel with the prevailing wind direction. An 18-inch-high embankment was constructed along this centerline so as to intersect the circumference of the pit, thereby separating each side from foam encroachment from the other during the fire extinguishing operation. The fire pit was flooded with water of sufficient depth to prevent islands from protruding through the surface of the fuel. Sufficient JP-4 fuel was charged into the fire pit through a system of underground piping from two 5,000-gallon storage tanks to sustain burning for 4 minutes at maximum intensity.

The melting time of an aircraft skin was approximated by exposing 12 of the aluminum panel configurations shown in figure 42 on either side of the vertical steel obstacle 6 feet above the surface of the fuel and at 18-foot intervals. A rough estimate of the quantity and type of auxiliary agents required to extinguish the wheel (tire) and engine fires associated with a C-5 aircraft was simulated using stacks of rubber tires and four engine mockups (figure 43) positioned in the fire pit in the relative positions in which they would appear on the aircraft. The fuel flow rate into each of the four simulated engines was 12 gallons per minute.

In each experiment, the primary objective was to provide protection to the aircraft within the survival time (reference 22) of the aluminum fuselage skin under the conditions established. Therefore, the thermocouple data showing the temperature rise of the aluminum panels 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 British thermal units (Btu)/ft^2 -sec.

This differentiation is necessary, because the objective of the firefighting team is to protect the aircraft from damage by laying a blanket of foam adjacent to the fuselage and extending it outward until the fire is brought under control and extinguished. This may permit the fuel to burn excessively long in front of the radiometer mounts, even though the fuselage is out of immediate danger.

A description of the fire monitoring equipment comprising thermocouples and radiometers is presented in appendix G. Visual assessment of the effectiveness of the foam dispensing systems was obtained from two instrumentation cameras (appendix H) and by one roving documentary cameraman.

EXPERIMENT No. 1 - DETERMINATION OF THE MINIMUM AFFF APPLICATION RATE FOR THE PROTECTION OF LARGE AIRCRAFT.

The first experiment employed a fire area of 20,554 ft (161.77 feet in diameter) which is the practical critical fire area associated with large military aircraft such as the C-5 and E-4A/B-747. The fire test bed and equipment array are presented schematically in figure 44. This experiment was designed to evaluate the fire extinguishing effectiveness of AFFF (FC-206) at two different foam solution application rates simultaneously. The foam dispensing nozzles were the same as those employed on the A/S 32P-4 and A/S 32P-2 vehicles. However, the A/S 32P-2 nozzle was mounted on an experimental fire truck test bed. Foam was discharged on the left side of the aircraft mockup from the A/S 32P-2 nozzle at the rate of 500 malfunction which permitted some of the foam to fall short of the fire pit. The estimated time during which foam was not effectively discharged onto the fire was 11 seconds, which reduces the actual application time to 44 seconds; this is in closer agreement with the calculated value of 39 seconds for obtaining fire control at the higher solution application rate. The photographic analysis of the A/S 32P-4 operation also revealed the possibility that visibility from the cab may have been impaired to some extent, which interfered with the optimum placement of foam on the fuel surface by the operator. From the photographs presented in figure 49 a general comparison may be made concerning the relative visibility of the fire pit provided the nozzle operator from his position within the cab of the A/S 32P-4 truck and by the operator of the special 250-gal/min foam nozzle from the monitor platform.

The photograph in figure 49a presents a view of the 400-gal/min solid stream discharge from the A/S 32P-4 turret nozzle taken from the motion picture film strip after test 2. The picture suggests that considerable skill and practice may be required by the nozzle operator in achieving a continuous and uniform foam blanket over a burning fuel surface employing either the solid or dispersed patterns, from his position below the point of discharge. The 800-gal/min solid foam stream would further tend to decrease the operator's direct view of his objective, while the fully dispersed pattern would be most effective in dispensing large quantities of foam under conditions where long range and precise placement are not required.

The photograph in figure 49b presents a view of the special 250-gal/min nozzle dispensing 3-percent AFFF in a solid stream over the left side of the aircraft mockup at the conclusion of test 2. Foam nozzle operation from the monitor platform provides a clear view of the fire in relation to the foam stream range when the nozzle position is either horizontal or lower. However, as the nozzle is elevated above the horizontal, the perspective of foam range is largely lost and the operator must rely heavily upon his judgement of the stream range based upon experience and training with the equipment.

EXPERIMENT NO. 2 - DETERMINATION OF THE MINIMUM AFFF APPLICATION RATE FOR THE PROTECTION OF MEDIUM AIRCRAFT.

In preparation for the second experiment, the fire pit area was reduced to 10,028 ft^2 which is representative of the practical critical fire area of a medium size aircraft. All other features of the test bed remained the same. The configuration and instrumentation of the mockup is shown schematically in figure 50.

In this experiment, a 6-percent solution of AFFF (FC-206) was discharged from the A/S 32P-4 vehicle at 400 gal/min which provided an application rate of 0.079 $gal/min\text{-}ft^2$ on the right side of the mockup. On the left side, a 3-percent solution of AFFF (FC-203) was dispensed from a previously evaluated (reference 3) nozzle at 250 gal/min thereby providing an application rate of 0.049 $gal/min\text{-}ft^2$.

The simulated 3-dimensional engine fires were attacked with Halon 1211 from the A/S 32P-13 vehicle and the Class A material (tires) fires with dry chemical powder. For purposes of comparison, Halon 1211 was dispensed on the right side of the mockup and Karate Massiv on the left side.

The objective of the second test was to extend the information developed during the first experiment to include a determination of the capability of the 3-percent AFFF

TABLE 22. SUMMARY OF THE LARGE-SCALE FIRE TESTS

	Test 1		Test 2	
	Right	Left	Right	Left
	161 ft/20,554 ft^2		106 ft/10,028 ft^2	
Fire Diameter/Fire Area Solution Rate-gal/min	800	500	400	250
Solution Application Rate - gal/min/ft^2	0.078	0.049	0.079	0.049
Dispensing Equipment	Nozzle P-4	Nozzle P-2	Nozzle P-4	Nozzle (Special)
Foam Agent	AFFF 6%	AFFF 6%	AFFF 6%	AFFF 6%
Fire Preburn Time - S	25	25	40	40
Fire Control Time After Start of Foam - S	Front 54 Rear 55*	Front 39 Rear 55	Front 38 Rear 92*	Front 70 Rear 67
Average Fire Control Time After Foam - S	54.5	47	65	68.5
Fire Control Time After Igntion - S	Front 79 Rear 811*	Front 64 Rear 80	Front 78 Rear 132*	Front 110 Rear 107
Average Fire Control Time After Ignition - S	80	72	105	108.5
Fire Extinguishing Time - S	85*	65*	95*	99*
Fire Damage to Simulated Fuselage Skin (Aluminum Panels)	Moderate	Minor	Severe	Severe

*Estimated from photographic coverage

Figure 56 presents an overview of one phase of the firefighting activities conducted during test 1. The foam streams are shown entering the pit on the right (A/S 32P-4 nozzle) and left (A/S 32P-2 nozzle) sides of the mockup. An analysis of the instrumentation camera coverage indicated that approximately 11 seconds of the total foam discharge from the A/S 32P-4 truck fell short of the fire pit, some evidence of this is visible in figure 56. Two A/S 32P-13 vehicles were also employed (figure 56) to dispense Halon 1211 on the left and Purple K powder on the right side of the aircraft mockup in an attempt to extinguish the simulated jet engine fires. Neither Halon 1211 nor Purple K were capable of extinguishing these complex fires, which was due principally to the excessively long distance (32 feet) these mockups were from the rim of the fire pit. Due to the complexity of the simulated jet engine fires, entrance into the fire pit area by the firefighters was deemed excessively hazardous and therefore abandoned.

In the second experiment (figure 50), 6-percent AFFF (FC-206) was dispensed from the A/S 32P-4 vehicle positioned on the right (upwind) front end of the mockup at 400 gal/min which provided an application rate of 0.079 gal/min-ft^2; while 3-percent AFFF (FC-203) was dispensed on the left (downwind) rear end of the mockup at 250 gal/min providing an application rate of 0.049 gal/min-ft^2.

During test 2, the quartering wind produced more severe environmental conditions than those encountered during test 1. This is evident in figure 57, which shows the flame-torching effects and severe hot-air turbulence that developed on the downwind side of the mockup. This condition severely taxed the firefighting capability of the 3-percent AFFF agent and foam dispensing nozzle. Notwithstanding these adverse environmental conditions, the fire was brought under control in 68.5 seconds which attests favorably to the effectiveness of the 3-percent AFFF agent and dispensing equipment. The fire on the upwind side of the mockup was brought under control within 65 seconds (average) although during 7 seconds of this time the 6-percent AFFF discharge fell short of the fire pit as evidenced in figure 58.

A comparison of the photographs in figure 58 shows that the fire damage to the panels on the upwind (right) side of the aircraft mockup was significantly less than that on the downwind side and that those nearest to the point of foam discharge sustained the least damage.

Figure 57 presents an overview of one phase of the firefighting activities performed during test 2. Foam (FC-206) is shown being discharged from the A/S 32P-4 truck at the right front end of the mockup, while the 3-percent (FC-203) is being discharged at the left rear end from a position behind the fire plume. During this experiment, attempts were made to extinguish the simulated jet engine fires employing two A/S 32P-13 trucks. One vehicle was committed to the right side of the fire pit using Halon 1211 while the second was positioned on the left side employing Karate Massiv dry chemical powder. Neither of these attempts were successful in extinguishing the simulated jet engine fires even though the mockups were positioned only 10 feet from the pool rim. The halocarbon discharge failed due to a significant loss of pressure resulting from a leak in the discharge line, while the dry chemical powder failed due to packing at the nozzle. An inquiry into the incidence of packing in the powder discharge lines of several different systems indicated that this may occur as a consequence of having the lines charged with dry chemical for extended periods of time or of incomplete purging of the system after use. Packing in the lines may occur regardless of the type of powder employed, therefore, care should be exercised in preparing the unit for use to preclude this potential equipment malfunction.

Table 23. AIRFIELD/AIRCRAFT CHARACTERISTICS INTERFACING AGFSRS OPERATIONS

Physical Airfield Characteristics

- Runway Conditions (texture i.e. grooved etc.)
- Runway Cant
- Composition of Shoulders
- Structure of Overrun Areas
- Unsurfaced Areas
- Visual Landing Aids
- Electronic Landing Aids
- Taxiway Adequacy
- Surrounding Terrain (mountains/water etc.)
- Condition of Unsurfaced Areas
- Runway Barriers
- Runway Layout (Effect on AGFSRS Response Time)

Environmental and Climatic Conditions

- Ambient Temperature Profile
- Prevailing Wind Conditions
- Annual Precipitation (rain, ice, snow)
- Overall Visibility (fog etc.)

Operational Characteristics

- Flight Operations
- Flight Activities
  - Training
  - Combat
- Flight Traffic
  - Accident/Incident Statistics
- Ground Operational Activities
  - AGFSRS Fire Prevention Measures
  - AGFSRS Overall Training Level

Aircraft Characteristics

- Aircraft Size and Number
  - Small
  - Medium
  - Large
- Fuel Load
- Aircraft Engine Configuration
  - Size
  - Number
  - Location

Aircraft Occupants

- Crew
- Ambulatory Passengers
- Nonambulatory Occupants

fire-control time occurs under a fixed set of conditions. This has been accomplished using two different 6-per cent type AFFF agents dispensed at rates of 250 and 400 gal/min on JP-4 fuel fires (reference 3). The superimposed envelopes presented in figure 60 define the fire control and extinguishing times for two manufacturers' (A and B) AFFF agents. This data was obtained under standardized fire conditions employing solution application rates from 0.048 to 0.154 gal/min-ft^2.

These data show that manufacturer A's agent is more effective than manufacturer B's agent at the lower solution application rates, which is evidenced by the fact that the A agent becomes asymptotic with the abscissa at approximately 0.13 gal/min/ft^2 while the rate for the B agent is approximately 0.154 gal/min-ft^2. Therefore, based upon experimental data 0.13 gal/min-ft^2 was established as the application rate for AFFF in FAA AC 150/5210-6B. However, since the AFFF agents available from the U.S. Qualified Products List (QPL) varied from 0.13 to 0.154 gal/min-ft^2, the rate of 0.15 gal/min-ft^2 was chosen for calculating the minimum AGFSRS water requirements. Therefore, based upon the demonstrated effectiveness of the AFFF agents and foam dispensing equipment,it is evident that solution application rates in excess of 0.15 gal/min-ft^2 would not theoretically provide an improved firefighting capability for the AGFSRS. One of the more significant advantages inherent in the high-capacity equipment derives from the longer throw range and more effective foam dispersion pattern which can be achieved.

However, the relatively high foam discharge rates and water capacity provided by the current AGFSR vehicles makes it impracticable to provide cost/effective protection for the smaller aircraft. This is evident from table 24, which indicates that for small aircraft group 1, set 2, the application rate over the practical critical fire area using three P-4 vehicles (turrets only) simultaneously would be 0.698 gal/min-ft^2 or an excess of 0.548 gal/min-ft^2 over the experimentally determined rate of 0.15 gal/min-ft^2. If one P-4 vehicle was committed to protecting each side of the fuselage, which is considered the minimum for military aircraft, the solution application rate would be 0.465 gal/min-ft^2 or an excess of 0.315 gal/min-ft^2 over the established rate of 0.15 gal/min-ft^2. A more effective and practicable distribution of AFFF could be achieved by providing a rapid intervention vehicle (RIV) capability at airfields for protecting small and medium size aircraft.

A dual agent RIV with a foam solution capacity of 1,000 gallons having a turret discharge rate of 500 gal/min and 500 pounds of dry chemical powder, would be capable of securing a 3,333-square-foot JP-4 fuel fire within 60 seconds, as well as providing a significant 3-dimensional fire extinguishing capability. Additionally, these vehicles would be capable of achieving a significantly shorter response time to the accident site, which is vital for assuring the safety of crew, occupants, and the aircraft.

The profiles presented in figure 61, show the acceleration and deceleration rates determined for the A/S 32P-13, P-4 and P-2 vehicles and the upgraded acceleration rates proposed by the ICAO and NFPA for future firefighting vehicles. The minimum maximum-speed proposed by the ICAO and NFPA for these second generation vehicles is being increased from 50 mph to 62 and 65 mph, respectively.

The relationship between the current AGFSRS allowance for aircraft fire protection and the minimum firefighting foam equipment requirement based upon the practical critical fire area is summarized in table 24. The table identifies all aircraft as being either small, medium, or large, with these three general categories further subdivided into sets. There are two sets each in the small and medium categories and one in the large. The large aircraft category was formerly comprised of two sets which were subsequently combined to produce an expansion of set 5. The concept of aircraft size in terms of the practical critical fire area is illustrated in figure 62. The information in table 24 is further divided into four groups in which group 1 presents the current allowance for aircraft fire protection, while groups 2 and 3 show the total AFFF solution requirements for small, medium and large aircraft based upon a solution application rate of 0.05 and 0.15 gal/min-ft^2. Group 4 is divided into two subgroups, the first of which presents the projected minimum AGFSRS requirements based upon current U.S.Air Force inventory and one new rapid intervention vehicle (RIV), while the second subgroup shows the optimum equipment mix based solely upon the current equipment inventory.

SUMMARY OF RESULTS

The results obtained from laboratory experiments, large-scale fire tests and full-scale tactical fire modeling experiments, employing dry chemical powders (DCP), Halon 1211 and aqueous-film-forming foam (AFFF) both singly and in selected combinations on JP-4 fuel fires are:

1. Two groups of DCP's were identified by the laboratory equivalency ranking procedure employing JP-4 fuel, namely; those with threshold powder weights (TPW's) of 1.4 grams and below and those with TPW's of 2.5 grams and above.

2. Based upon their low TPW's three DCP's were selected for further testing, i.e., Monnex (TPW 0.7 gram), Purple K (TPW 0.9 gram) and Karate Massiv (TPW 1.0 gram).

3. The average TPW required to extinguish jet A fuel fires employing Monnex, Purple K and Karate Massiv was approximately three times greater than that required for Avgas and JP-4 fuels.

4. When AFFF (FC-203, FC-206) was evaluated for compatibility with Purple K, Karate Massiv and Monnex in accordance with the procedure presented in appendix C the time required to drain 25 ml of AFFF solution exceeded 2 minutes.

5. Of the three DCP's selected for further testing Karate Massiv demonstrated the longer effective discharge time (48.75 seconds) from the A/S 32P-13 vehicle followed closely by Purple K (46.5 seconds), while Monnex had an effective discharge time of 33.0 seconds.

6. The results of the three dimensional throw range experiments demonstrated that Karate Massiv extinguished the largest number of ground fire pans and aerial cans, followed in succession by Monnex and Purple K powder.

7. The simultaneous discharge of Purple K and Halon 1211 from adjacent nozzles employing the A/S 32P-13 vehicle reduced the number of ground fire pans and aerial cans extinguished to a value below that demonstrated by either agent singly.

19. The results obtained by the simultaneous discharge of Halon 1211 and Purple K from the A/S 32P-13 vehicle were unexpected in that it required over twice as long (40.2 seconds) to extinguish the 33-foot-diameter JP-4 fuel fire than it did using Purple K (19.7 seconds) alone.

20. The simultaneous discharge of FC-206/Purple K and FC-206/Monnex at combined rates of 0.0069 and 0.008 pounds per second per square foot respectively (on 33-foot-diameter JP-4 fuel fires) achieved extinguishment in 12.8 and 18.4 seconds respectively. The FC-206/Monnex combination closely approximated the effectiveness of FC-206 alone which extinguished the fire in 18.0 seconds at 0.0082 pounds per second per square foot while the FC-206/ Purple K combination demonstrated a 29-percent reduction in the fire-control time over AFFF alone.

21. The transit times of the A/S 32P-13 and P-4 vehicles calculated by means of the segmented time trail methodology over the measured 3976-foot response route on the Atlantic City/Technical Center Airport was 69.9 and 90.0 seconds, respectively. The accuracy of this test procedure was validated by conducting corresponding demonstration runs over the same course which required a total time of 65 seconds and 90 seconds, respectively.

22. The application of AFFF (3- or 6-percent types) at solution rates from 0.049 to 0.079 gallons per minute per square foot on large (20,554 ft^2) and medium (10,028 ft^2) JP-4 fuel fires employing the air aspirating foam nozzles currently provided on some A/S 32P-4 and A/S 32P-2 AGFSRS vehicles was capable of controlling the fires within 47 to 68.5 seconds and extinguishment within 65 to 99 seconds after the start of foam discharge.

23. The experimental minimum quantities of AFFF solution required to control the practical critical fire area for medium and large aircraft based upon solution application rate of 0.05 gal/min-ft^2 were: medium size Set 3 - 290 gal, Set 4 - 501 gal and large Set 5 - 1028 gal.

24. The estimated minimum practicable quantities of AFFF solution required to control the practical critical fire area for medium and large aircraft based upon a solution application rate of 0.15 gal/min-ft^2 were: medium size Set 3 - 869 gal, Set 4 - 1504 gal and large Set 5 - 3083 gal.

25. The maximum temperature and heat flux recorded on the left and right side of the aircraft mockup during test 1 were: 1120° F/5 Btu/ft^2 -sec and 1280° F/1.4 Btu/ft^2 -sec, respectively.

26. The maximum temperature and heat flux recorded on the left and right side of the aircraft mockup during test 2 were: 1900° F/11 Btu/ft^2 -sec and 2000° F/2.2 Btu/ft^2 -sec, respectively.

27. The average fire control times obtained for test 1 on the left (AFFF rate 0.049 gal/min-ft^2) and right (AFFF rate 0.078 gal/min-ft^2) side of the aircraft mockup were 47 and 54.5 seconds respectively (average 50.75 seconds).

28. The average fire control times obtained for test 2 on the left (AFFF rate 0.049 gal/min-ft^2) and right (AFFF rate 0.078 gal/min-ft^2) side of the aircraft mockup were 68.5 and 65 seconds respectively (average 66.75 seconds).

10. Of the three dry chemical powders (Purple K, Karate Massiv, Monnex) selected for evaluation in the A/S 32P-13 vehicle, only Purple K extinguished the 33-foot-diameter JP-4 fuel fire. Under equivalent experimental conditions Karate Massiv provided a longer fire control time than Monnex.

11. A rationale was developed which establishes the minimum quantity of dry chemical powder for the protection of small, medium and large military aircraft as that required to extinguish an area of fuel surface equivalent to 10 percent of the practical critical fire area for each aircraft set.

12. Based upon the recommended maximum human exposure level of 2 percent for Halon 1211 at 120 degrees Fahrenheit (UL Standard 1093) in confined areas (not vented) the estimated maximum quantity of agent required for small, medium and large military aircraft fuselages is approximately 30, 170 and 300 pounds respectively.

13. No synergism was demonstrated between the homogeneous and heterogeneous fire extinguishing agents when they were discharged simultaneously on large JP-4 fuel fires from the A/S 32P-13 vehicle.

14. The simultaneous discharge of Purple K and AFFF (FC-206) on 33-foot-diameter JP-4 fuel fires was effective in reducing the fire control time by 29 percent over foam alone, while the combined discharge of Monnex and AFFF was essentially equivalent to that for foam alone.

15. The transit time of AGFSRS vehicles over the operational portions of an airfield may be satisfactorily estimated by employing the segmented time trial methodology.

16. The approximate minimum AFFF (FC-203; FC-206) solution application rate for obtaining fire control and extinguishment of large (10,028 to 20,554-ft^2) JP-4 fuel fires within 60 and 90 seconds respectively, employing air aspirating foam nozzles lies between 0.045 and 0.055 gal/min-ft^2.

17. The estimated minimum practicable AFFF (FC-203; FC-206) solution application rate for protecting small, medium, and large military aircraft from fire damage is 0.15 gal/min-ft^2.

18. The most severe thermal insult develops on the downwind side of an aircraft fuselage when it is exposed under uniform free-burning pool fire conditions.

19. The achieving of fire control of the paractical critical fire area associated with an aircraft in 60 seconds and extinguishment within 90 seconds is a realistic goal for the AGFSR services.

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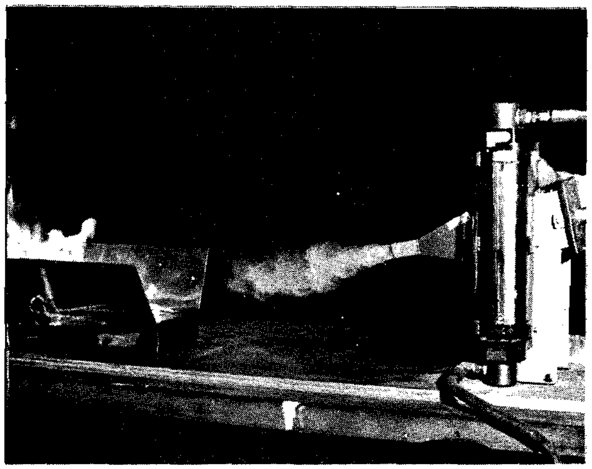
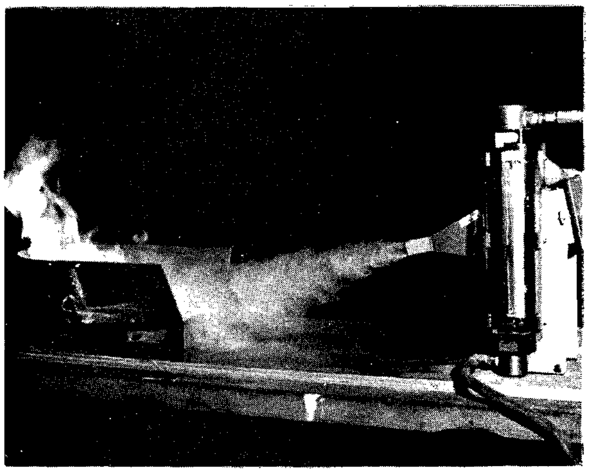
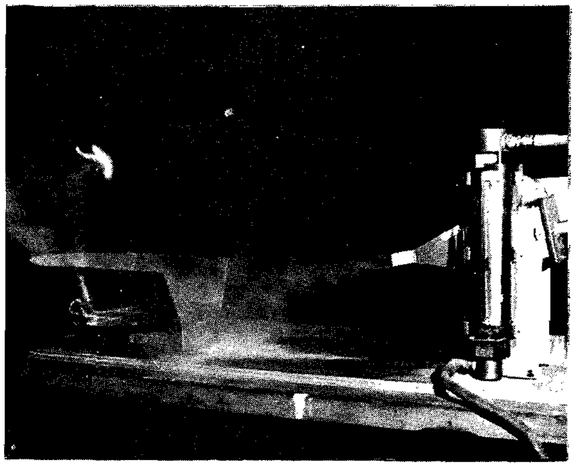


2a Initial Powder Discharge



2b Partial Flame Extinguishment

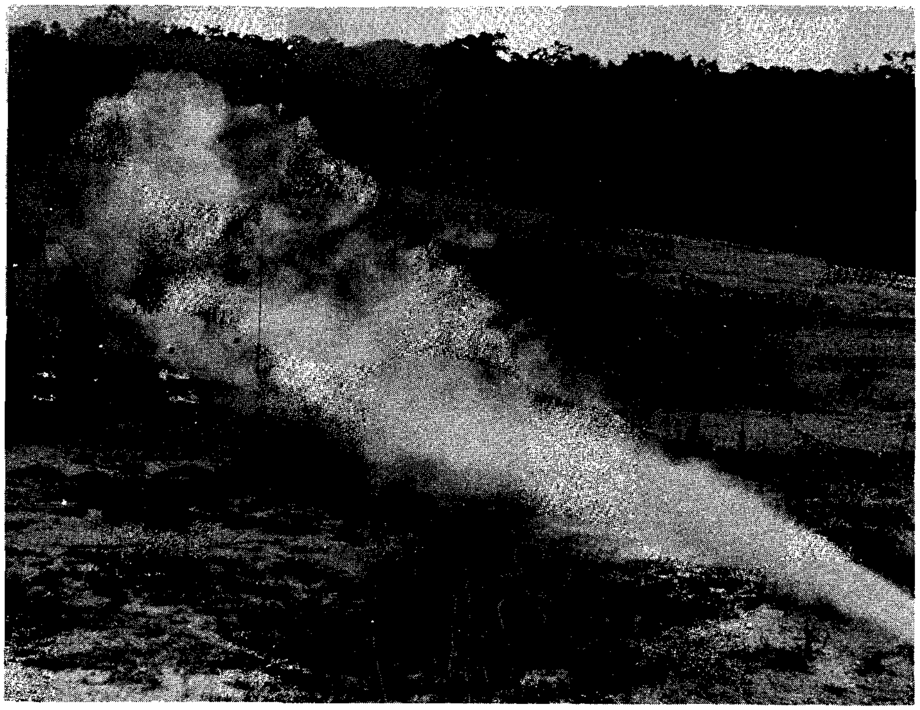


2c Final Flame Extinguishment

FIGURE 2. LABORATORY DRY CHEMICAL POWDER TEST SHOWING THE PROGRESS OF FIRE EXTINGUISHMENT

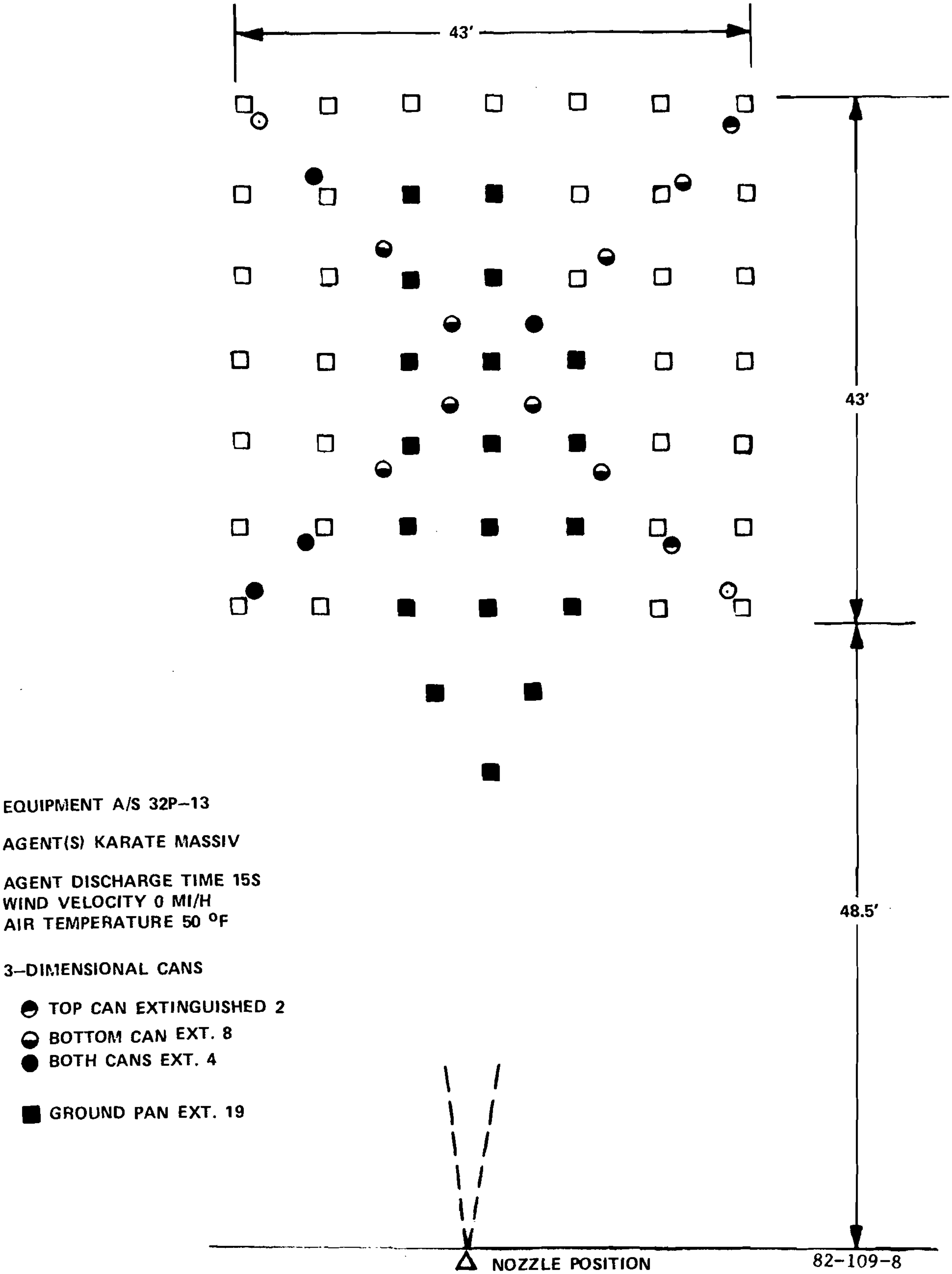
FIGURE 4. U.S. AIR FORCE A/S 32P-13 DRY CHEMICAL POWDER NOZZLE SHOWING THE SLEEVE INSERTS

(a) Initial Discharge of Agents Showing the Compact Streams



(b) Five Seconds After Discharge Showing the Dispersion of the Agents Over the Grid Area

FIGURE 6. SIMULTANEOUS DISCHARGE OF PURPLE K POWDER AND HALON 1211 OVER THE THREE-DIMENSIONAL FIRE TEST GRID



EQUIPMENT A/S 32P–13

AGENT(S) KARATE MASSIV

AGENT DISCHARGE TIME 15S
WIND VELOCITY 0 MI/H
AIR TEMPERATURE 50 °F

3–DIMENSIONAL CANS

- ◓ TOP CAN EXTINGUISHED 2
- ◒ BOTTOM CAN EXT. 8
- ● BOTH CANS EXT. 4

- ■ GROUND PAN EXT. 19

FIGURE 8. EFFECTIVE THROW RANGE OF KARATE MASSIV DRY POWDER

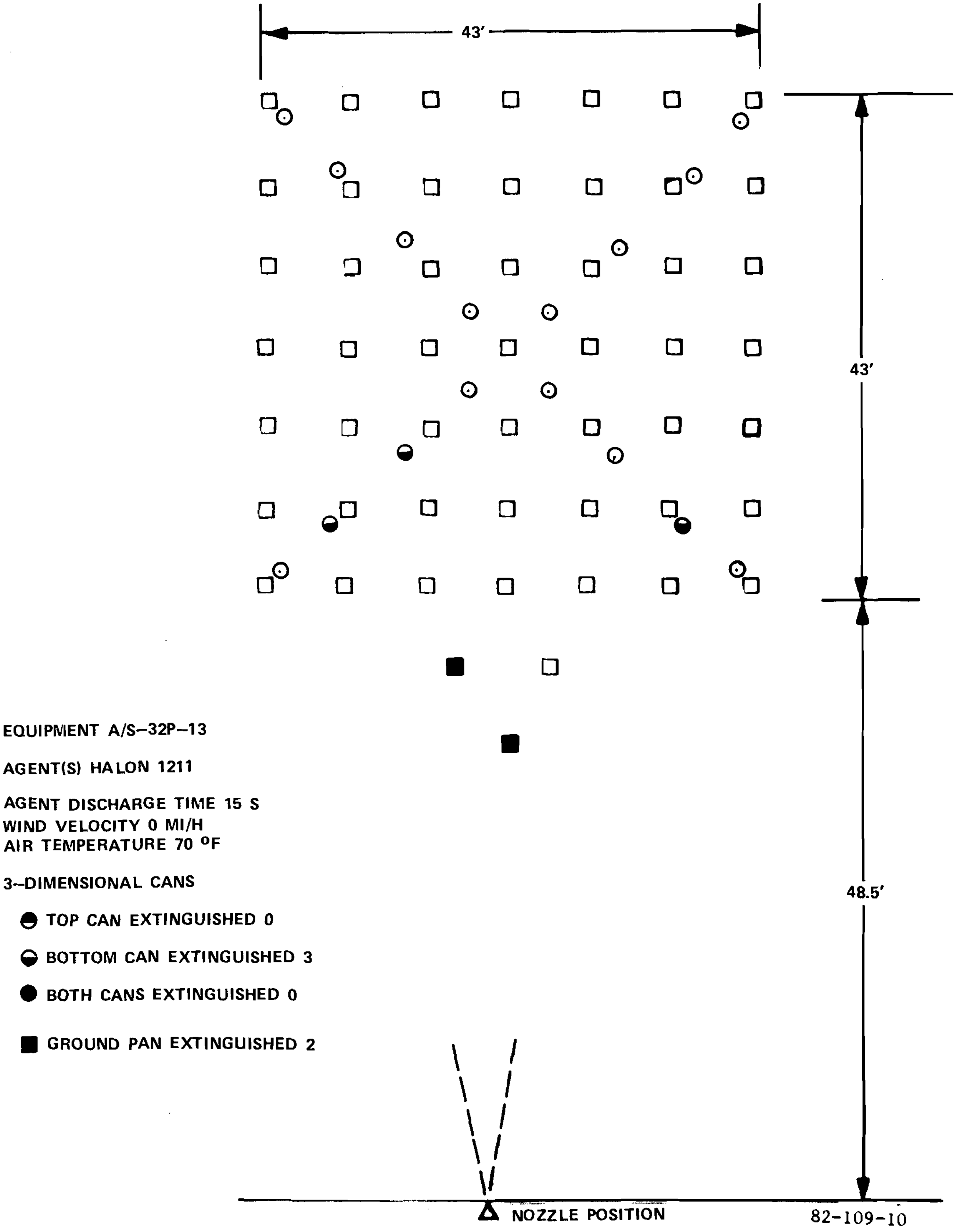


FIGURE 10. EFFECTIVE THROW RANGE OF HALON 1211

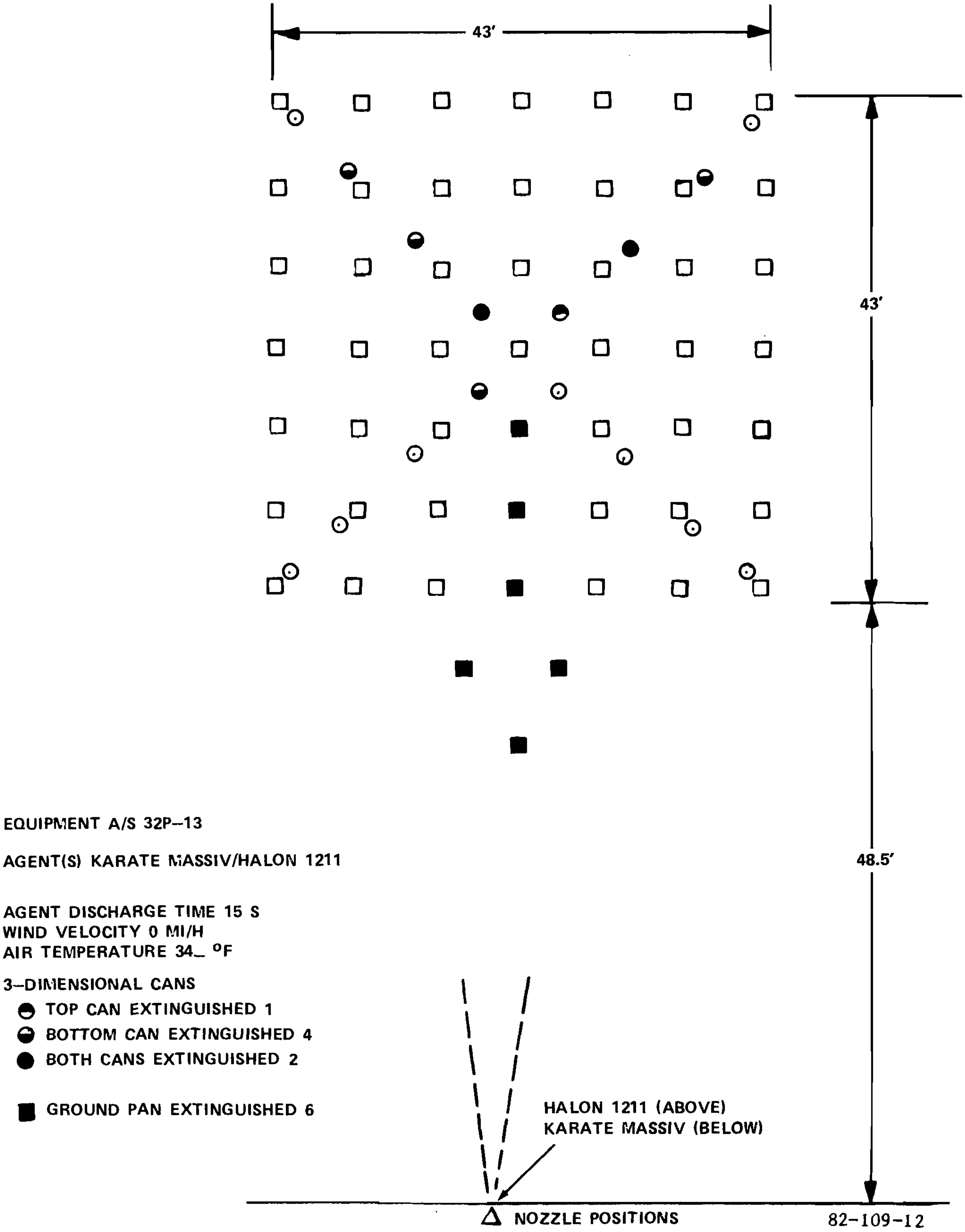
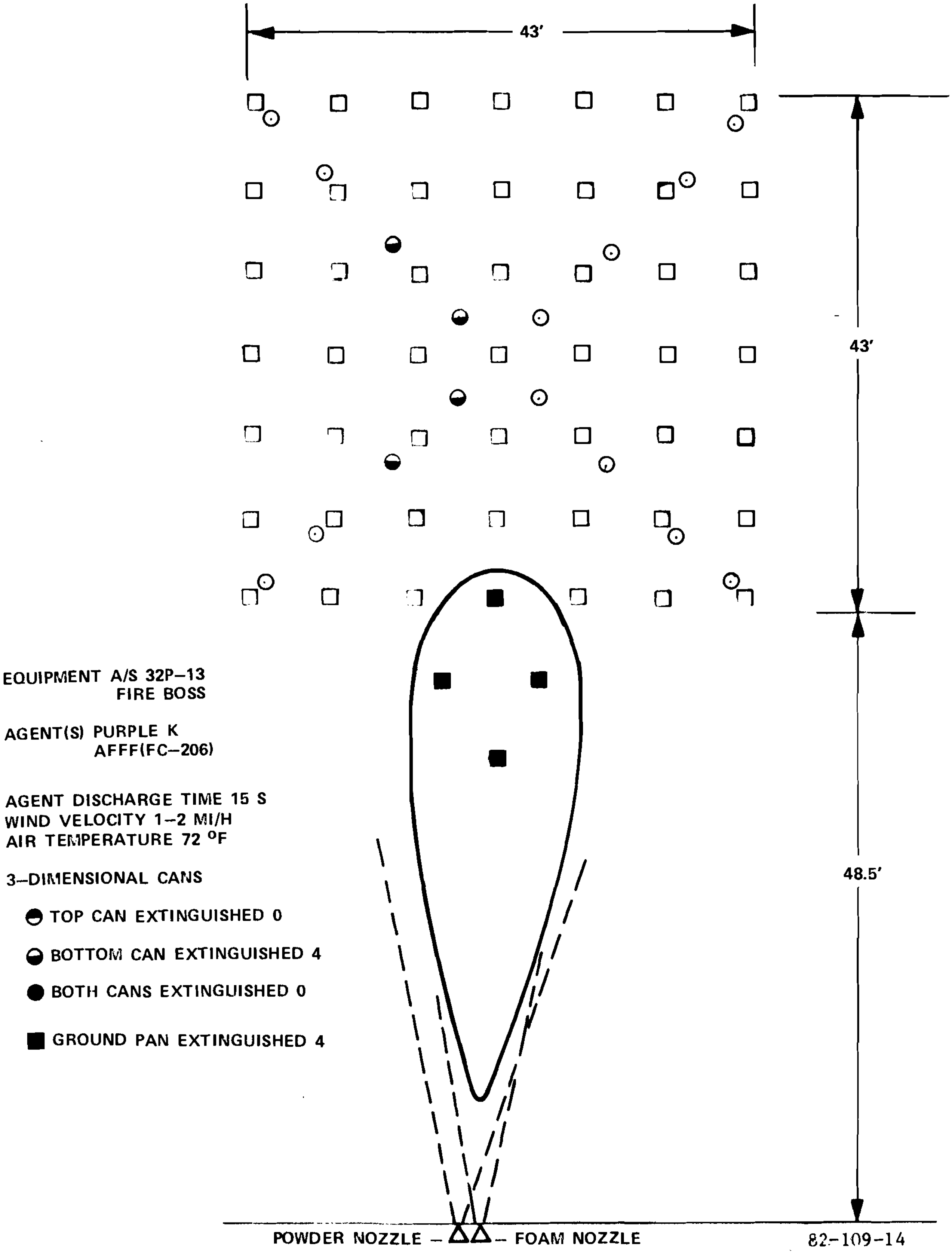


FIGURE 12. EFFECTIVE THROW RANGE OF KARATE MASSIV (BELOW) AND HALON 1211 (ABOVE)



EQUIPMENT A/S 32P-13
FIRE BOSS

AGENT(S) PURPLE K
AFFF(FC-206)

AGENT DISCHARGE TIME 15 S
WIND VELOCITY 1-2 MI/H
AIR TEMPERATURE 72 °F

3-DIMENSIONAL CANS

◓ TOP CAN EXTINGUISHED 0

◒ BOTTOM CAN EXTINGUISHED 4

● BOTH CANS EXTINGUISHED 0

■ GROUND PAN EXTINGUISHED 4

FIGURE 14. EFFECTIVE THROW RANGE OF PURPLE K POWDER AND AFFF (FC-206) SIMULTANEOUSLY

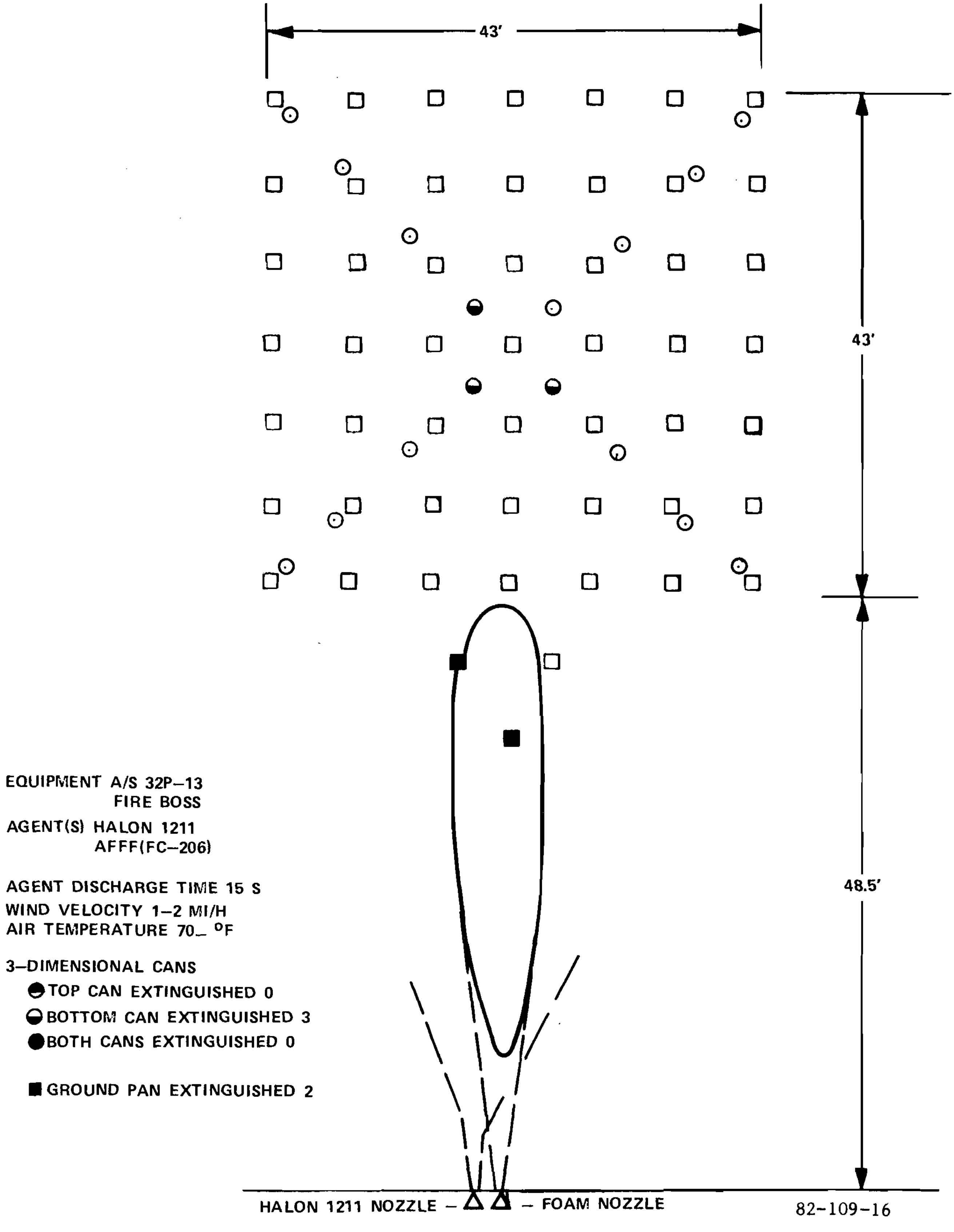
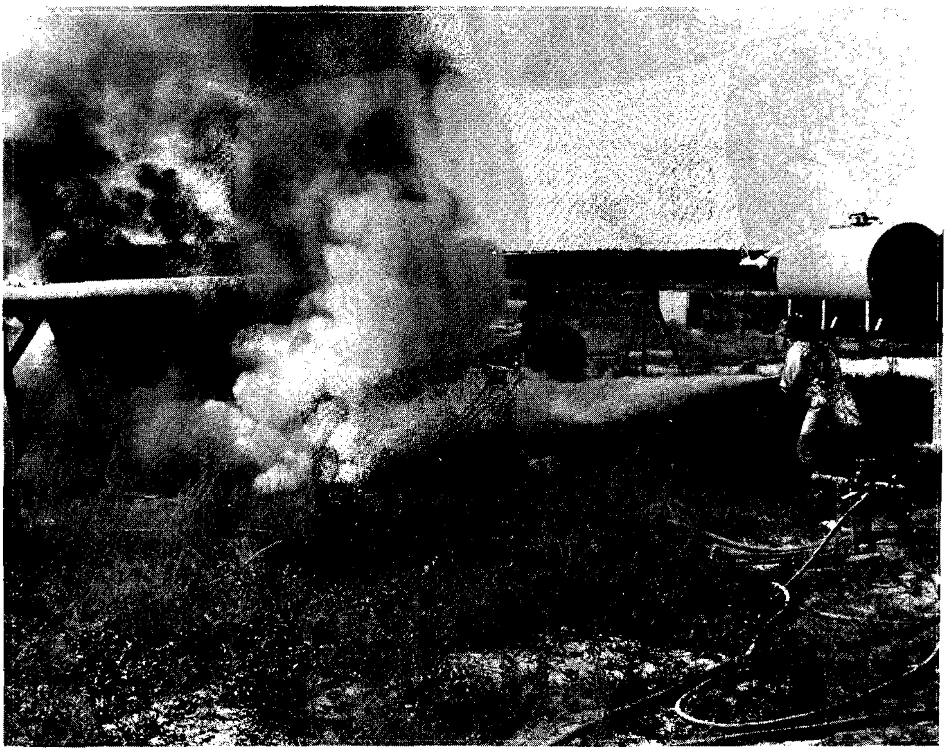
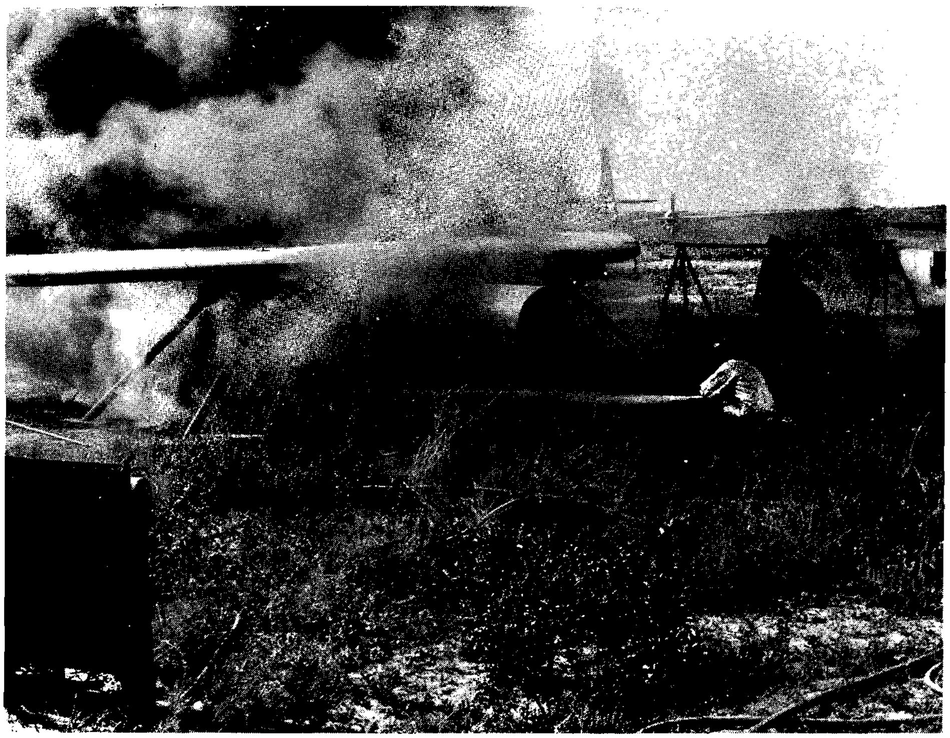


FIGURE 16. EFFECTIVE THROW RANGE OF HALON 1211 AND AFFF (FC-206) SIMULTANEOUSLY

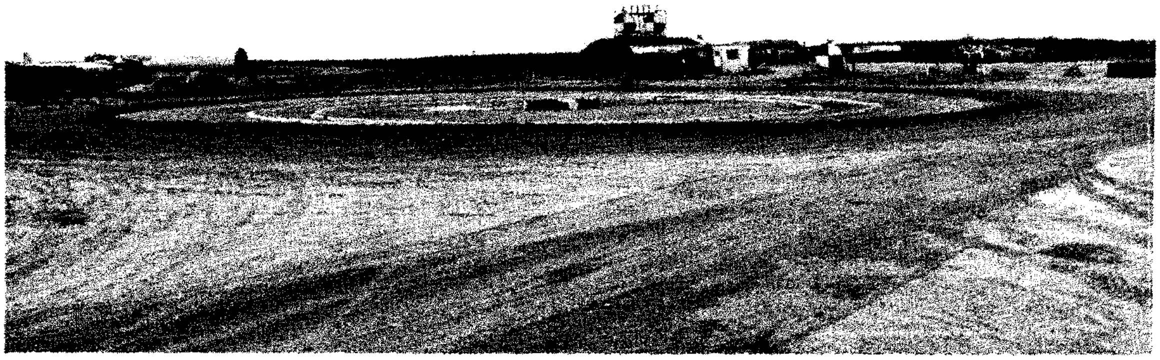


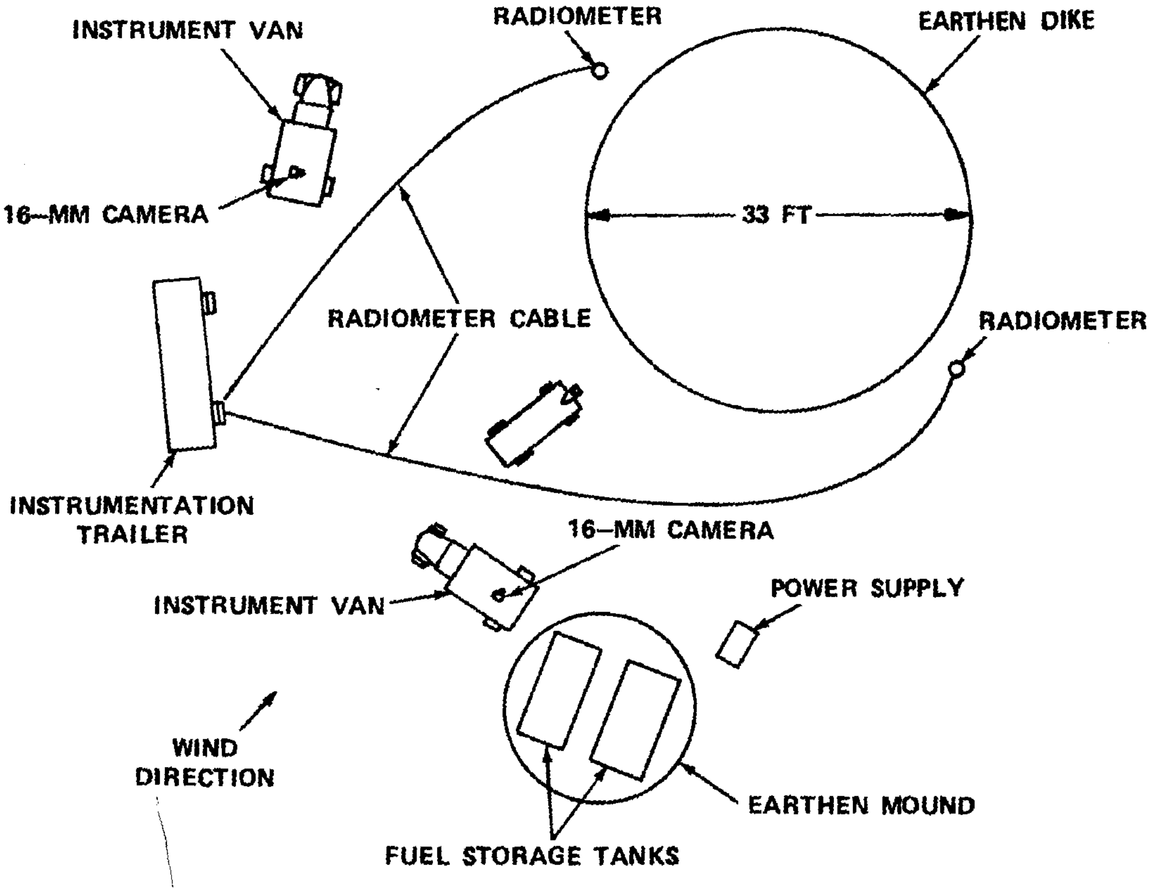
(a) Typical Fire Extinguishing Attack with Purple K Powder



(b) Typical Fire Extinguishment Employing Halon 1211

FIGURE 19. FIRE EXTINGUISHING EXPERIMENTS EMPLOYING THE J-47 ENGINE FIRE TEST BED USING PURPLE K POWDER AND HALON 1211 FROM THE A/S 32P-13 VEHICLE





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(b) SCHEMATIC VIEW

FIGURE 21. PICTORIAL AND SCHEMATIC PRESENTATION OF THE FIRE TEST FACILITY

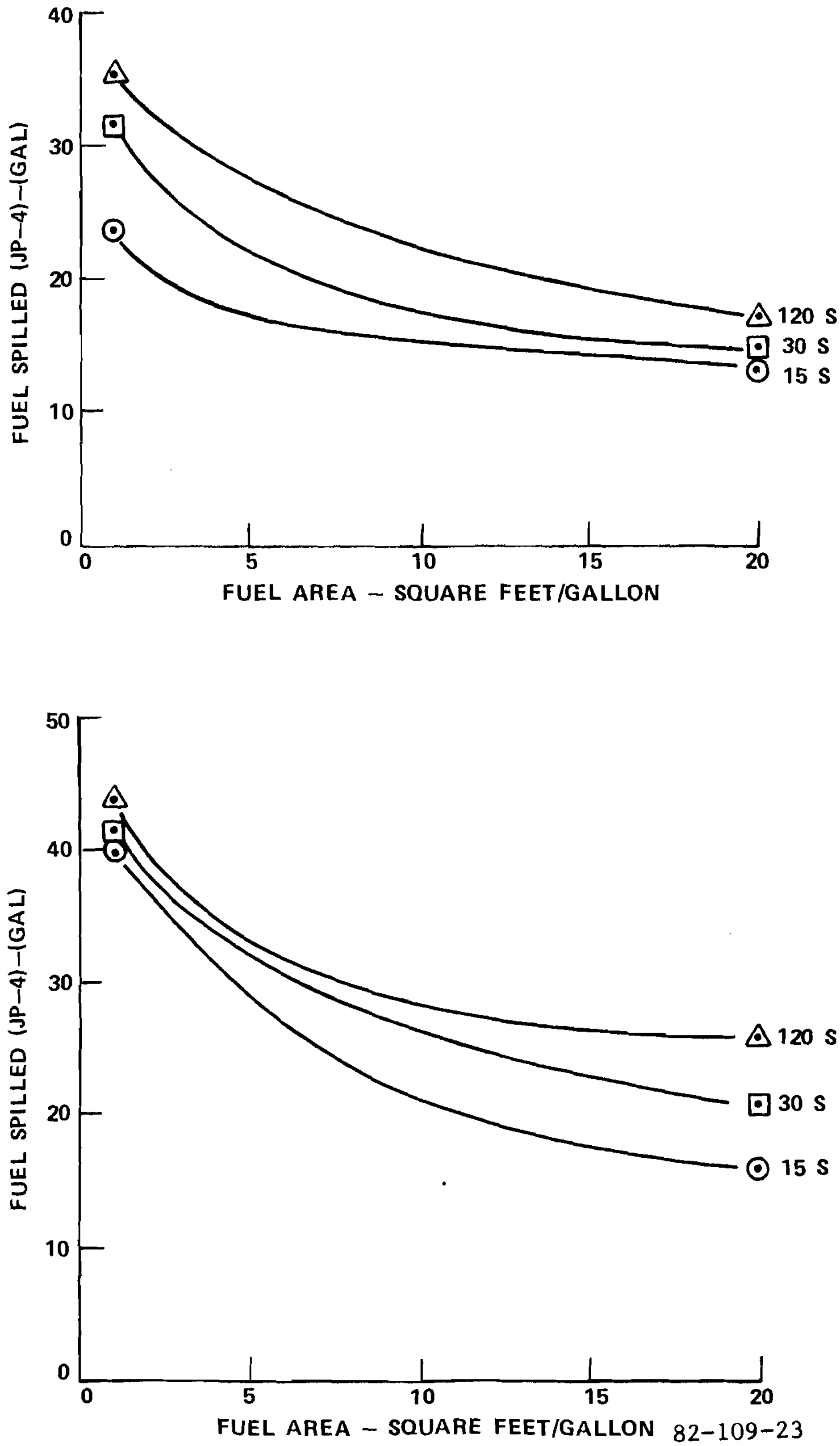

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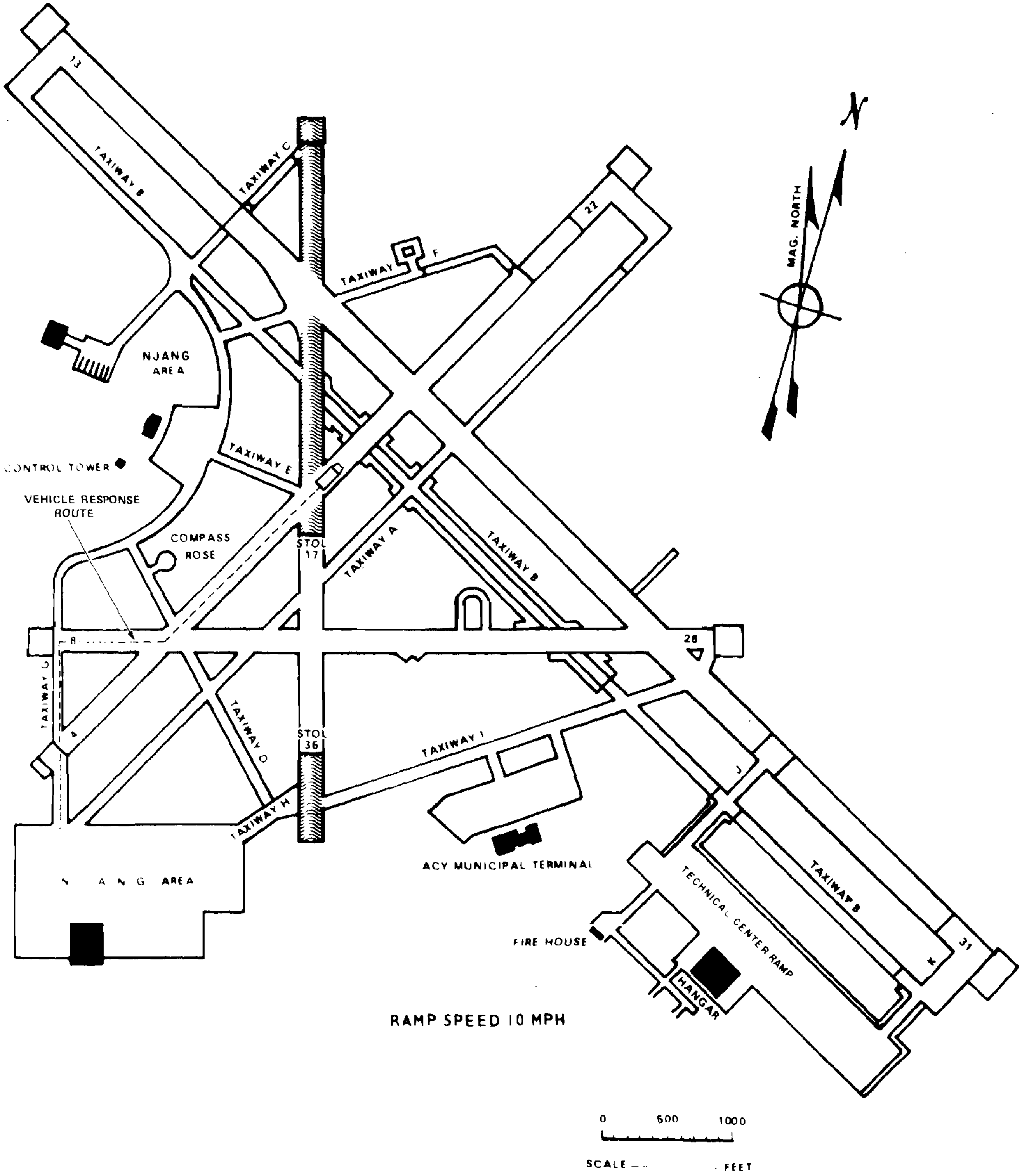
FIGURE 23. AREA OF FUEL SPREAD ON A RUNWAY SURFACE BEFORE AND AFTER IGNITION



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NAFEC ATLANTIC CITY AIRPORT, ATLANTIC CITY, NEW JERSEY

FIGURE 25. FAA TECHNICAL CENTER/ATLANTIC CITY AIRPORT SHOWING THE VEHICLE RESPONSE ROUTE

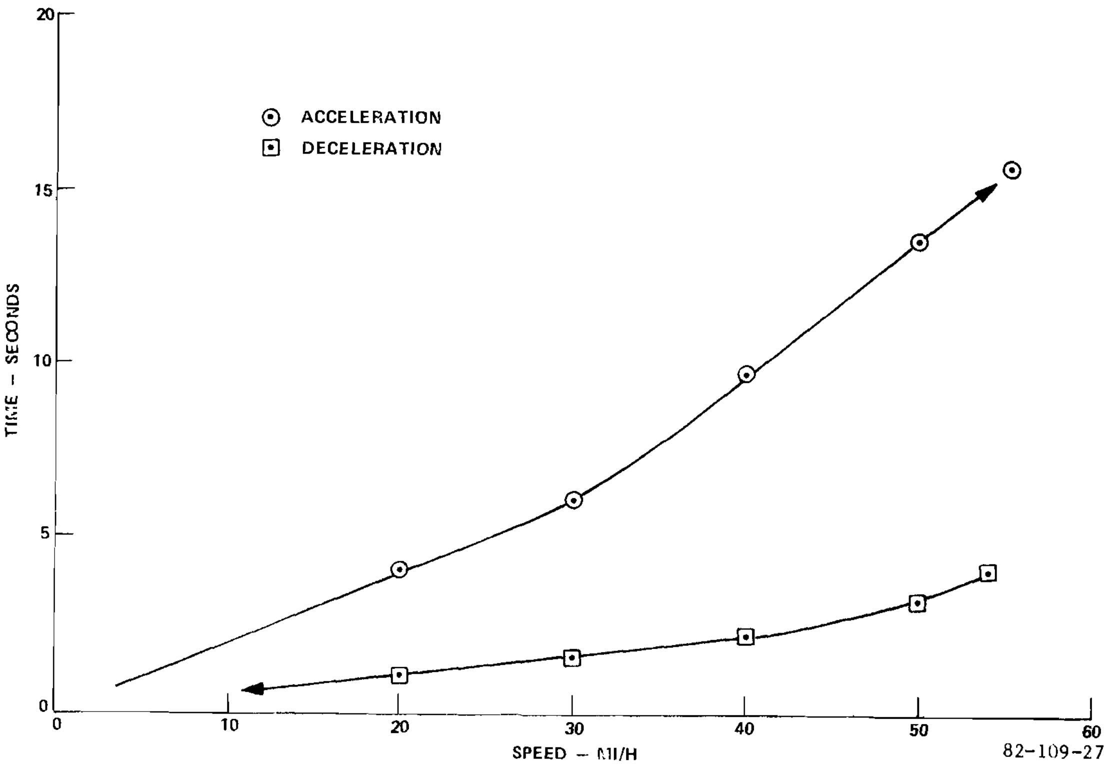


FIGURE 27. ACCELERATION AND DECELERATION RATES OF THE A/S 32P-13 VEHICLE AS A FUNCTION OF TIME

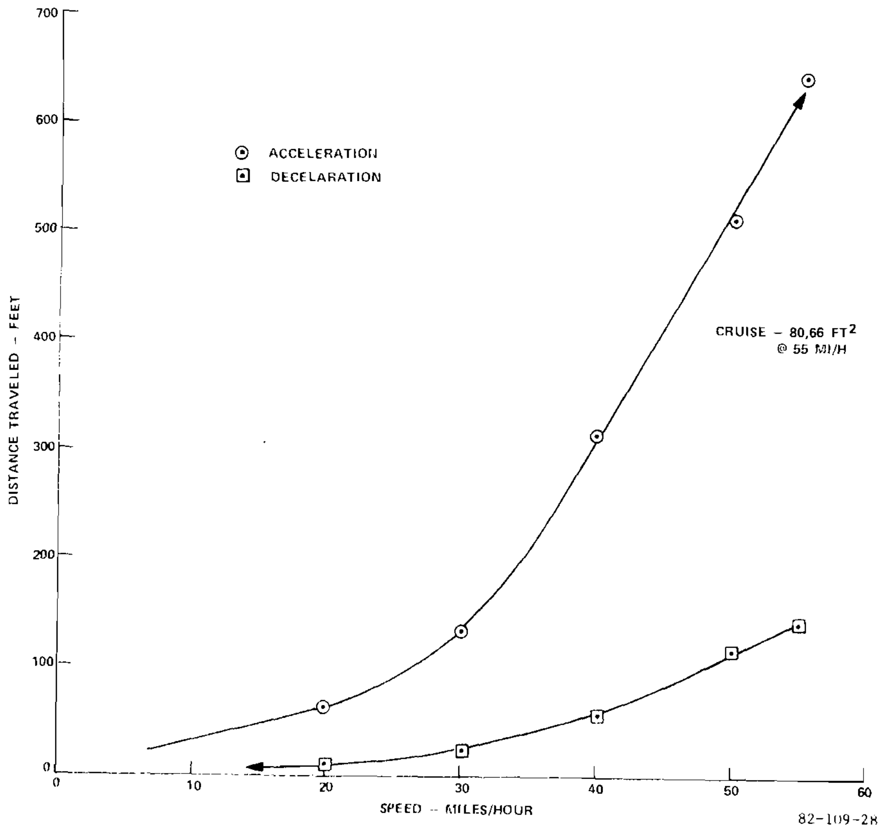


FIGURE 28. DISTANCE TRAVELED BY THE A/S 32P-13 VEHICLE AS A FUNCTION OF THE ACCELERATION AND DECELERATION RATES

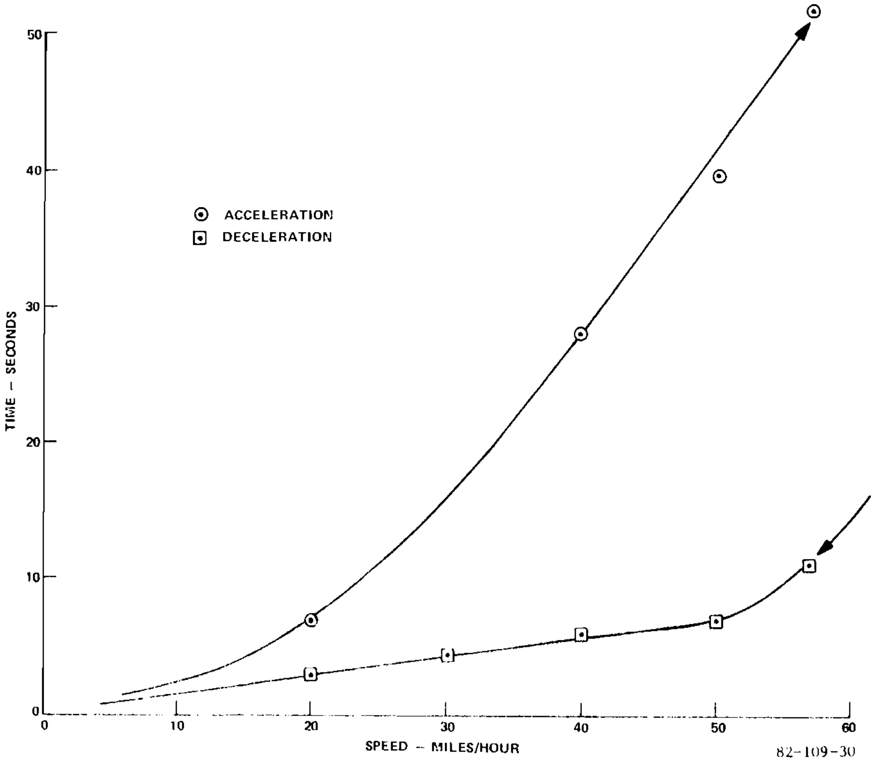


FIGURE 30. ACCELERATION AND DECELERATION RATES OF THE A/S 32P-4 VEHICLE AS A FUNCTION OF TIME

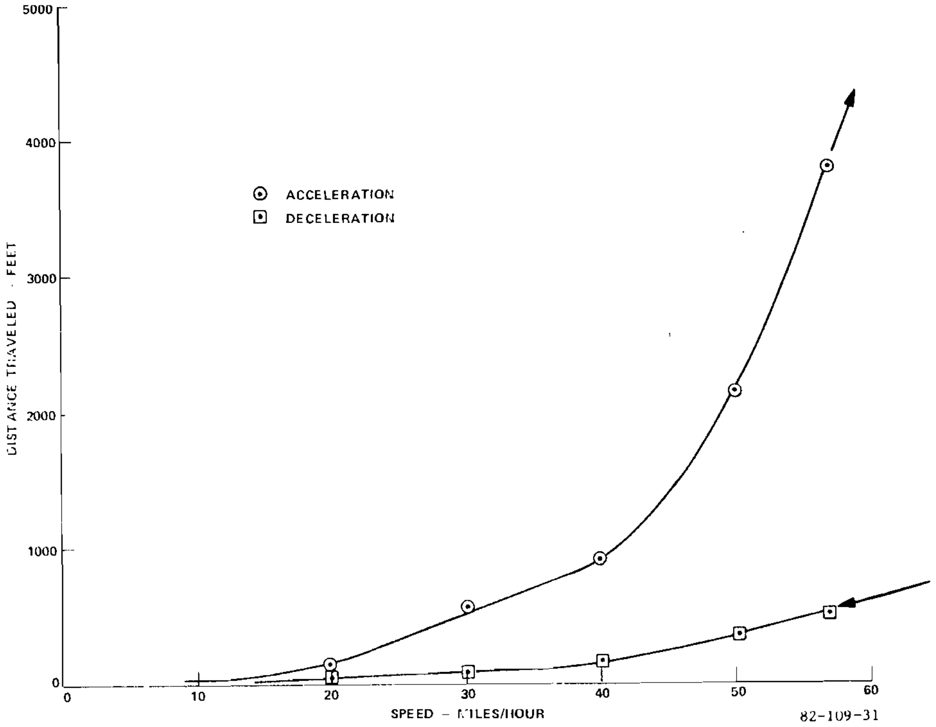


FIGURE 31. DISTANCE TRAVELED BY THE A/S 32P-4 VEHICLE AS A FUNCTION OF THE ACCELERATION AND DECELERATION RATES

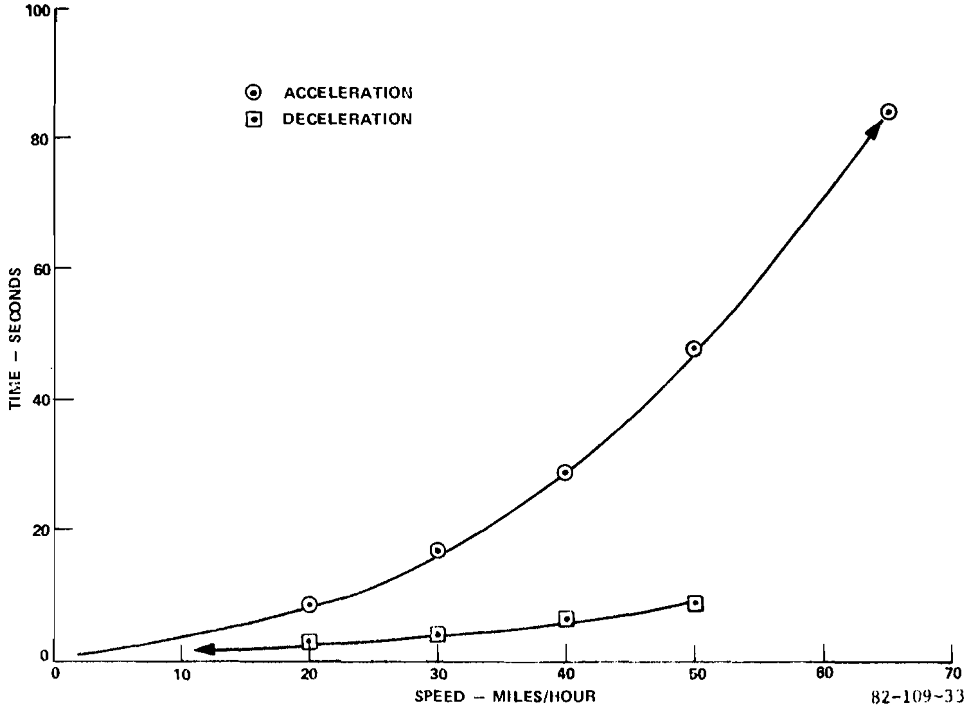


FIGURE 33. ACCELERATION AND DECELERATION RATES OF THE A/S 32P-2 VEHICLE AS A FUNCTION OF TIME

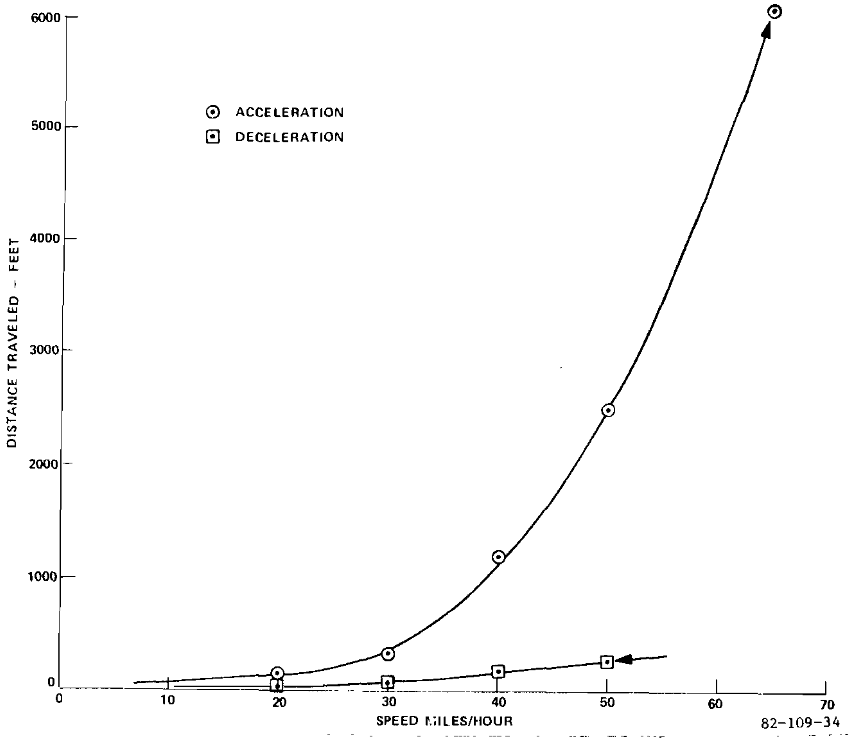


FIGURE 34. DISTANCE TRAVELED BY THE A/S 32P-2 VEHICLE AS A FUNCTION OF THE ACCLERATION AND DECELERATION RATES

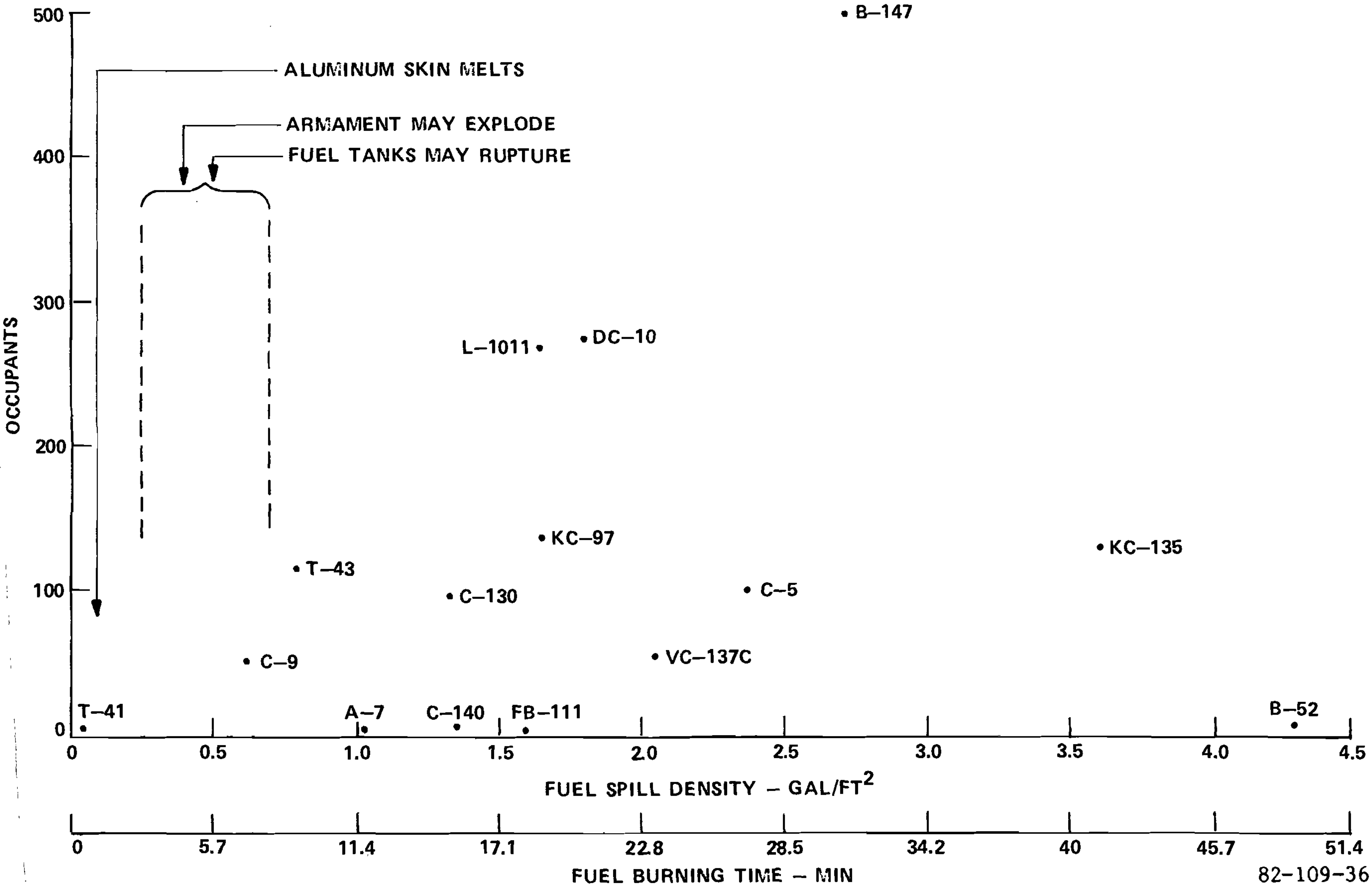


FIGURE 36. POTENTIAL LIFE HAZARDS TO MILITARY AIRCRAFT OCCUPANTS

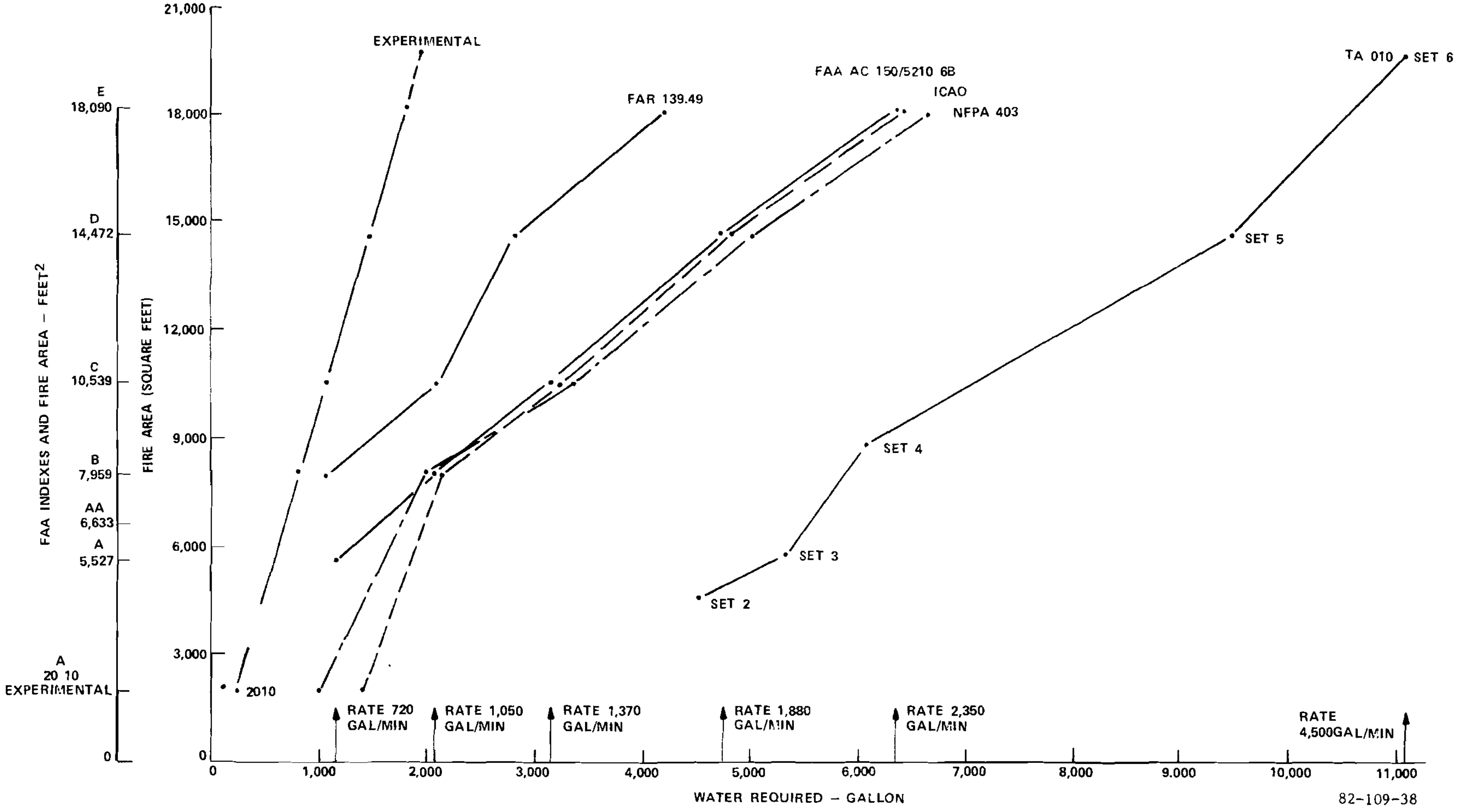


FIGURE 38. COMPARISON OF WATER QUANTITIES FOR THE CRASH FIRE RESCUE SERVICES

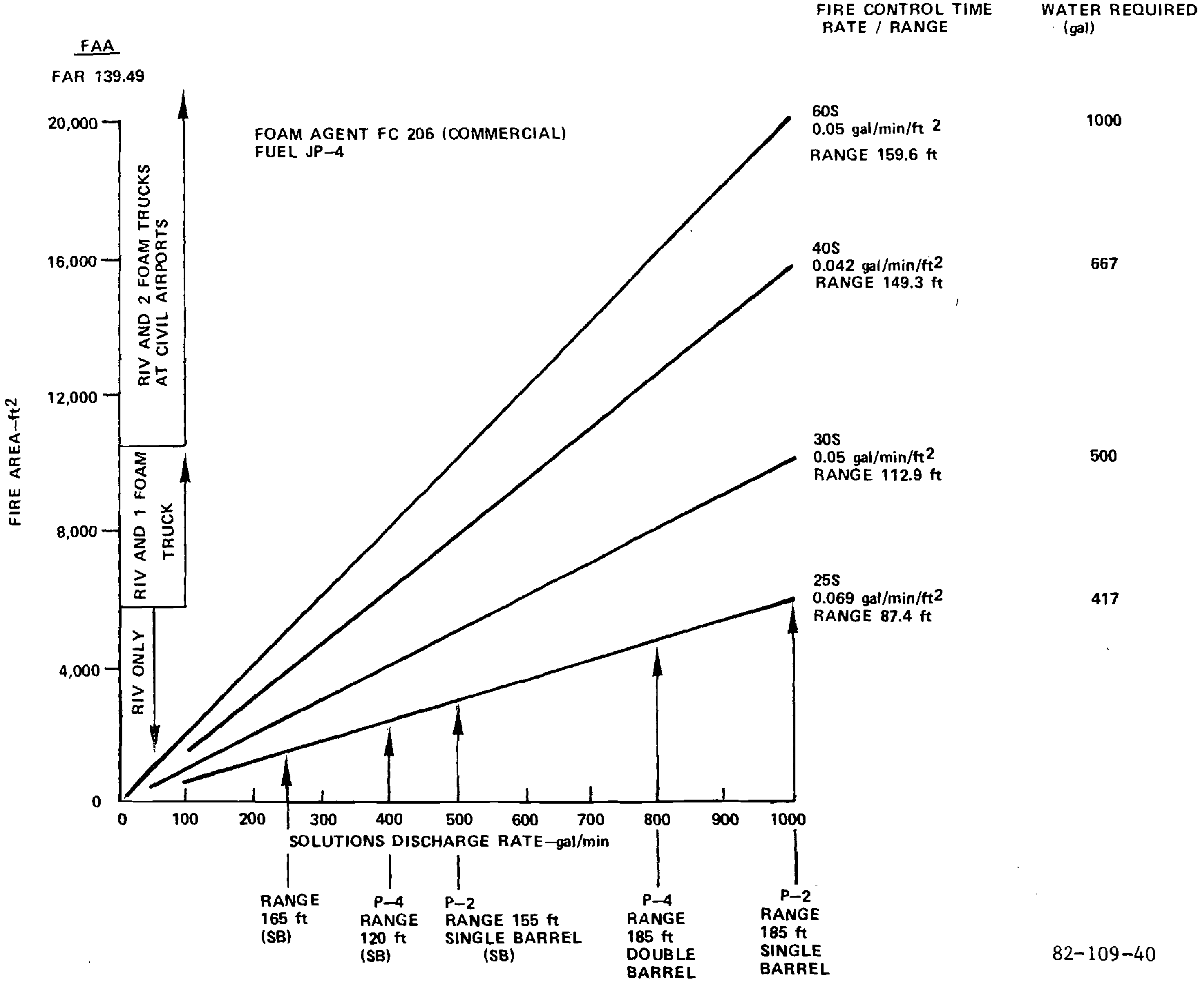


FIGURE 40. THEORETICAL FIRE CONTROL TIME AS A FUNCTION OF AFFF SOLUTION DISCHARGE RATE AND FIRE SIZE

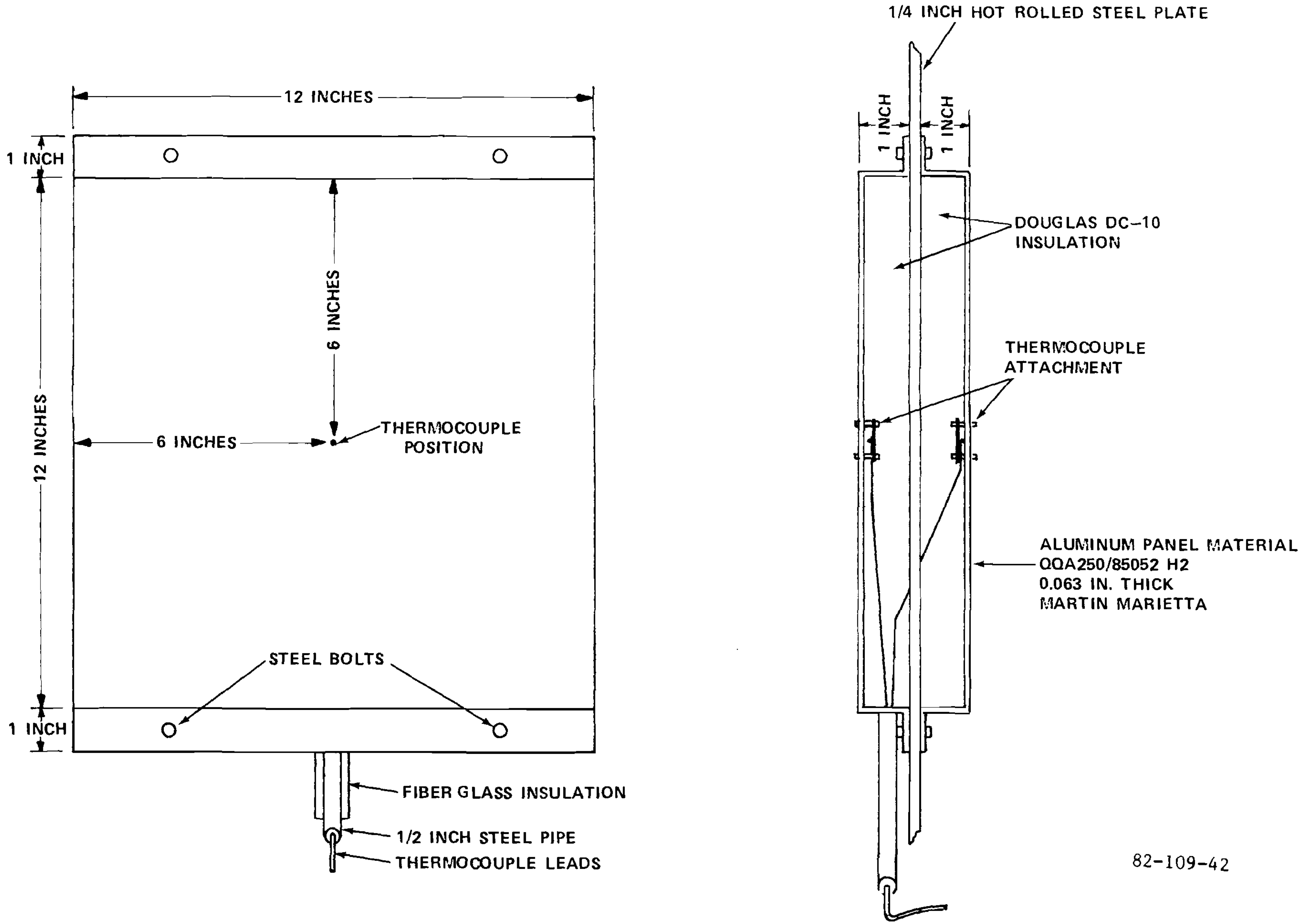


FIGURE 42. SIMULATED AIRCRAFT SKIN PANEL CONSTRUCTION

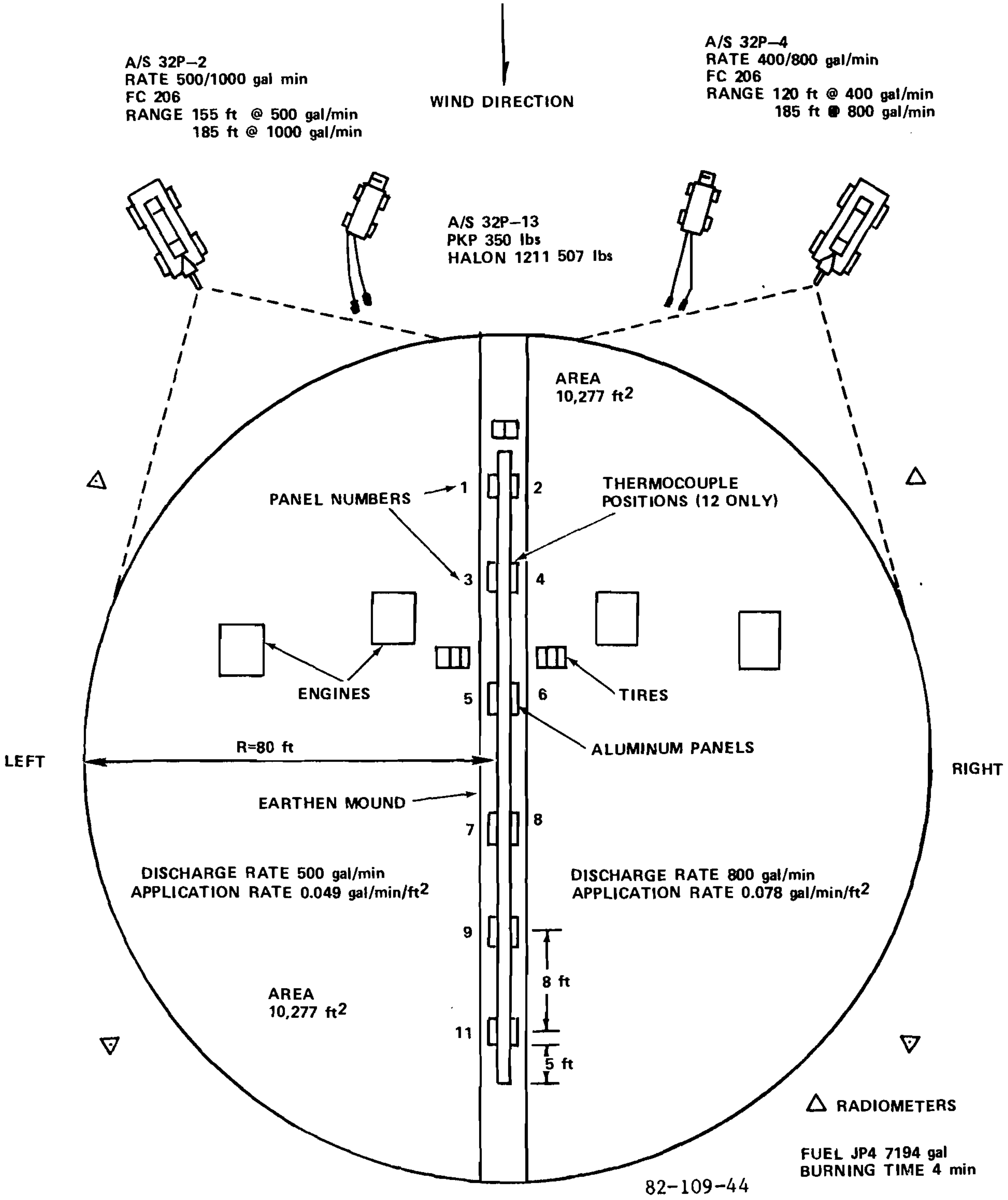


FIGURE 44. EXPERIMENT NO. 1 FIRE TEST BED CONFIGURATION FOR LARGE AIRCRAFT

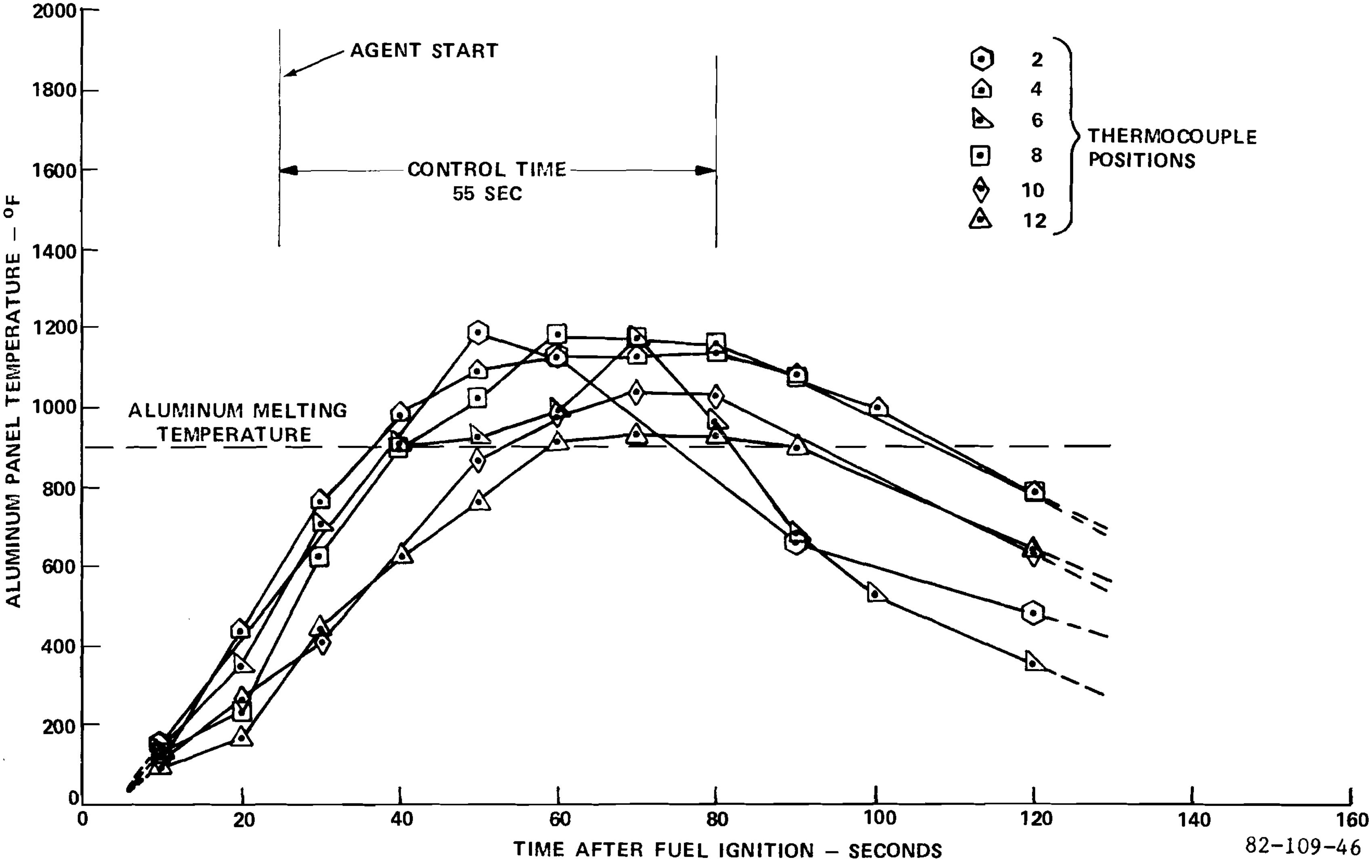


FIGURE 46. TEMPERATURE DATA PROFILES FROM THE RIGHT SIDE OF THE AIRCRAFT MOCKUP (TEST NO. 1)

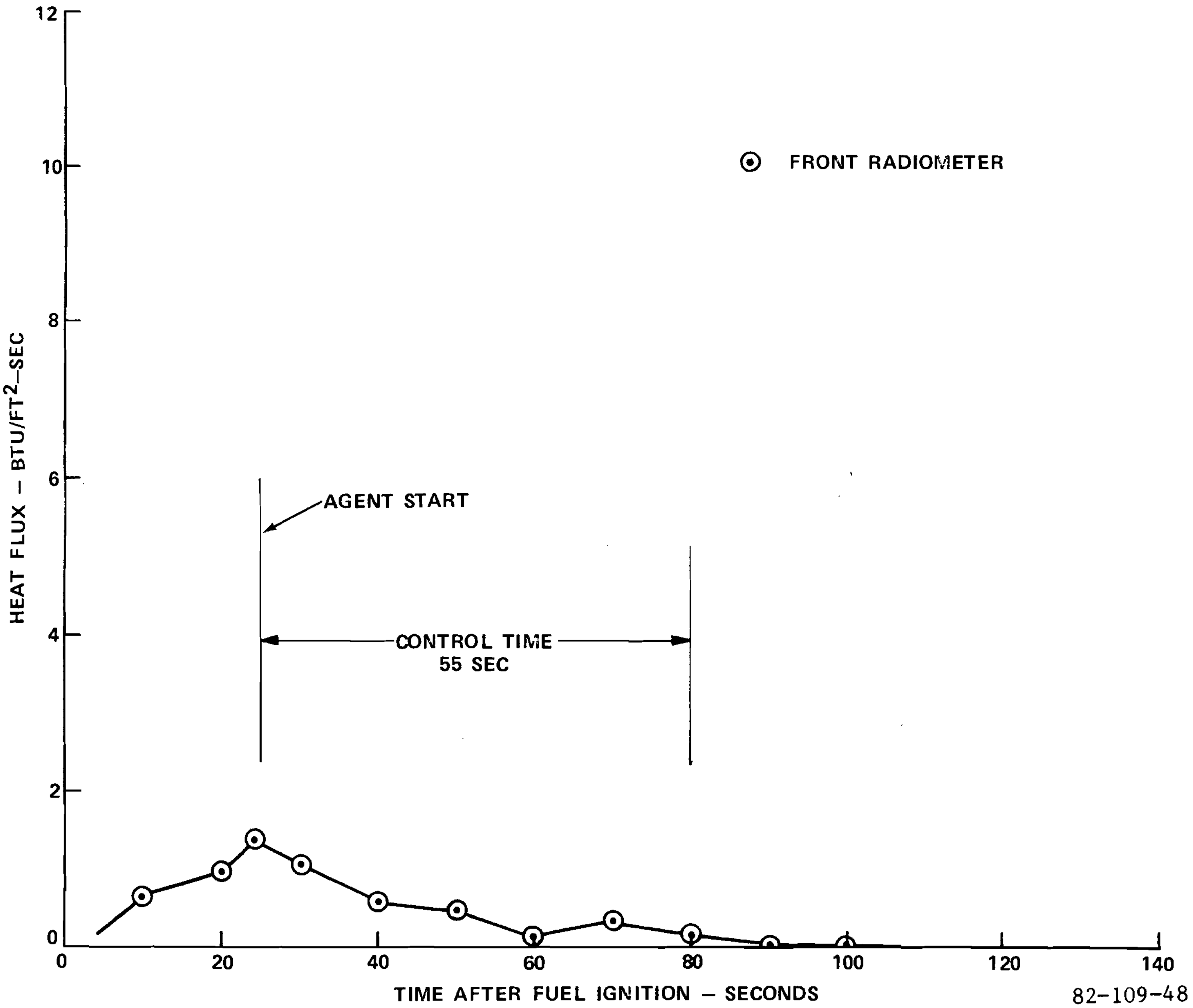


FIGURE 48. HEAT FLUX DATA SHOWING THE PROGRESS OF FIRE CONTROL ON THE RIGHT SIDE OF THE AIRCRAFT MOCKUP (TEST NO. 1)

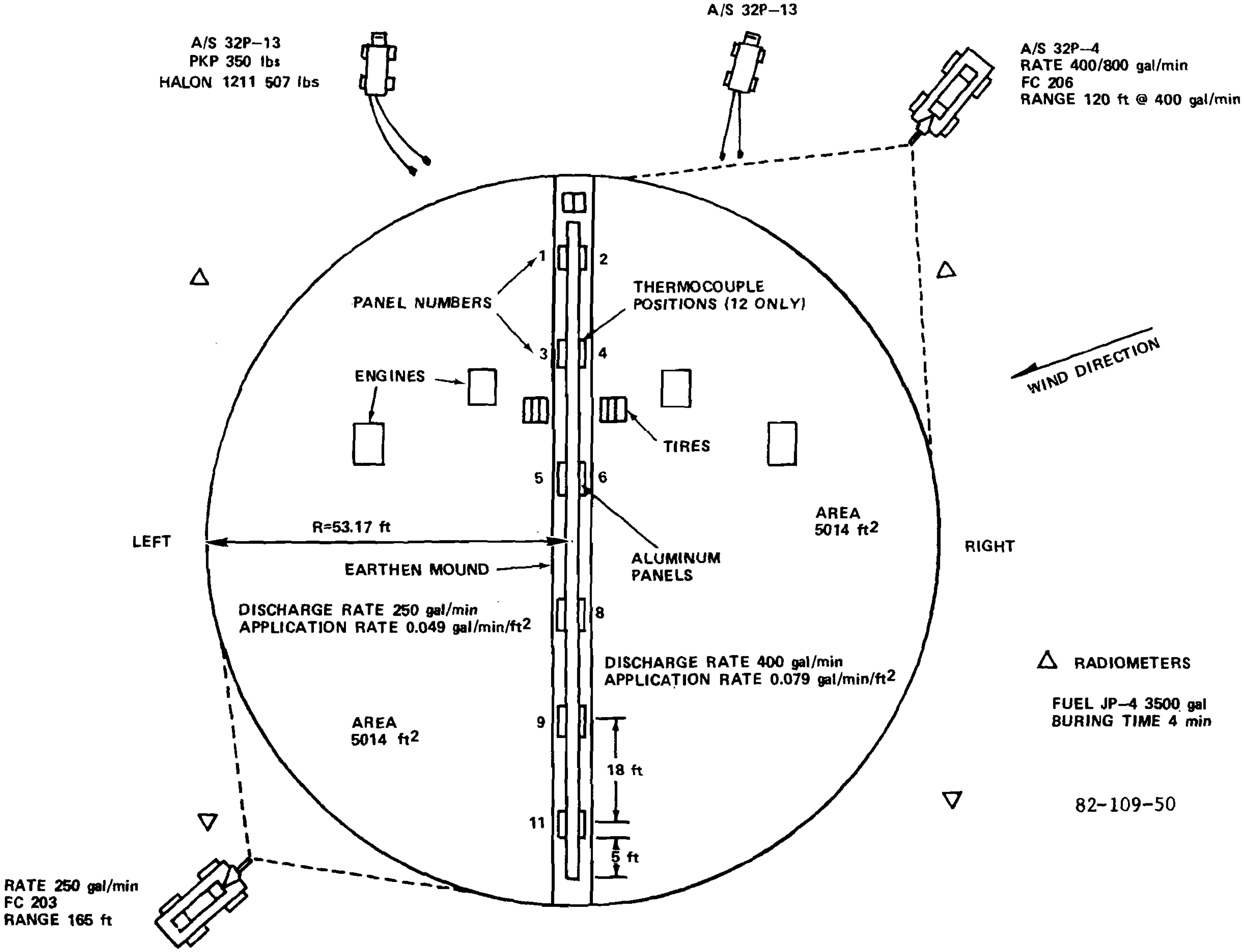


FIGURE 50. EXPERIMENT NO. 2 FIRE TEST BED CONFIGURATION FOR MEDIUM SIZE AIRCRAFT

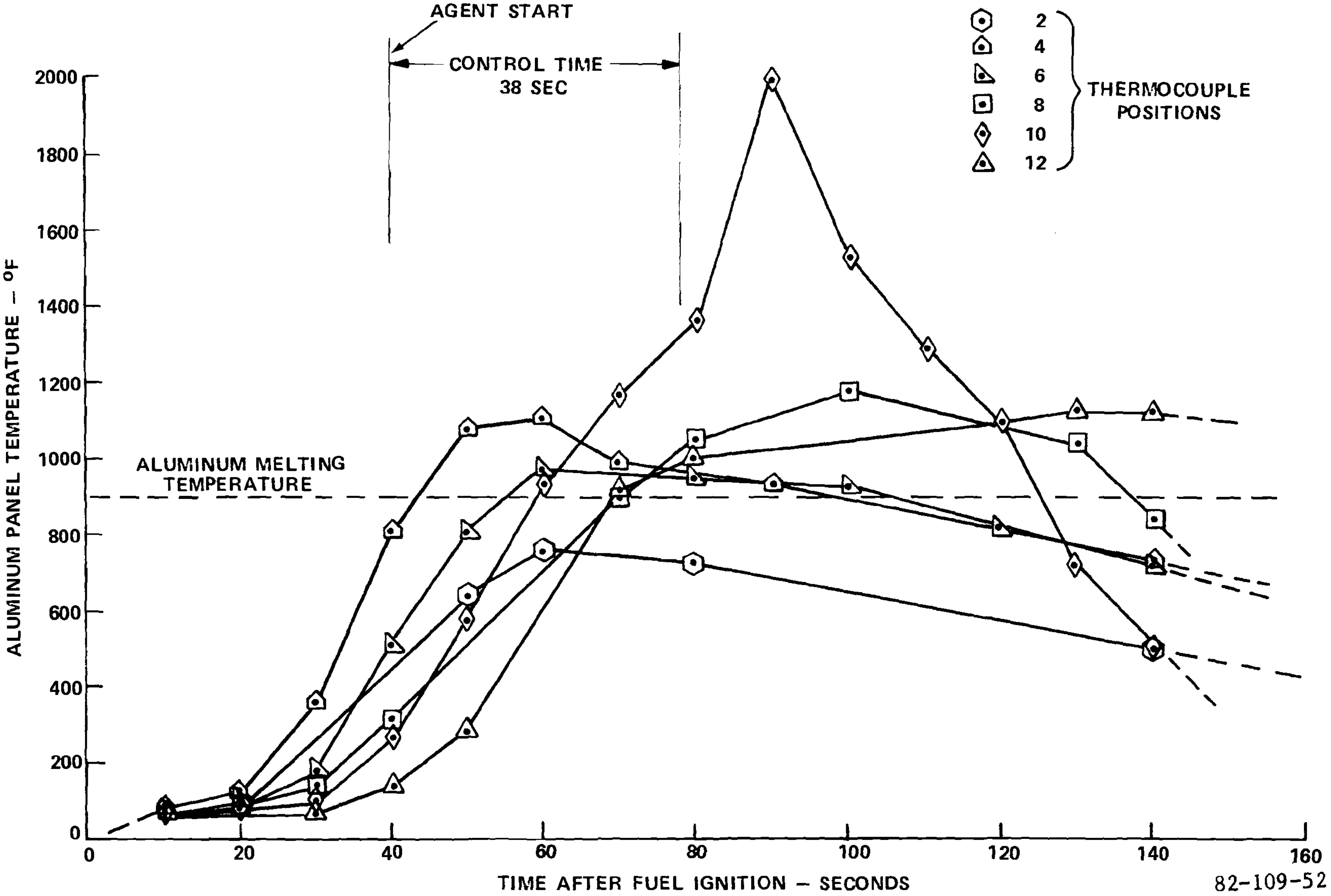
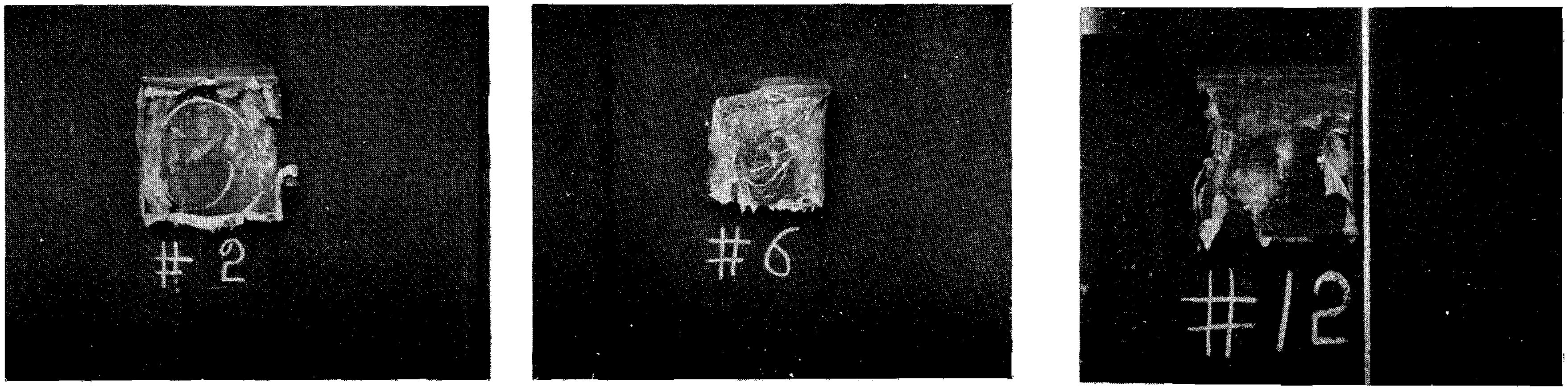


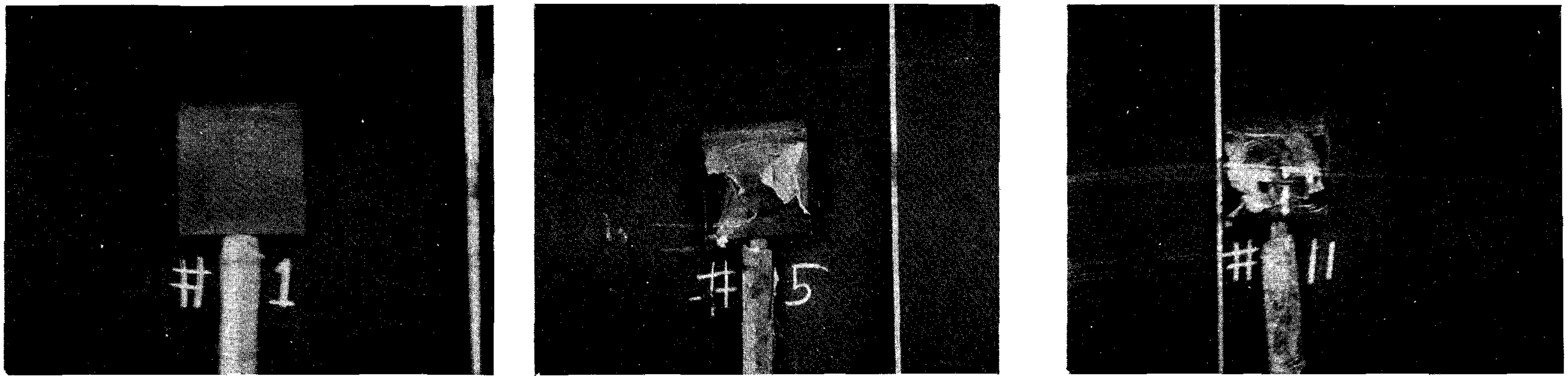
FIGURE 52. TEMPERATURE DATA PROFILES FROM THE RIGHT SIDE OF THE AIRCRAFT MOCKUP (TEST NO. 2)

RIGHT SIDE OF MOCKUP



Station 2 Station 6 Station 12

LEFT SIDE OF MOCKUP



Station 1 Station 5 Station 11

FIGURE 55. COMPARISON OF THE FIRE DAMAGE SUSTAINED BY THE ALUMINUM PANEL MOCKUPS DURING TEST NO. 1

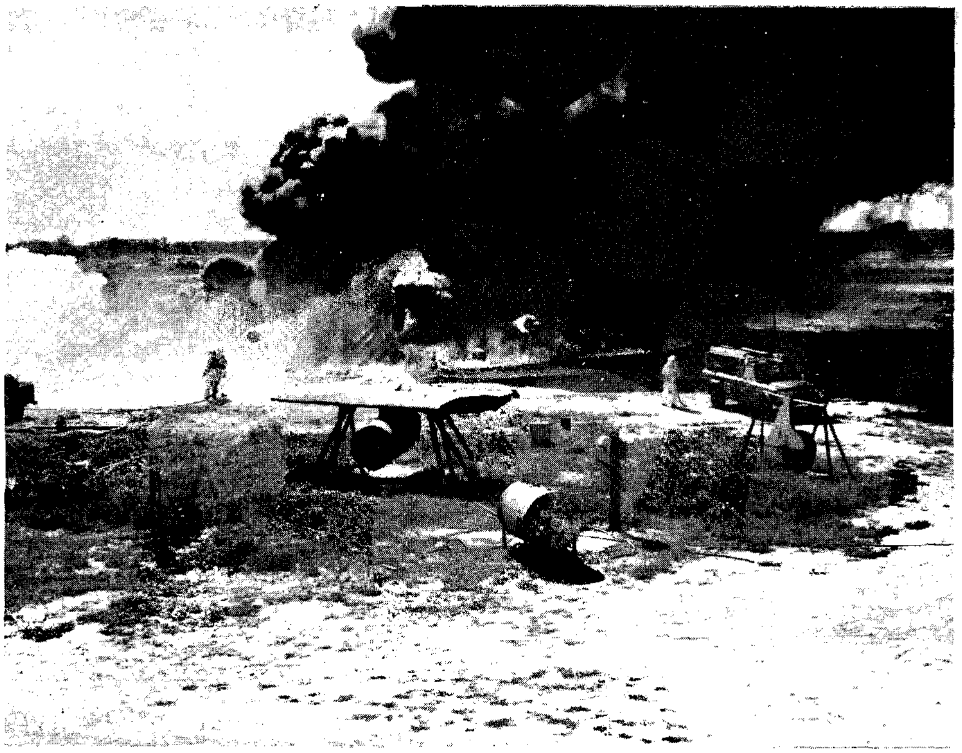


FIGURE 57. OVERALL VIEW OF THE ACTIVITIES PERFORMED DURING TEST NO. 2

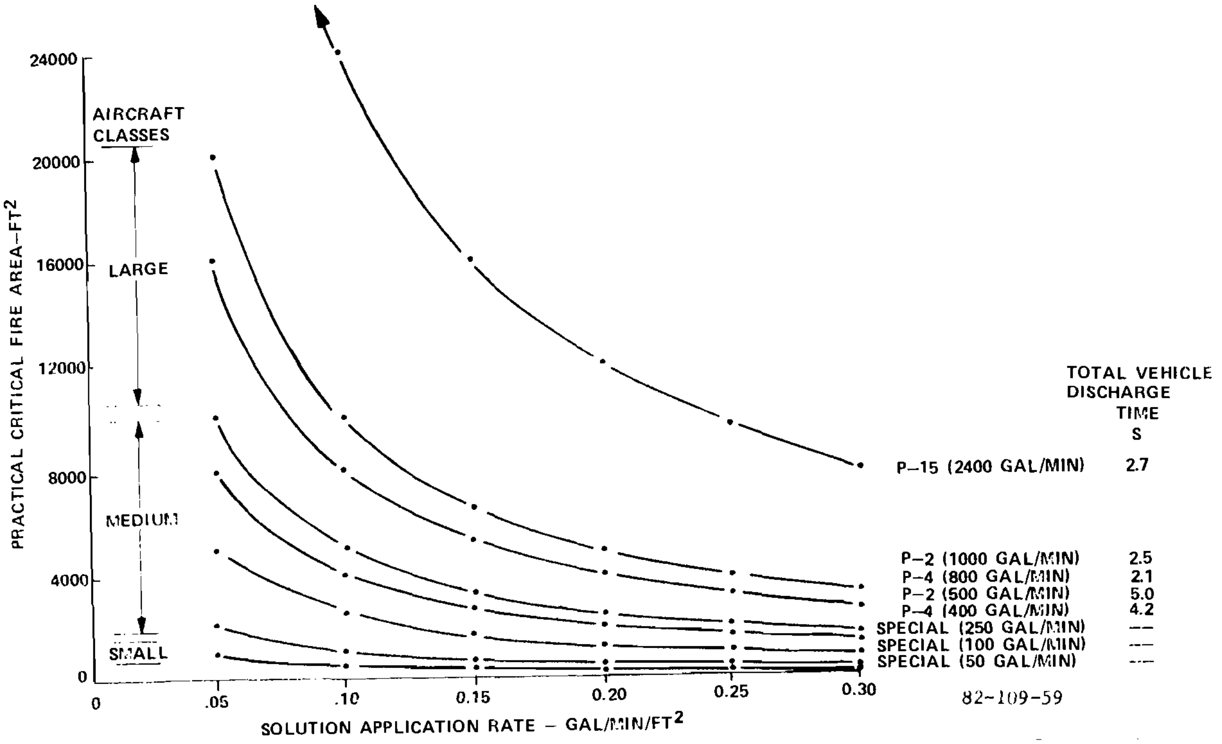


FIGURE 59. FOAM SOLUTION (AFFF) APPLICATION RATE IN TERMS OF THE PRACTICAL CRITICAL FIRE AREA FOR SMALL, MEDIUM, AND LARGE AIRCRAFT

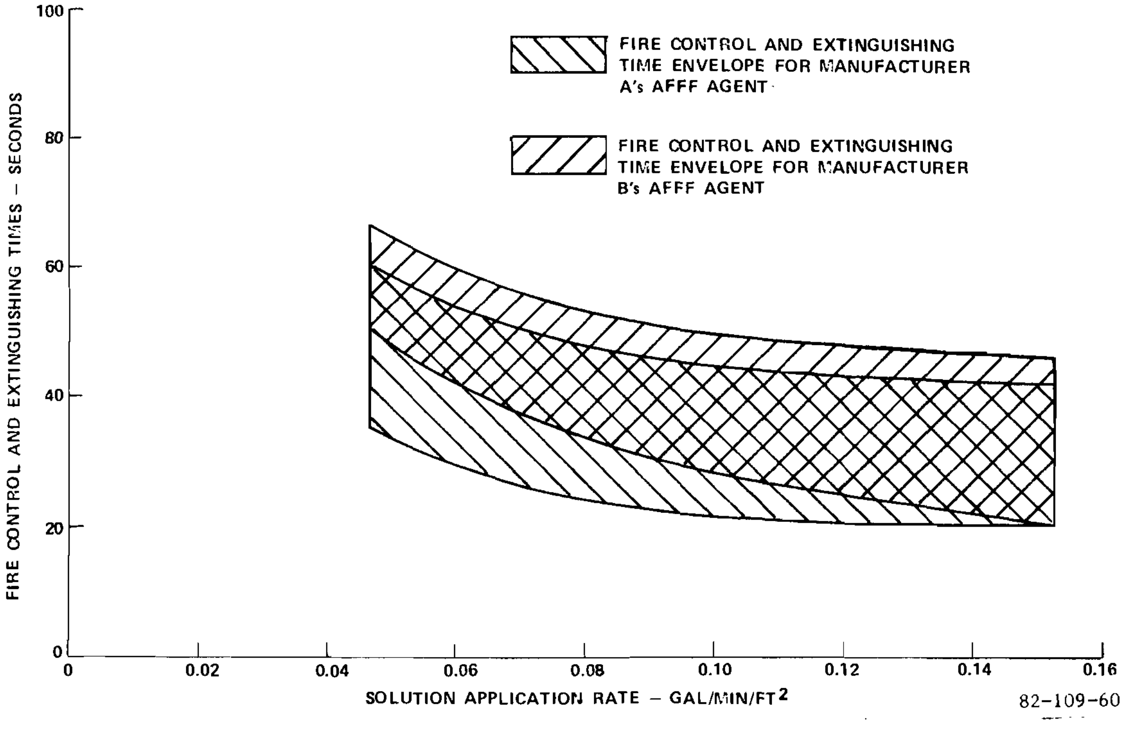


FIGURE 60. COMPARISON OF THE FIRE CONTROL AND EXTINGUISHING TIMES FOR MANUFACTURER A'S AND B'S AFFF AGENTS AT 250 AND 400 GAL/MIN ON JP-4 FUEL FIRES

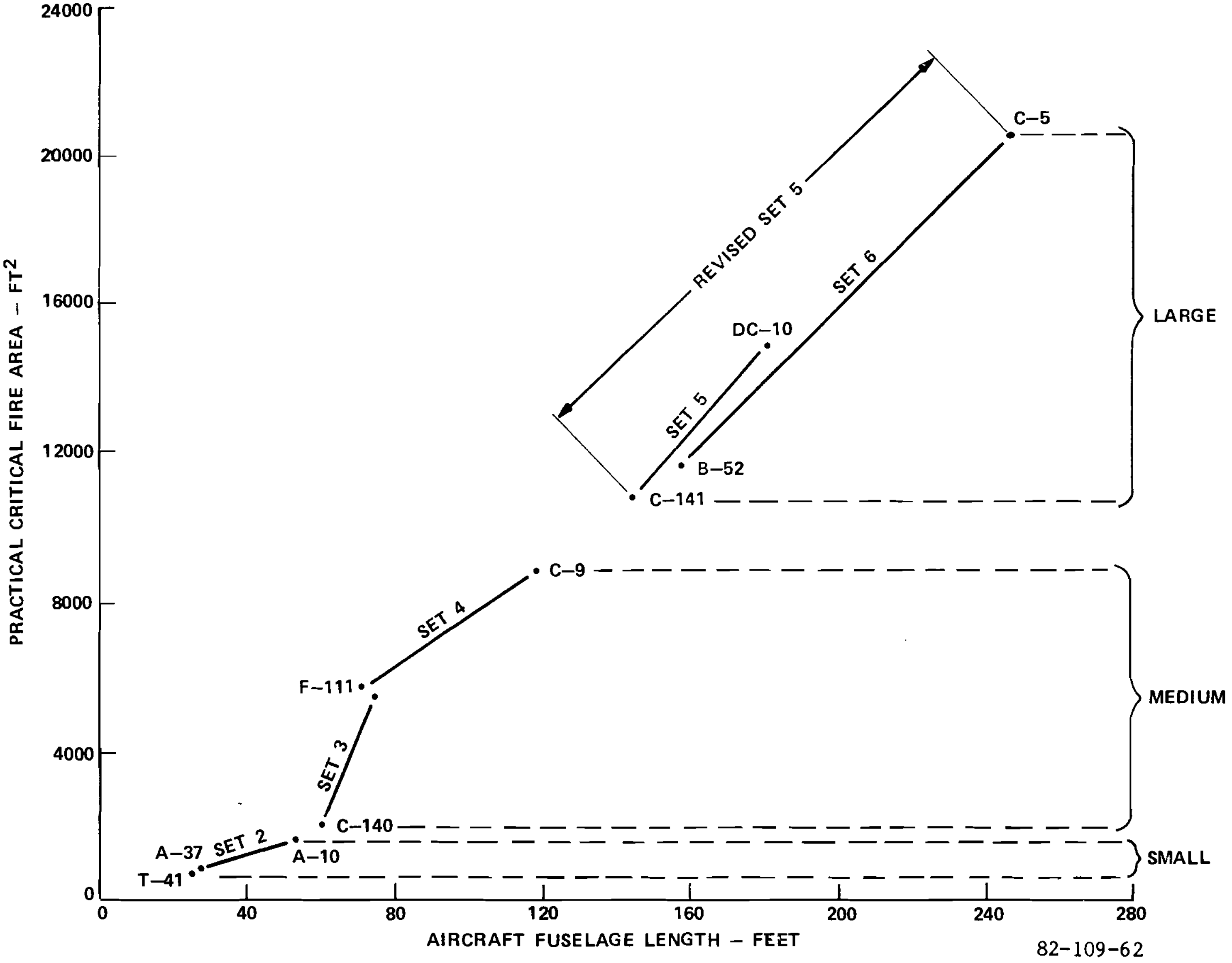
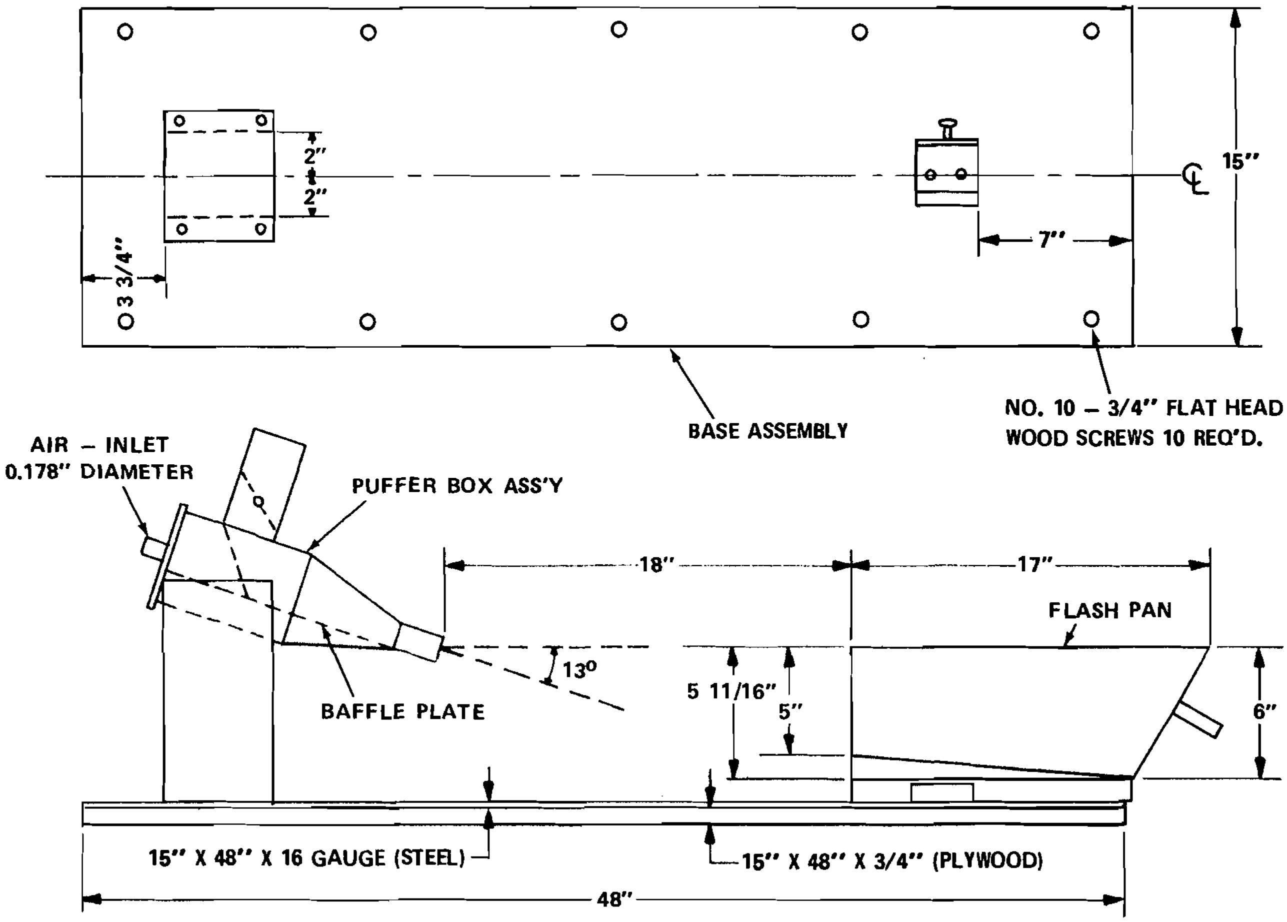
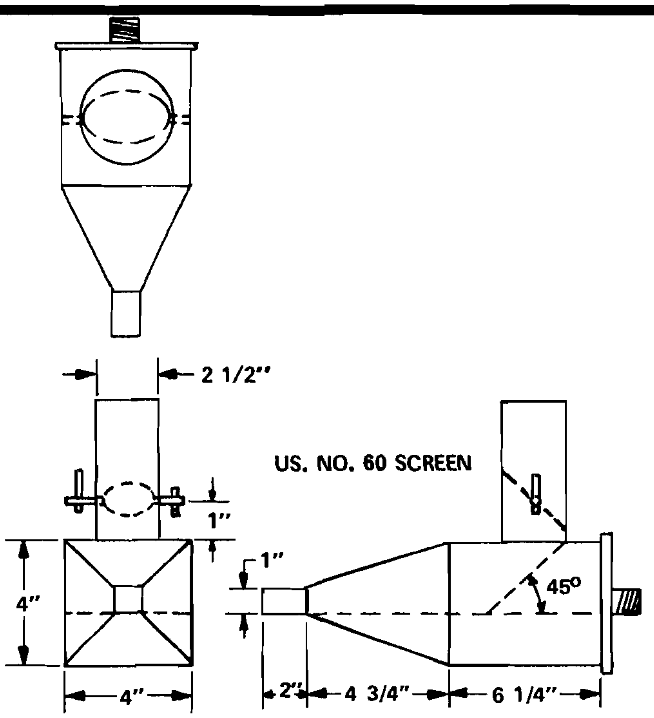


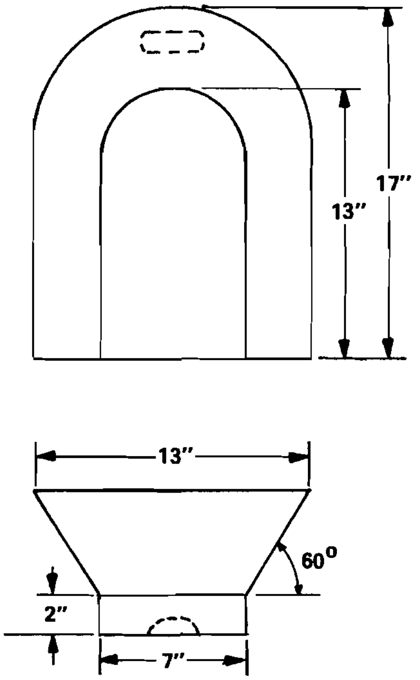
FIGURE 62. AIRCRAFT PRACTICAL CRITICAL FIRE AREA AS A FUNCTION OF FUSELAGE LENGTH

APPENDIX A

DRY CHEMICAL POWDER TEST EQUIPMENT


2"
2"
3 3/4"
7"
15"
℄
BASE ASSEMBLY
NO. 10 – 3/4" FLAT HEAD
WOOD SCREWS 10 REQ'D.
AIR – INLET
0.178" DIAMETER
PUFFER BOX ASS'Y
18"
17"
FLASH PAN
13°
BAFFLE PLATE
5 11/16"
5"
6"
15" X 48" X 16 GAUGE (STEEL)
15" X 48" X 3/4" (PLYWOOD)
48"


2 1/2"
US. NO. 60 SCREEN
1"
4"
1"
45°
4"
2"
4 3/4"
6 1/4"


17"
13"
13"
60°
2"
7"

NOT TO SCALE

APPENDIX B

FIREFIGHTING AGENT MANUFACTURERS

DRY CHEMICAL POWDERS

Powder Base/Type	Manufacturer
Potassium Chloride (Super K)	Pyro Chemicals Inc., Boonton, New Jersey, USA
Potassium Bicarbonate (Purple-K Powder, PKP)	The Ansul Company, Marinette, Wisconsin, USA
Sodium Bicarbonate	The Ansul Company, Marinette, Wisconsin, USAA
Monnex (Urea-Potassium Bicarbonate)	ICI Americas Inc. Wilmington, Delaware, USA
Potassium Sulfate (Totalit Super)	Total Foerftner Ladenburn, West Germany
Potassium Sulfate (Karate)	Ruhl Chemie Friedrichsdorf, West Germany
Potassium Sulfate (Karate Massiv)	Ruhl Chemie Friedrichsdorf, West Germany
Potassium Bicarbonate (BCE-101-K)	Ruhl Chemie Friedrichsdorf, West Germany
Monoammonium Phosphate (ABCDE Tropolar)	Ruhl Chemie Friedrichsdorf, West Germany

LIQUID VAPORIZING AGENTS

Halon 1211 (BCF)	ICI Americas Inc. Wilmington, Delaware USA

FOAM FIREFIGHTING AGENTS

Aqueous Film Forming Foam (AFFF) AFFF FC-206 AFFF FC-203	3M Center St. Paul, MN USA

APPENDIX C

LABORATORY FOAM-POWDER COMPATIBILITY TEST

This test method is a modification of that required in reference 16 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 the proper quantity of foam liquid concentrate with the required volume of fresh water at 70 degrees +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 r/min for exactly 2 minutes. During the mixing process, the bowl is made to rotate at approximately 1 r/s. At the end of the 2-minute 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 seconds, after which a 15-ml sample of the test fuel 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 and screeded-off level with the rim. The pan is then placed on a stand having a slope of 1 inch in 12 inches toward the front and constructed so that the top of the pan and the foam surface is 2 3/8 inches below a radiating metal surface. The heat source consists of a 1,000-watt electrical hotplate with a 7-inch-diameter face (Edwin L. Wiegard Co., Pittsburgh, Pa., Model ROPH-100 or equivalent) mounted upside down over a 6-1/2-inch-diameter hole in a 1/2-inch-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-inches-square and 1/2-inch-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-second 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 2.0 minutes 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 D

RELATIVE TOXICITY OF THE HALOGENATED HYDROCARBON FIRE EXTINGUISHING AGENTS

Table 15-38. Relative Toxicity of Some Common Halide Fire Extinguishing Agents Using the Underwriters' Laboratories, Inc., Groupings

Agent	Chemical Formula	Halon No.	UL Toxicity Grouping
Bromotrifluoromethane	$CBrF_3$	1301	Group 6
Bromochlorodifluoromethane	$CBrClF_2$	1211	Group 5
Dibromotetrafluoroethane	$C_2Br_2F_4$	2402	Group 5 or 4
Dibromodifluoromethane	CBr_2F_2	1202	Group 4
Chlorobromomethane	CH_2BrCl	1011	Group 3
Carbon tetrachloride	CCl_4	104	Group 3

Table 15-37A. Approximate Lethal Concentrations* for 15-min Exposure to Vapors of Various Fire Extinguishing Agents Research by U. S. Army Chemical Center

Agent	Formula	Halon No.	Approximate Lethal Concentration in Parts per Million	
			Natural Vapor	Decomposed Vapor
Bromotrifluoromethane	$CBrF_3$	1301	800,000	14,000†
Bromochlorodifluoromethane	$CBrClF_2$	1211	324,000	7,650
Carbon dioxide	CO_2	—	658,000	658,000
Dibromodifluoromethane	CBr_2F_2	1202	54,000	1,850
Chlorobromomethane	CH_2BrCl	1011	65,000	4,000
Carbon tetrachloride	CCl_4	104	28,000	300
Methyl bromide	CH_3Br	1001	5,900	9,600

* Based on tests with white rats by the Medical Laboratories, U. S. Army Chemical Center.

† Subsequent tests by Kettering Laboratory of the University of Cincinnati (unpublished data) with a commercial Halon 1301 of improved quality indicated that the lethal concentration of decomposed vapor is at least 20,000 parts per million.

APPENDIX E

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS UNITED STATES AIR FORCE
WASHINGTON, D.C.

AGENT SELECTION GUIDE FOR THE A/S32P-13 VEHICLE

1. Aircraft Tire Fires:	Halon 1211 is preferred. Halon 1211 has the ability to extinguish deep seated tire fires. Dry Chemical has limited capability. Dry chemical will extinguish some tire fires provided fire involvement is of short duration. Fires that have burned deep into the cord area of the tire will reignite upon completion of agent discharge.
2. Fuel Spill Fires:	Dry Chemical is preferred. Dry chemical capability to accomplish quick flame knockdown coupled with area of coverage provided by the associated nozzle make it the preferred agent. Halon 1211 has limited capability. Halon 1211 is effective against small spill fires especially those hidden or obstructed by aircraft or other debris.
3. Aircraft Engine Fires:	Halon 1211 is preferred. Halon 1211 has proven to be very effective in extinguishing engine nacelle type fires. The agents ability to flow around engine vanes and other obstacles coupled with its relative cleanliness makes it the prefered agent for engine type fires. Dry Chemical has limited capability. Tests have shown that this agent successfully extinguished nacelle fires that had little or no obstruction but failed to extinguish fires when 3/4 or more of the available opening was blocked with vanes. Extinguishment with dry chemicals would necessitate extensive cleanup of engine components.
4. Aircraft Wing/Flowing Fuel Fires:	Dry Chemical is preferred. Tests have shown dry chemical to be effective for extinguishing large cascading fuel fires located on exterior surfaces of heated metal. Quick and continual movement of the nozzle was necessary to achieve extinguishment. Halon 1211 has limited capability. This agent dispensed through its associated nozzle is somewhat effective on small fires. It is ineffective on large fires of this nature since the gaseous agent quickly penetrates the fire and dissipates.

APPENDIX F

TABLE OF SPECIFICATIONS FOR THE A/S 32P-13 VEHICLE

2-1. VEHICLE.

Model	A/S 32P-13 and A/S 32P-13A
Type	Truck, Fire Fighting, Airfield Ramp

2-1A. TRUCK.

	A/S 32P-13	A/S 32P-13A
Length, in.	201.7	205.64
Width, in.	82.0	86.0
Height, in. (max.)	83.0	82.0
Wheelbase, in.	131.75	131.00
Tread, front, in.	63.5	64.9
Tread, rear, in.	63.0	64.4
GVW, lb (rated)	9000	8000
GVW, lb (actual)	7285	7245
Mfr.	IH	AMG
Model	1210	46
Type Pickup	Bonus Load	Series J20

2-2. DRY CHEMICAL FIRE FIGHTING UNIT.

Manufacturer	The Ansul Company
Model	S-350
Type agent	(Specification O-D-1407) PKP (Purple "K")
Expellant	Nitrogen
Capacity (nitrogen cylinder)	250 cu. ft.
Pressure (charged cylinder)	2265 psi
Capacity (PKP tank)	350 lb.
Operating pressure	225 ± 25 psi
Dimensions:	
Height (overall)	44.25 in.
Width (base)	42 in.
Length (base)	34 in.

2-3. HALON FIRE FIGHTING UNIT.

Refurbished by	The Ansul Company
Model	1211
Type agent	(Specification MIL-B-38741) Bromochlorodifluoromethane
Expellant	Nitrogen
Capacity (nitrogen cylinder)	110 cu. ft.
Pressure (charged cylinder)	2100 psi
Capacity (Halon tank)	507 lb.
Operating pressure	200-225 psi
Dimensions:	
Height	30.5 in.
Width	29 in.
Length	42.4 in.

2-4. HOSE REELS.

Manufacturer	Tokheim Corporation
Model	MFT 22-10-15A
Hose diameter (inside)	1 in.
Hose length	100 ft.
Dimensions:	
Height	23.2 in.
Width	26.25 in.
Length	22.25 in.

2-5. HALON NOZZLE.

Manufacturer	The Ansul Company
Hose connector	1 in. - 11-1/2 NPSH SWIVEL UNION
Rate	305 PPM ± 5%
Effective range	35 ft.

2-6. DRY CHEMICAL NOZZLE.

Manufacturer	The Ansul Company
Hose connection	1-1/4 in. - 11-1/2 NPSH SWIVEL UNION
Rate	7.25 PPS ± 10%
Effective range	53 ft.

APPENDIX G

ELECTRONIC FIRE-MONITORING EQUIPMENT

The instrumentation employed for the required parametric measurements consisted of radiometers and cameras. Thermal data were recorded on a Speed Servo 11, two-channel crossover potentiometer analog recorder, model L1102S, manufactured by the Esterline Angus Instrument Corporation and was equipped with an event marker which was manually activated when foam was discharged

Two heat flux transducers manufactured by Heat Technology Laboratory Inc., Model GRW 20-64D-SP, were mounted on steel poles and positioned on the diameter of the fire pits at right angles to the wind. These radiometers measured the radiant heat flux and were rated at 10 ± 1.5 millivolts (mV) at 15 Btu/ft^2 -sec. The angle of view was 120 degrees. Each unit was provided with a calibration curve by the manufacturer.

APPENDIX H

PHOTOGRAPHIC TEST PLAN

Each full-scale outdoor fire modeling experiment was monitored by two 16mm Lo Cam motion picture instrumentation cameras, both equipped with a 15mm lens exposing Ektachrome Commercial color film, type 7252, at 24 frames per second operated by one photographer each from fixed, elevated positions strategically located around the fire test bed. An elapsed-time clock, graduated in minutes and seconds, was within the line of sight of each camera. The experiments required the instrumentation cameras to start operating 0.5 minutes prior to fuel ignition and to continue running until the end of foam agent discharge.

Documentation coverage of the fire tests was provided from a 16mm Arriflex motion picture camera equipped with a 12mm to 120mm Angenieux zoom lens exposing Ektachrome Commercial color film, type 7252, at 24 frames per second. This camera was operated by one photographer from various positions around the fire test bed selected at his discretion.

One still photographer shot a minimum of six different exposures marking critical events before, during, and after each full-scale fire-modeling experiment using a 120mm Mamiya RB-67 camera equipped with a 90mm Mamiya/Sekor lens exposing Veri-Color II (VPS) roll film. The exposures provided 8- by 10-inch glossy color prints, 2- by 2-inch color slides, and 8- by 10-inch color viewgraphs of each full-scale fire modeling experiment.