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USAAVLABS TECHNICAL REPORT 67-39
AIRCRAFT FUEL CELL EXPLOSION SUPPRESSION SYSTEMS
AND THEIR APPLICABILITY TO ARMY AIRCRAFT

By
George H. Custard
James D. Donahue

July 1967

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-415(T)
FALCON RESEARCH AND DEVELOPMENT COMPANY
DENVER, COLORADO

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FORT EUSTIS, VIRGINIA 23604

This report was prepared by Falcon Research and Development Company under the terms of Contract DA 44-177-AMC-415(T). Work consisted of analyzing the fuel systems of 16 models of Army aircraft to determine which of 5 known fuel cell explosion suppression media would provide the most protection for the least cost in terms of weight, maintenance, and economics.

The contractor reviewed the literature pertaining to chemical inerting and suppression systems, gas purge systems, and halo-carbon additive systems. In addition, the work performed by other Government agencies in the areas of collapsible bladders and reticulated foam tank fillers was also studied, and limited ballistic testing was conducted with these two systems.

This report presents the results of the efforts described above and contains conclusions and recommendations applicable to the installation of specific explosion suppression systems in selected Army aircraft. The conclusions and recommendations are concurred in by this Command.

Task 1F121401A1500303

Contract DA 44-177-AMC-415(T)

USAAVLABS Technical Report 67-39

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by

George H. Custard
James D. Donahue

Prepared by

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Denver, Colorado

for

U.S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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Laboratories, Fort Eustis, Virginia 23604.

SUMMARY

The study covered by this report has focused attention upon the potential means of protecting the vapor spaces of Army aircraft fuel systems from the threat of fire and explosions caused by incendiary ammunition hits. As a means of implementing and quantifying passive defense data, the fuel containment of 16 models of Army aircraft has been studied, and the capacity, location, shape, surface area, empty weight, and tank material of these aircraft have been determined. These data have been used in conjunction with the parameters of the potential vapor space protection techniques to provide estimates of the weight penalties and dollar costs associated with the passive defense measures applied to the aircraft of interest.

Data relative to the fuel systems of the following aircraft are presented: UH-1B, UH-1D, U-1A, U-6A, U-8D, U-8F, OH-6, OH-13, Ol-F, OV-1A, OV-1B, OV-1C, CH-34, CH-37, CH-47, CH-54.

The passive defense measures which have been reviewed and considered by the study include: inert gas purging, fire detection and suppression by chemical means, collapsible internal tank bladders, reticulated foam tank fillers, and the direct addition of halocarbons to fuel.

The conclusions and recommendations which have resulted from the study are qualified to the extent that work is still in progress at several facilities on two of the most attractive passive defense measures. Thus, findings, subsequent to this report, may possibly indicate modifications to the conclusions presented herein.

Open-cell reticulated polyurethane foam has been found to be very effective in preventing explosions within tank vapor spaces for unpressurized fuel systems. This material has been shown to be compatible with aircraft fuel and engine components and to offer the most reliability for internal tank protection at acceptable costs.

Direct addition of halocarbons to fuel, while not fully tested at this time, offers potential for immediate "quick fix" protection on existing aircraft.

The other protection measures studied, while feasible, offer less protection and reliability than reticulated foam when all of the factors associated with long-term aircraft use are considered.

FOREWORD

The work summarized in this report was conducted under Contract DA 44-177-AMC-415(T) during the period 1 September 1966 to 31 March 1967. The project was under the technical direction of Mr. Francis P. McCourt, Chief, Safety and Survivability Division, and Mr. William J. Nolan, Project Engineer.

The study was conducted by the Falcon Research and Development Company under the guidance of Mr. Arthur M. Krill, President. Mr. George H. Custard served as Project Supervisor and was ably assisted by Mr. John R. Hobough and Mr. James D. Donahue. Other persons assisting in the project at the Falcon Research and Development Company include Mr. Charles E. Eppinger, Mr. Gale S. Weeding, Mr. Donald Saum, Mr. Harold Fisher, Mr. James McFadden, Mr. Chester Allapowa, and Mrs. Jerry Foster.

CONTENTS

	<u>Page</u>
SUMMARY	iii
FOREWORD	v
LIST OF ILLUSTRATIONS	ix
LIST OF TABLES	xiii
I. INTRODUCTION	1
II. FUEL FLAMMABILITY	3
A. FUEL VAPORIZATION	4
B. FUEL OXIDATION	7
C. IGNITION	10
D. SUMMARY	10
III. FUEL CELL FIRE AND EXPLOSION SUPPRESSION SYSTEMS	12
A. CHEMICAL EXTINGUISHANT SYSTEM	12
B. FIRE SUPPRESSION THROUGH FUEL ADDITIVES	45
C. INERT GAS PURGE SYSTEMS	49
D. COLLAPSIBLE INTERNAL TANK BLADDERS	67
E. RETICULATED FOAM FUEL TANK FILLERS	84
IV. TARGET DESCRIPTION AND ANALYSIS	117
A. AIRCRAFT CHARACTERISTICS	117
B. CONDITIONAL PROBABILITY OF FUEL CELL PENETRATION	141

V.	SUMMARY OF INTERNAL TANK PROTECTION SYSTEM	
	WEIGHT AND COST ESTIMATES	144
A.	THE APPROACH TO COMPARISON	144
B.	WEIGHT PENALTY GUIDES	146
C.	DOLLAR COST EVALUATION	149
VI.	CONCLUSIONS	153
VII.	RECOMMENDATIONS	156
	REFERENCES	158
	DISTRIBUTION	167

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Altitude-Temperature Flammability Limits of JP-4 Under Equilibrium Conditions	8
2	Altitude-Temperature Flammability Limits of JP-4 Under Dynamic Conditions and High Energy Ignition	9
3	Pressure Histories for Several Fuel/Air Mixtures	14
4	Spectral Bands Used for Radiation Measurement .	16
5	Peak Radiation Data for Caliber .50 Incendiary Ammunition	18
6	Early Radiation Rise for Caliber .50 Incendiary Ammunition Bursts	19
7	Radiation Intensity for the Combustion of Lean JP-4/Air Mixtures	20
8	Radiation Intensity for the Combustion of Rich JP-4/Air Mixtures	21
9	Dispersal Range Rates for Various Extinguishants, 120cc of Agent and 1000mg Booster Charge	25
10	Pressure-Temperature Relationships for Fire Suppression Agents of Interest	34
11	Reduction of Equilibrium Flammability Limits by the Addition of Bromotrifluoromethane to JP-4	48
12	Sea Level Flammability Limits for JP-4 and Gasoline Vapors With Nitrogen Inerting	54
13	Sea Level Flammability Limits for JP-4 Vapor With Carbon Dioxide Inerting	55

<u>Figure</u>		<u>Page</u>
14	Permissible Oxygen Concentration for CO ₂ and N ₂ Inerted Fuel/Air Mixtures With JP-4 Vapor	56
15	Quantities of Nitrogen and Carbon Dioxide Required for Inerting JP-4 Vapor	57
16	Sea Level Flammability Limits for JP-4 Vapors Under Attack by Caliber .50 Armor-Piercing Incendiary Ammunition With Nitrogen Inerting	58
17	Summary of Available Flammability Data for Gun-Fired Incendiary Ammunition	59
18	Nitrogen Container Weight for Steel Tanks	62
19	Nitrogen Container Weight for Titanium Tanks	63
20	Fuel Cell Arrangements for Collapsible Bladder Testing	69
21	Test Cell and Function Plates in Position for Vapor Space Tests	70
22	Caliber .30 M-14 Armor-Piercing Incendiary Burst Location Within the Test Target	72
23	Test Cell After Firing Caliber .30 M-14 Armor-Piercing Incendiary Through Explosive Fuel/Air Mixture	73
24	Entrance and Exit Holes After Firing Caliber .30 M-14 Armor-Piercing Incendiary Through Vapor Space	74
25	Test of the Collapsible Bladder Concept for Internal Fuel Tank Passive Defense	76
26	Test of a Reticulated Foam-Filled Fuel Tank Impacted by a Caliber .30 M-14 API Projectile	96
27	The Interaction of a Reticulated Foam Barrier With a Burning Fuel/Air Mixture	98

<u>Figure</u>		<u>Page</u>
28	Reticulated Foam Surface Before and After Exposure to the Fire Shown in Figure 27 . . .	105
29	Fuel Tank Configuration and Location for the UH-1B Aircraft	119
30	Fuel Tank Configuration and Location for the UH-1D Aircraft	120
31	Fuel Tank Configuration and Location for the U-1A Aircraft	121
32	Fuel Tank Configuration and Location for the U-6A Aircraft	122
33	Fuel Tank Configuration and Location for the U-8D Aircraft	123
34	Fuel Tank Configuration and Location for the U-8F Aircraft	124
35	Fuel Tank Configuration and Location for the OH-6 Aircraft	125
36	Fuel Tank Configuration and Location for the OH-13 Aircraft	126
37	Fuel Tank Configuration and Location for the O-1F Aircraft	127
38	Fuel Tank Configuration and Location for the OV-1A, B, and C Aircraft	128
39	Fuel Tank Configuration and Location for the CH-34 Aircraft	129
40	Fuel Tank Configuration and Location for the CH-37 Aircraft	130
41	Fuel Tank Configuration and Location for the CH-47 Aircraft	131

<u>Figure</u>		<u>Page</u>
42	Fuel Tank Configuration and Location for the CH-54 Aircraft	132
43	Weight Penalties for Internal Tank Protection Systems	147
44	Costs of Internal Tank Protection System . . .	156

TABLES

<u>Table</u>		<u>Page</u>
I	Specification Properties of Aviation Fuels . . .	3
II	Estimated Properties of Typical U.S. Fuels . . .	6
III	Booster Power Versus Capsule Size	23
IV	Physical Properties of Fire Suppression Agents .	36
V	Weight Estimates for a Chemical Fire Suppression System	38
VI	Weight and Cost Estimates for a Fuel Additive System	50
VII	Nitrogen Gas Container Data	61
VIII	Weight Estimates for a Nitrogen Gas Purge System	65
IX	Cost Estimates for a Nitrogen Gas Purge System .	66
X	Weight Estimates for Collapsible Bladder Fuel Systems	80
XI	Ten-pore Foam Barrier Performance Under Various Conditions With a 2.4% N-PENTANE-Air Mixture . .	92
XII	Twenty-pore and 40-pore Foam Barrier Performance Under Various Conditions With a 2.4% N-PENTANE-Air Mixture	92
XIII	Reticulated Foam Requirements and Weight Penalties for Specific U.S. Army Aircraft . . .	107
XIV	Cost Estimates for Reticulated Foam Systems in Army Aircraft	112
XV	Fuel System Characteristics for Specific U.S. Army Aircraft	134

<u>Table</u>		<u>Page</u>
XVI	Conditional Probabilities of Hits on Aircraft Fuel Cells Given a Hit on the Aircraft	142
XVII	Classification of U. S. Army Aircraft by Fuel System Capacity	146

I. INTRODUCTION

The objective of the study summarized in this report is to investigate five suggested methods of explosion suppression within aircraft fuel cells to define those systems most suitable to a series of specific Army aircraft. To achieve this objective, the available technical data regarding the suggested approaches to fuel cell protection have been surveyed and analyzed. Where data were clearly lacking regarding a specific technical approach, limited experimental tests were conducted to indicate the feasibility of the approach and to determine major parametric effects.

The passive defense of aircraft in general and of fuel tanks in particular has been of major concern to military aircraft designers and the using services for more than half a century. This project has benefited greatly from the hundreds of man-years of work which earlier investigators have devoted to various aspects of the fuel protection problem. Some of the data presented in this report are taken directly from the findings of earlier programs, and many conclusions rest squarely on the overall understanding which other investigators have made possible.

The primary requirement of this study is an analysis of the internal fuel tank protection requirements of Army aircraft under attack by incendiary ammunition of the caliber .30 to 20 mm size range. Particular emphasis is directed to the caliber .30 round, but larger sizes are also considered.

The approaches to internal fuel tank protection considered in this analysis include:

1. Fire detection and explosion suppression by chemical means.
2. Fuel additives.
3. Inert gas purging.
4. Collapsible internal tank bladders.
5. Reticulated foam tank fillers.

The aircraft fuel systems considered are:

- | | |
|----------------|--------------------|
| 1. UH-1B and D | 7. O-1F |
| 2. U-1A | 8. OV-1A, B, and C |
| 3. U-6A | 9. CH-34 |
| 4. U-8D and F | 10. CH-37 |
| 5. OH-6 | 11. CH-47 |
| 6. OH-13 | 12. CH-54 |

The physical characteristics of each aircraft fuel system have been studied to determine the applicability of each suggested protection measure, and recommendations have been made regarding the most feasible methods. Estimates of the weight penalties and dollar costs for each type of protection system have been made as an aid to the selection of the most favorable protection techniques.

II. FUEL FLAMMABILITY

Fuel flammability is of paramount importance to the aircraft fuel fire problem. The types of fuel presently used in Army aircraft are aviation gasoline and JP-4. These fuels are straight chain and ring hydrocarbons blended to give desired fuel properties. The ASTM specifications for aviation gasoline and JP-4 are given in Table I. All aviation gasoline, regardless of its octane rating, must meet these specifications.

TABLE I
SPECIFICATION PROPERTIES OF AVIATION FUELS

Properties Primarily Affecting <u>Ignitability</u>	<u>Aviation Gasoline</u> ASTM D-910	<u>JP-4</u> ASTM C-1655
Distillation, °F		
10% Evaporated (Max)	158	-
20% Evaporated (Max)	-	280
50% Evaporated (Max)	221	370
90% Evaporated	212-257	470 (Max)
Final Boiling Point (Max)	338	-
Sum of 10-50% Evap Temp (Min), °F	307	
Distillation Recovery (Min), %	97	
Distillation Residue (Max), %	1.5	1.5
Distillation Loss (Max), %	1.5	1.5
Reid Vapor Pressure (Max), PSI	7	3
<u>Other Properties Affecting Hydrocarbon Composition</u>		
Heat Content (Min), Btu/Lb	18720-18800	18400
Gravity, °API	-	45-57
Aromatics, Vol (Max), %	-	20
Olefins, Vol (Max), %	-	5
Freezing Point (Max), °F	-76	-60
<u>Other Properties Affecting Use</u>		
Mercaptan Sulfur, Wt (Max), %	-	0.003
Sulfur (Max), %	0.05	0.3
Copper Strip Corrosion (Max)	No. 1	No. 1

TABLE I (Continued)

Other Properties Affecting Use (Continued)	Aviation Gasoline	JP-4
	ASTM D-910	ASTM C-1655
Existent Gum (Max), Mg/100 Ml	-	7
Potential Gum (Max), Mg/100 Ml	6	14
Gum by Copper Dish (Max), Mg/100 Ml	5	-
Water Tolerance, Ml/Change	± 2	± 2
<u>Additives</u>		
TEL (Max), Ml/Gal	0.5-4.6	-
Dye Content	0.5-4.6	None
Antioxidant, Lb/1000 BSL	4.2	Optional
Metal Deactivator	-	Optional
Corrosion Inhibitor	-	Optional

In order for the combustion of liquid fuel to take place, these conditions must exist:

1. The fuel must be vaporized.
2. Sufficient oxygen must be present.
3. An energy source for ignition must be provided.

A. FUEL VAPORIZATION

The molecules of a liquid fuel are constantly moving, and the higher the temperature, the greater the state of agitation. As a given molecule reaches the surface of the liquid and is moving fast enough, it will break through the interface and escape into the vapor phase. The continued repetition of this process is known as evaporation. The reverse, in which molecules pass from the gas phase into the liquid phase, is called condensation. Both processes occur simultaneously.

Volatility expresses the ease with which molecules escape, and is dependent upon the temperature of the system. If molecules escape frequently at normal ambient temperatures, the

fuel is said to have high volatility; if they escape infrequently, the fuel has low volatility. The volatility of an aircraft fuel is measured and controlled through distillation characteristics and either its vapor pressure (Reid)¹ or its flash point². Distillation characteristics are a measure of the volatility of the fuel over its entire boiling temperature range, while its Reid vapor pressure and flash point data are indicative of the ability of the lower boiling portions of the fuel to vaporize. Table I illustrates the differences in average distillation characteristics between aviation gasoline and JP-4 fuels.

The volatilities of these aircraft fuels have been established to fit the design requirements of the engine and to meet the requirements of wide supply. Thus, aviation gasoline has a Reid vapor pressure of between 5 and 7 psi, while JP-4 has one of less than 3 psi. When fuels have Reid vapor pressures below 1 psi, a flash point test is used, since it better defines initial volatility.

In order to compare each fuel in equivalent terms, certain pertinent properties not included in the specification have been estimated and are presented in Table II.

Distillation and other volatility data are usually reported under normal sea level pressure conditions. At altitudes above sea level, the weight of fuel which will volatilize into a given volume remains the same as that at sea level because the partial pressure of the fuel is dependent only upon temperature. The weight of air decreases with altitude, and thus the concentration of fuel in the vapor space rises with increasing altitude.

¹Reid vapor pressure is the measure of volatility of a fuel at a given temperature and closely specified conditions. A given volume of fuel is enclosed in a specified container equipped with a pressure gage and is heated to 100°F. When equilibrium is reached, the pressure is recorded as the Reid vapor pressure.

²Flash point indicates the temperature at which the fuel vapor/air mixture above a liquid will momentarily flash when ignited by a flame. It is an approximation of the temperature below which a liquid may be handled without danger of fire.

TABLE II
ESTIMATED PROPERTIES OF TYPICAL U.S. FUELS

	Aviation	
	Gasoline	JP-4
Flash Point, °F	-40	-20
Reid Vapor Pressure, psi	6.5	2.7
Approx Flammability Limits*, °F	-40 to +20	-20 to +60
*Fuel temperature range at sea level, within which the vapor in equilibrium with the fuel will form a flammable mixture with air.		

The fact that a hydrocarbon will not burn while it is in the liquid state is of prime importance in understanding the significance of volatility and vaporization. Fire occurs only when fuel vapor is mixed with a sufficient amount of oxidizer.

As a fuel's temperature is raised in an open vessel, its vapor pressure increases until it matches atmospheric pressure. In the case of a pure compound, this temperature is called its "boiling point". Aviation fuels are mixtures of many compounds, each of which has its own properties; the vaporization of such a mixture is not as simple as that of a pure compound. When aviation fuel is allowed to evaporate, the lighter components (those having higher vapor pressures and lower boiling points) will evaporate first, and the vapor pressure of the remaining liquid will decrease as it becomes richer in heavier components. Because of this weathering process, the equilibrium concentration of vapors in the free space above the liquid will be somewhat dependent on the relative volumes of liquid and free space and the length of time that the fuel has been held in a vented tank.

The importance of the vaporizing tendencies of fuels may be illustrated as follows. When fuel is held in an aircraft wing tank and exposed to high temperatures such as those which occur from the hot summer sun's beating on the wing's surface, the more volatile components of the fuel are vaporized to mix with the air above the fuel. Some of these vapors pass out of the vent, and the vapor pressure of the remaining liquid is lowered accordingly. In this manner, as the fuel is "weathered", its flammability range is changed and approaches

that of the less volatile fuels. In the case of aviation gasoline, its flammability range would gradually approach that of fresh JP-4 fuel.

B. FUEL OXIDATION

In order to meet the second combustion requirement, sufficient oxygen must be present to form a flammable mixture. That is a mixture which will continue to support the propagation of a flame after the ignition source has been removed. There are both lean and rich limits to such flammable fuel/air mixtures. The composition of the mixtures at the limiting conditions of flammability are dependent upon pressure, temperature, and, to some extent, the physical environment in which the flame exists. A flame front which is passing through a volume of fuel/air mixture may be considered to be in dynamic equilibrium with its environment. The heat liberated in the combustion process just equals the energy loss from the flame front so that the flame temperature and flame velocity are constant and representative of the mixture and the physical conditions existing within the container.

The following statements are true, for all practical purposes, when limited to aircraft fuels:

1. Decreasing the pressure narrows the temperature range for the ignition of flammable mixtures (Figure 1).
2. Fuel/air mixtures become nonflammable at pressure altitudes greater than 60,000 feet.
3. Relative humidity has only a slight effect on the flammability limits.
4. The presence of fuel mists over the liquid creates a wider range of flammable fuel/air mixtures (Figure 2).
5. When the oxygen content of the air in a tank is increased by the release of dissolved oxygen from the fuel, the lower flammability limit is extended slightly while the upper limit is extended considerably (Figure 1).

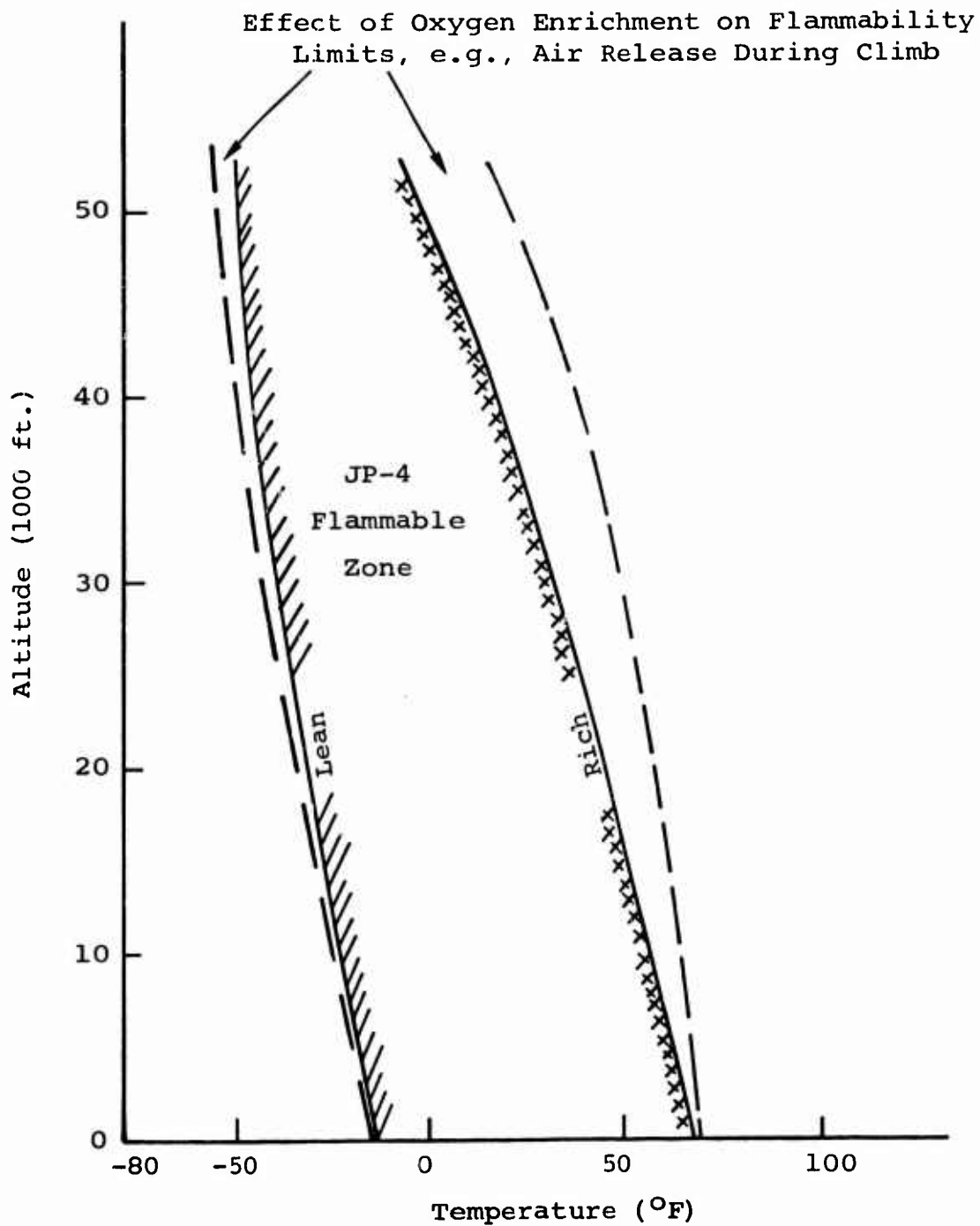


Figure 1. Altitude-Temperature Flammability Limits of JP-4 Under Equilibrium Conditions.

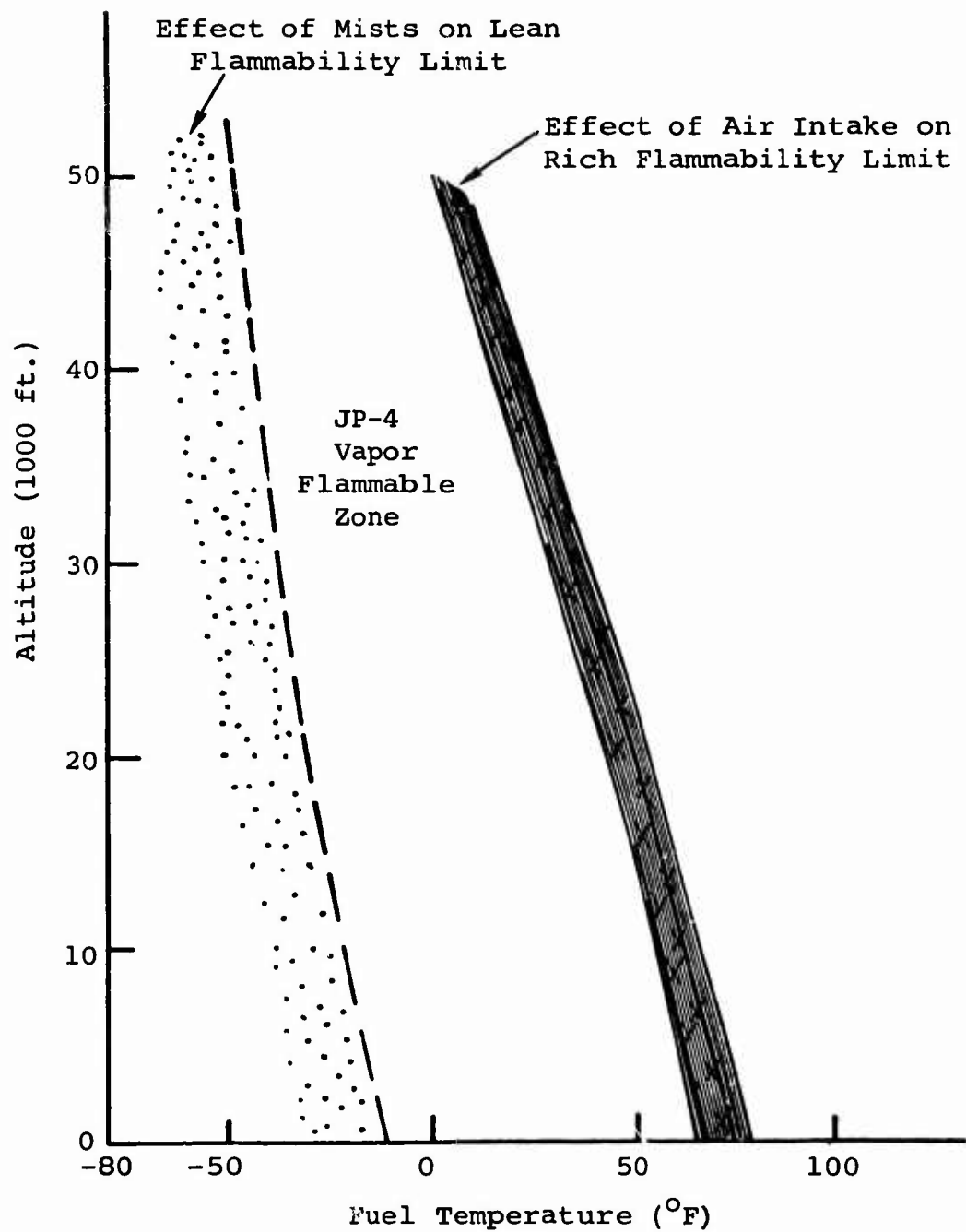


Figure 2. Altitude-Temperature Flammability Limits of JP-4 Under Dynamic Conditions and High Energy Ignition.

Practical hazards exist outside of the flammability limits when the fuel cell contents are not in equilibrium. During climbing, dissolved oxygen is released from the fuel, thus expanding the flammability limits. Vibration of the aircraft during flight can cause mist formation. Since mists do not coalesce quickly, the presence of the mist will cause the flammability limits to expand. Finally, all fuel systems on Army aircraft are vented to the atmosphere and are drawing in air or expelling fuel/air mixtures whenever the aircraft is changing altitude.

If the ratio of fuel vapor to air is within the limits represented by the equilibrium conditions, shown in Figures 1 and 2, then a flame will always propagate and a damaging fire may be expected for each ignition.

C. IGNITION

In the case of an aircraft fuel cell hit by incendiary ammunition, the ignition requirement is met by the incendiary burst. The round supplies an abundance of energy; therefore, if flammability conditions are met anywhere within the fuel tank, there is practically a 100% probability of ignition.

A massive ignition source can cause combustion to take place under conditions where a flame cannot be continuously propagated. Thus, if the entire vapor space of a fuel tank is filled with incendiary sparks, the thousands of "small fires" may produce an effect which is very similar to a propagating flame explosion. The effective flammability limits may be expanded to a considerable degree by very effective incendiary action.

D. SUMMARY

As a practical matter, the equilibrium flammability conditions are seldom met within a fuel tank of operating Army aircraft. Only when operating vapor space temperatures get down into the range of 75°F or less can a flame be propagated in the equilibrium tank vapor space when the fuel is JP-4. When the fuel is gasoline, equilibrium flammable conditions are even harder to achieve, since the operating temperature must not be higher

than about 20°F. The need for internal tank protection should not be dismissed too quickly on this basis, however, since several forces tend to prevent the equilibrium conditions from being achieved within a tank and generally the types of non-equilibrium conditions which do exist favor vapor space explosions.

A properly functioned incendiary bullet is a massive ignition source and can cause damaging fuel/air explosions under conditions which would be unfavorable for a lesser ignition source.

III. FUEL CELL FIRE AND EXPLOSION SUPPRESSION SYSTEMS (U)

A. CHEMICAL EXTINGUISHANT SYSTEM

The data illustrated in Figures 1 and 2 indicate that internal fuel cell explosions are rather improbable if equilibrium vapor mixture conditions exist. This fact is especially true for low-flying aircraft operating under very cold climatic conditions or at temperatures greater than 70°F. There are operating conditions, however, which will cause the vapor mixture in a fuel cell to deviate considerably from equilibrium and may thus increase the probability of an explosion mixture. For example, when the tanks are vented to the atmosphere and rapid changes in altitude cause the tank to bring in air, a very lean mixture may result. Such lean mixtures may be within the explosive limits, and they constitute a very real hazard.

When ignited by an incendiary bullet, the vapor in an aircraft fuel compartment may undergo combustion which creates pressures within a few milliseconds that are capable of destroying the aircraft. However, within these few milliseconds before the pressures generated burst the compartment, the combustion takes the form of a very fast propagating flame. An internal tank chemical fire extinguisher system can be effective in coping with the initial fire when the physical shape of the tank permits good "visibility" for the detector and an effective dispersal pattern of the extinguishant after release.

The effectiveness of a chemical fire suppression system depends primarily on its speed. If it can detect the presence of danger and actuate an extinguishing device within those milliseconds before the explosion attains destructive proportions, it can be very effective.

The Electronics Corporation of America (ECA), featuring its series of FIREYE fire detection systems, and the Fenwal Division of the Walter Kidde Corporation are among the leading developers of aircraft fire detection systems. To determine the nature of the parameters of an explosion which affect system operation, ECA studied the spectral qualities of ignition sources and ignited fuels of various fuel/air mixtures (Ref. 25). They determined time versus critical pressure

functions for incendiary ignited explosions in fuel compartments. Tests of detection time and range of detection were also performed. The most violent fuel explosions occur when the ignited fuel vapor contains a stoichiometric mixture of fuel and air. The chemical explosion suppression system must be able to deal with the worst of these conditions. ECA has conducted many explosion tests in fuel tanks of varying sizes using a range of fuel-to-air ratios. The pressure versus time profiles for several of the different fuel/air mixtures tested in a 4.3-cubic-foot fuel tank are presented in Figure 3. These tests were conducted using aviation gasoline. The results of tests conducted in 0.4-, 1.27-, and 36.2-cubic-foot tanks are similar and are presented in Reference 25.

The fuel-to-air ratio used in each test was determined by means of a combustible gas indicator manufactured by the Mine Safety Appliances Corporation. From these data, it was established that the maximum explosion conditions for a large tank occur at a fuel/air mixture of about 3.52% by volume. This agrees quite closely with results found by other workers in the field. Tests were run over a range of fuel-to-air ratios from 1.9% (lower flammability limit) to 7.0% (approaching the upper flammability limit). The most difficult extinguishing conditions are found to occur for fuel-to-air ratios lying between 3.0% and 4.0%.

In order to attain the required overall reaction speed, the detector device must operate automatically. Radiation sensing units which receive information of the explosion's birth through emitted radiation moving with the velocity of light seem to be most suitable for this purpose. Ideally, the detection unit should respond within 20 to 50 milliseconds to energize an extinguishing system within 100 milliseconds in order to provide sufficient lead time to perform the extinguishing action.

To take advantage of this lead time, the radiation detector must be matched with a high-speed extinguishant dispersal system which explosively distributes a fine, dense mist of an extinguishing agent over the area of combustion.

Detection Systems

All fires and explosions emit radiant energy which extends from the far-infrared to the ultraviolet region of the

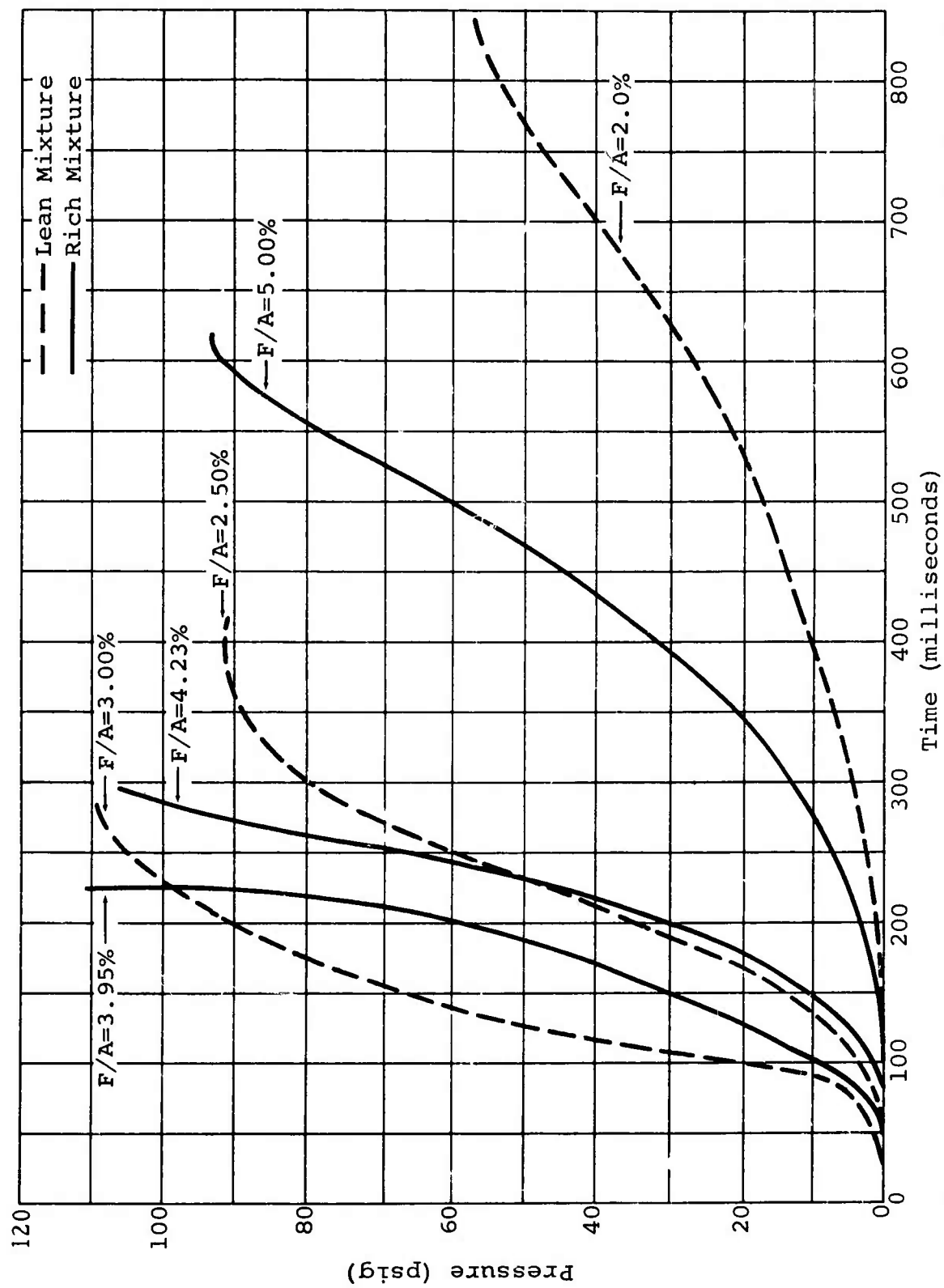


Figure 3. Pressure Histories for Several Fuel/Air Mixtures (4.3-cubic-foot tank and spark ignition).

spectrum. Most of the energy is present in the infrared region. Because infrared energy is also emitted by the sun and hot surfaces, undesirable radiation must be filtered out so that only infrared radiation from an explosion actuates the detector. A detector sensitive only to infrared radiation may be entirely suitable in a light-tight compartment such as the fuel cell and would serve as an excellent detector of fuel tank explosions.

It is characteristic of very sensitive high-speed radiation detectors that their sensitivity is limited to a given portion or band of the radiation spectrum. For example, there are various phototubes which are sensitive in the blue and in the visible bands, while lead sulfide (PbS) photoconductors can penetrate into the infrared portions of the spectrum.

To ensure that the detector employed is one which makes use of the strongest portion (with the fastest rise time) of the radiation emitted by an incipient explosion, extensive measurements were made of the spectral emission of both ignition sources and ignited fuel vapor. The spectra of each were analyzed separately, because, while the detector must be capable of detecting radiation from the burning vapor, it would be useful if it could also detect the entering of the ignition source, thus increasing the lead time available for the extinguishing action.

Measurements were made simultaneously in the four spectral bands shown in Figure 4. These bands, which range from the ultraviolet to the infrared, are covered by four detectors, each of which is paired with a filter to limit the spectral band which that detector could "see". Although PbS is sensitive over most of the visible range, phototubes were utilized for the first three bands and PbS was utilized for the infrared portion to make possible a clearer determination of the spectral distribution of the measured radiation.

Radiation intensity at a given distance from the source can be calculated with the formula

$$I = \frac{W}{4\pi R^2}$$

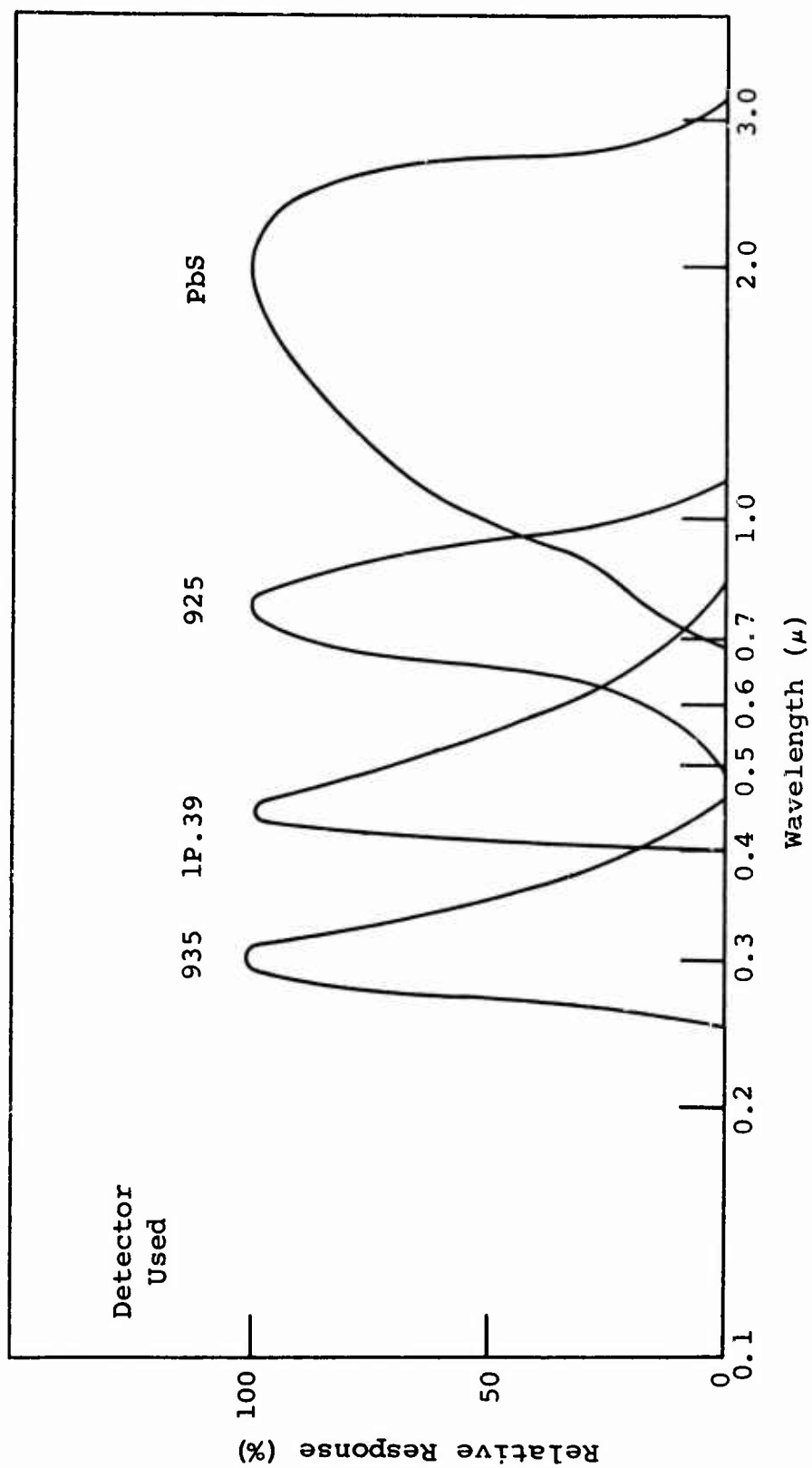


Figure 4. Spectral Bands Used for Radiation Measurement.

where I is the intensity in watts per square centimeter, W is the power output of the source in watts, and R is the distance from the source in centimeters.

Spectral Radiation From Incendiary Projectiles

Several spectral measurements were made of the radiation emitted by functioning caliber .50 incendiaries, burning both in air and in fuel vapor (JP-4, light naptha, aviation gasoline). Since no discernible difference in radiation spectra for a given incendiary during the first few microseconds was observed with different test-tank "atmospheres", the data presented in Figures 5 and 6 are not distinguished on this basis. Figure 5 indicates peak radiation properties of the burst, and Figure 6 gives detail during the early rise of radiation intensity.

Spectral Radiation From Ignited Fuels

In order to obtain true spectral measurements of radiation emitted by ignited fuel vapors which are undistorted by radiation from the ignition source, the vapor burned for these measurements was ignited by a low-intensity spark of short duration from an ordinary spark plug. Fuels used for these tests were JP-4, aviation gasoline, and several light hydrocarbon fuels such as hexane.

Figures 7 and 8 show the radiation from spark-ignited explosions of lean and rich JP-4 fuel and air mixtures.

With both mixtures there was a pronounced lag in the appearance of visible-red radiation. This was expected in the case of lean mixtures, since the blue flame typical of this type of mixture would not be expected to possess any visible-red radiation bands. This delay, moreover, has also been noted in rich and very rich mixtures, indicating that the initial explosion has the characteristics of a lean flame for a range of 20 to 35 milliseconds.

As a result of these studies, the PbS infrared-sensitive cell was judged to be a very adequate detection device for chemical suppression systems. Increasing radiation incident on the PbS cell causes the circuit to trigger a control unit. As many detector units as are needed can feed a single control

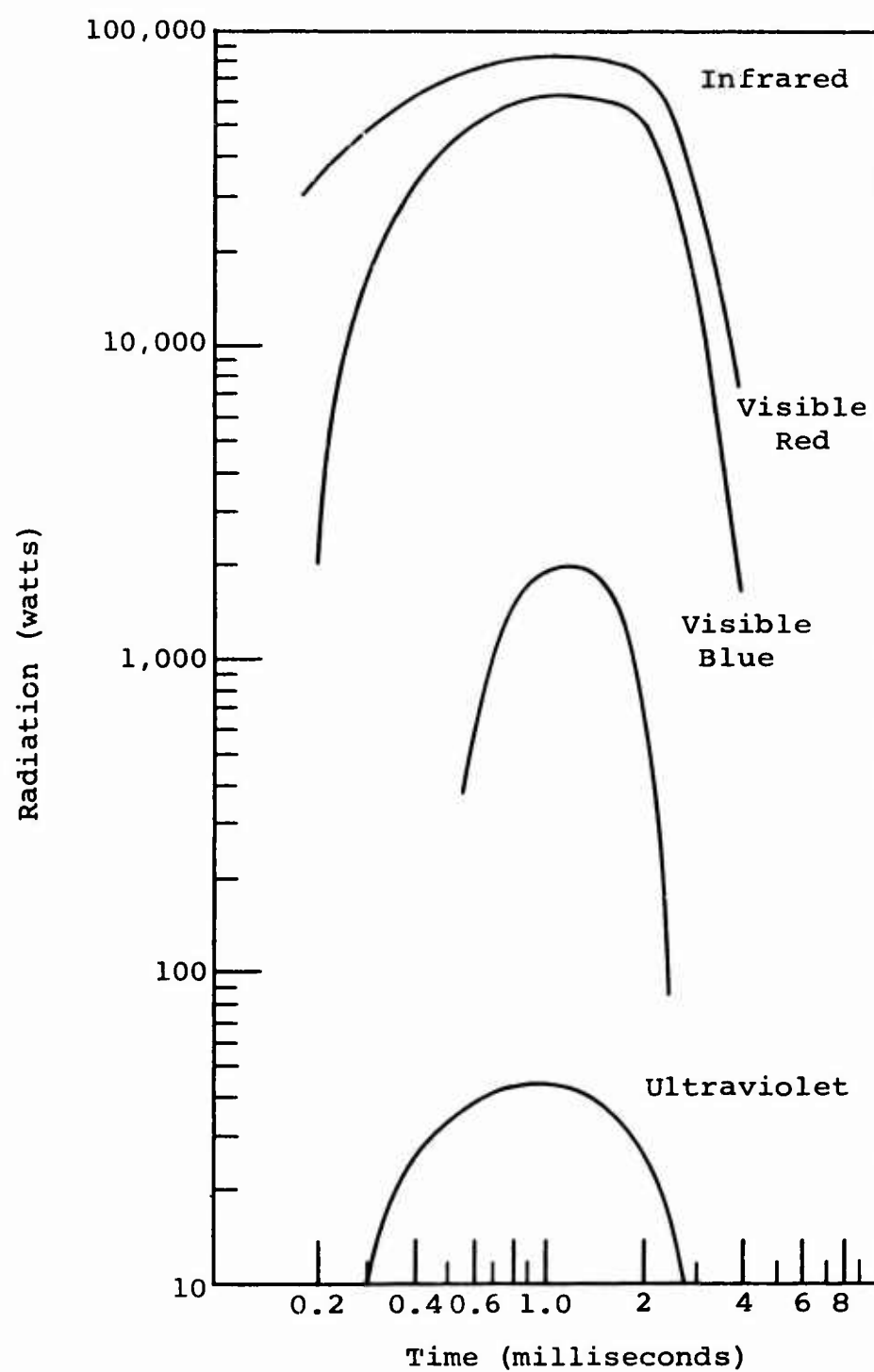


Figure 5. Peak Radiation Data for Caliber .50 Incendiary Ammunition.

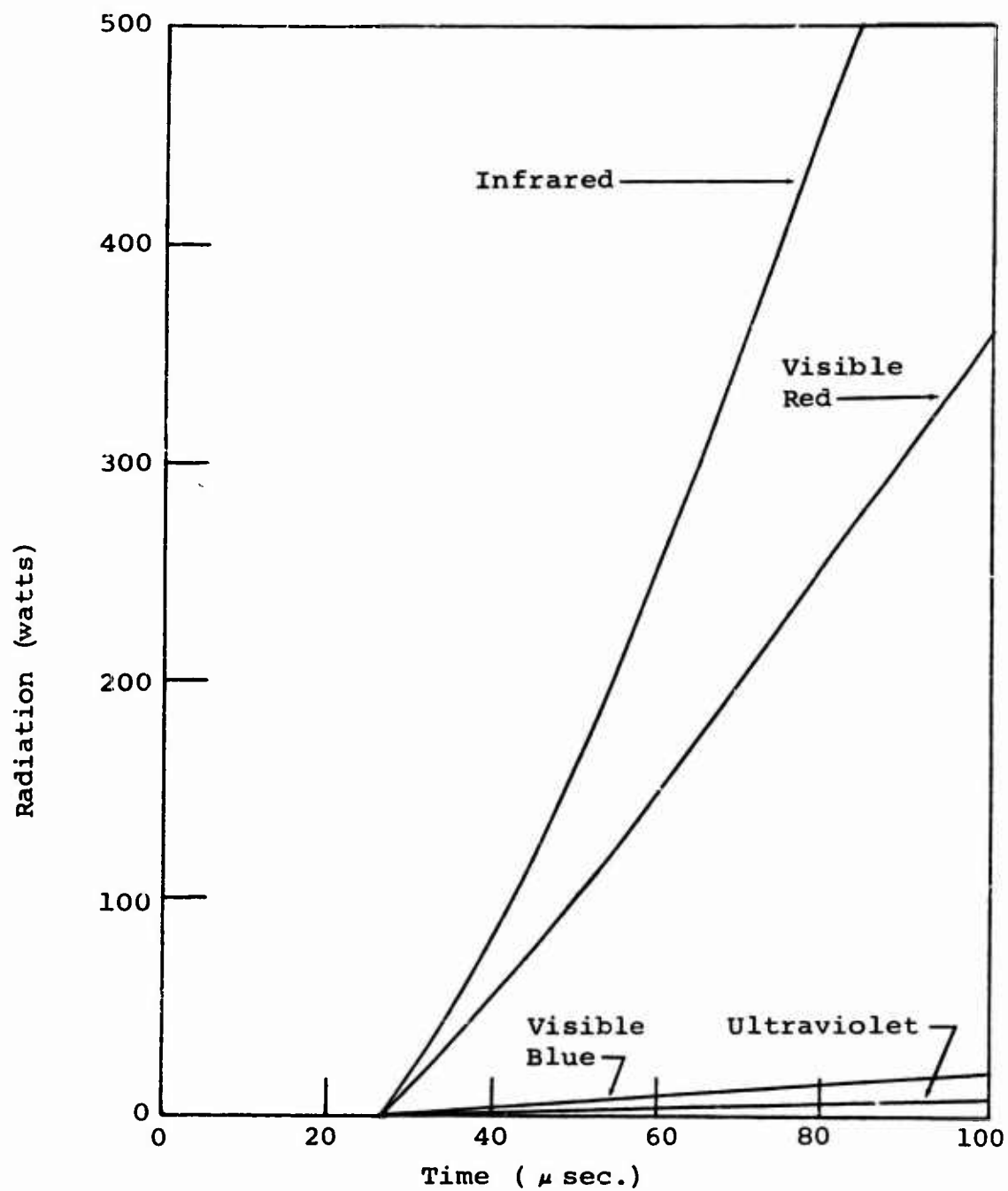


Figure 6. Early Radiation Rise for Caliber .50 Incendiary Ammunition Bursts.

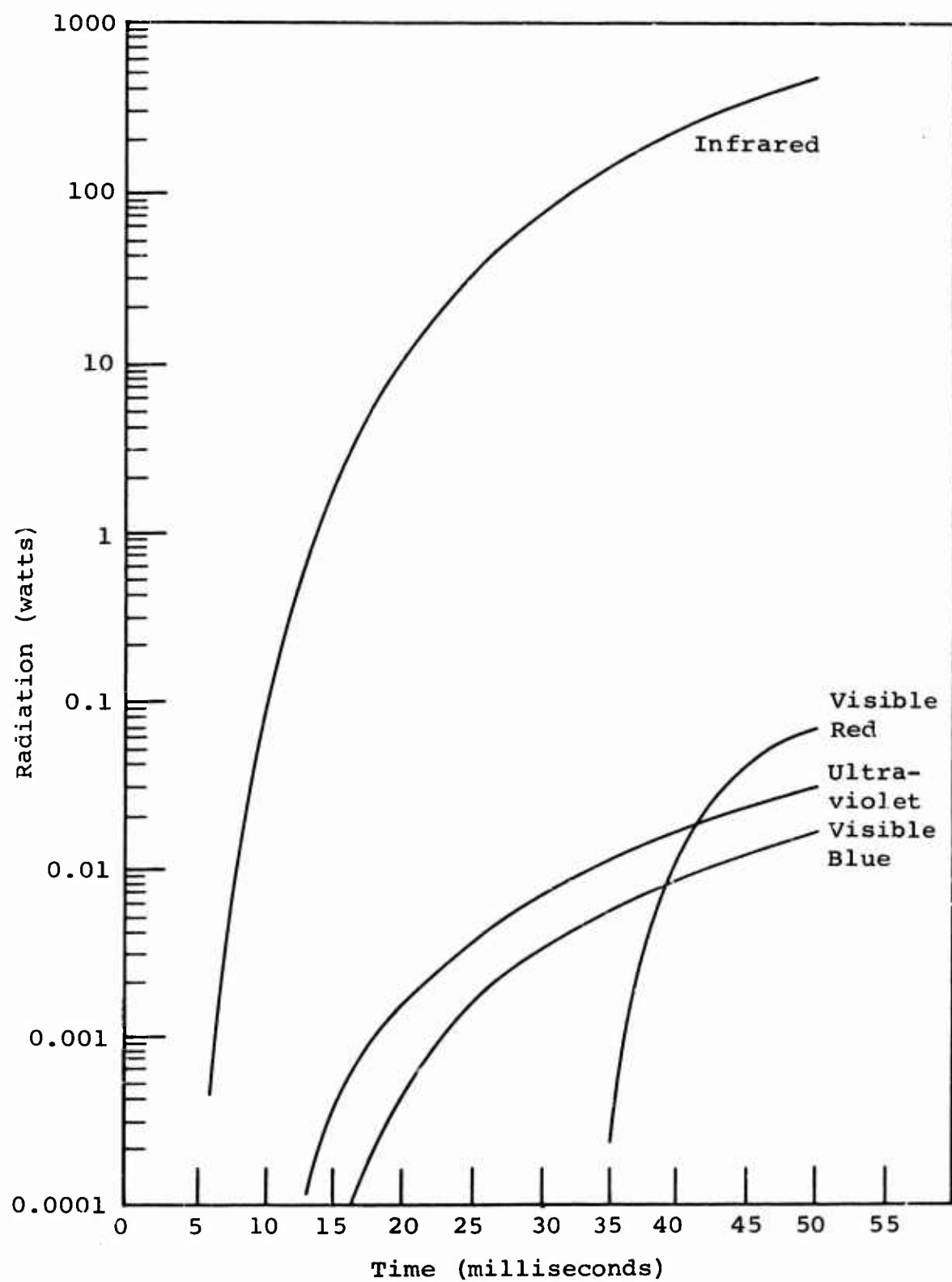


Figure 7. Radiation Intensity for the Combustion of Lean JP-4/Air Mixtures.

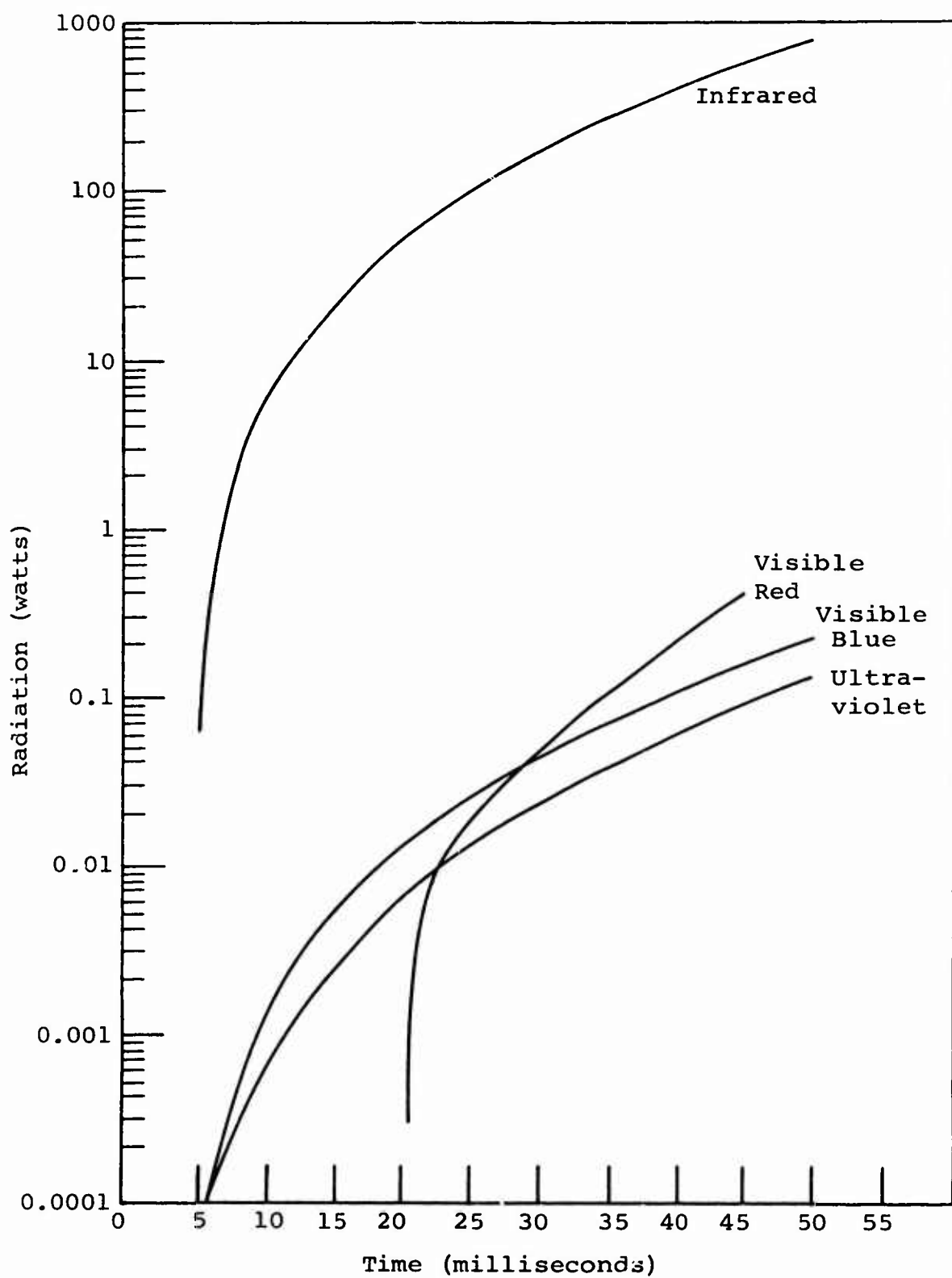


Figure 8. Radiation Intensity for the Combustion of Rich JP-4/Air Mixtures.

unit. Any number of extinguishers can be fired from a single unit if sufficient current to fire all the detonators is available.

Actuators

Following the successful detection of an incendiary hazard, it is necessary to promptly activate an actuator which will disperse the suppression agent in a suitable manner over its region of effectiveness.

In a typical system, there are three components: the infrared detector; the control unit, which amplifies the pulse received from the detector and in turn triggers a detonator switch; and the extinguishers, frangible capsules containing the extinguishing agent and an actuator or explosive charge to disperse it when power is applied via the detonator switch.

A wide variety of types of detonators and booster charges have been considered or could be used to actuate the extinguishing action. The brief discussion which follows is from the experience of the Electronics Corporation of America and will serve to illustrate the importance of various parameters involved in the action of this vital component of a suppression system

One test series involved the determination of detonator firing time versus applied voltage. Two types of detonators were considered: the Hercules type MK63, a high-impedance (3000 to 4000 ohms) carbon-bridge detonator actuated directly by the electric pulse output, and a Hercules type EC6-A1, a low-impedance (7 ohms) wire-bridge detonator which can be utilized when an explosive switch is used to actuate the detonators in the system by applying line voltage. The EC6-A1 detonator fires faster for a given applied voltage than does the MK63 detonator. Each time measurement was made individually by means of a scope upon which a portion of the detonator-energizing signal was used as zero-time indication, and rupture of a foil strip held against the detonator was used as firing-time indication.

As a result of the above-described tests, the EC6 type was designated as standard for all ECA extinguishing systems. Using the EC6-A1 detonators, the number of detonators which could be fired from a single detonator switch was determined.

The results of a series of tests, using increasing numbers of detonators, showed that at least 20 detonators could be fired reliably from an 18-volt supply by a single detonator switch. It is possible that this number can be increased.

A technique which was found to increase reliability of detonator firing is that of connecting a small resistance in series with each detonator, and then connecting all resistance-detonator combinations in parallel. If one detonator fires more quickly than another or otherwise short circuits, it will not prevent all other detonators from firing. The optimum series resistor was found to be 3.3 ohms for an 18-volt detonator-actuation signal with the EC6-A1 detonator.

An additional safety device may be added to the system by grounding the case of the detonator so that no static charge can be built up to cause the detonator to fire the extinguisher accidentally.

Once the use of a standard detonator has been established, it becomes necessary to determine the optimum booster capsule. Optimization rather than maximization is required, because the increase in dispersal radius obtained by increasing from one booster power to the next must be large enough to offset any increased risk in handling incurred by a more powerful booster charge.

A summary of optimum booster power versus nominal capsule size is given in Table III.

TABLE III
BOOSTER POWER VERSUS CAPSULE SIZE

Nominal Size (cc)	Booster Power (mg of PETN)
25	300
50	400
100	1600
200	2400

In this study, the relative dispersal ranges of the following halocarbons were examined: bromochloromethane, bromochlorodifluoromethane, dibromodifluoromethane, bromotrifluoromethane, and trichloromonofluoromethane.

Figure 9 shows that CHBr_2Cl provides a somewhat better dispersal range than other agents tested (20% better than CH_2BrCl). However, this advantage over the standard aircraft fire extinguishing agent, $\text{CH}_2\text{BrCl}(\text{CB})$, is heavily offset by the fact that CHBr_2Cl has a specific gravity of 2.440 against that of 1.930 for CB, making it 25% heavier than the latter. Thus, although the use of CHBr_2Cl as the extinguishing agent would reduce the amount of agent required, the weight of the extinguishing system would not be reduced; conversely, it might be increased. Therefore, CB has continued to constitute the extinguishing agent in many suppression systems.

Another parameter evaluated for its effect on dispersal range was agent temperature. CH_2BrCl and CHBr_2Cl were tested at both -65°F and 150°F . No significant difference in dispersal was observable except for a slightly higher dispersal rate after 5 milliseconds for cooled CHBr_2Cl . The latter, however, does not appear to be large enough to affect the extinguishing operation appreciably.

Extinguishing Agents

The past decade has witnessed a great deal of study and investigation of extinguishing agents and the mechanisms of their participation in the chemical and physical processes of combustion.

Water acts as a diluent and heat sink. Carbon dioxide acts as a diluent and, if frozen, as a coolant. Foams and the heavy vapors of carbon tetrachloride blanket pools of fuel and mechanically separate fuel from oxidant. Finely subdivided solids such as sodium bicarbonate become effective surfaces for inerting active flame carrier species and disrupt the flame by mechanical and perhaps chemical means. Other agents such as hydrobromic acid may enter into the flame propagating mechanism and induce extinguishment by chemical means.

Present technology indicates that chemical disruption of the flame front produces the greatest effectiveness per unit of

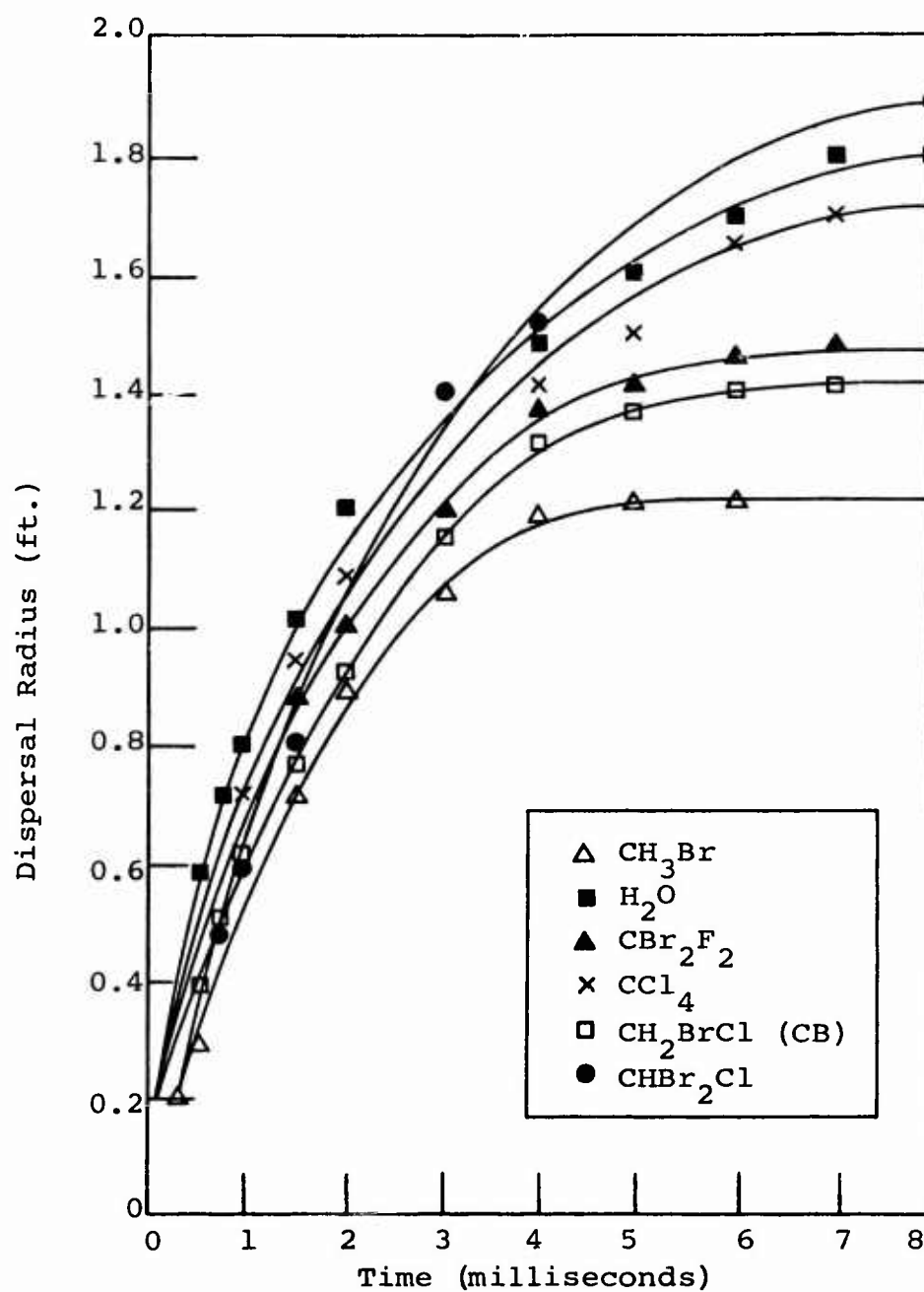
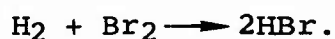


Figure 9. Dispersal Range Rates for Various Extinguishants, 120cc of Agent and 1000mg Booster Charge.

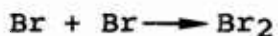
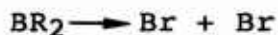
agent volume, an important weight-saving factor to be considered in selecting an agent for airborne vehicles. Therefore, only agents that extinguish hydrocarbon flames chemically received consideration in this study. Recent studies indicate that hydrocarbon flames are inhibited by reactions that remove the chain carriers.

For many years, it was believed that flames were extinguished by either cooling the reactants below ignition temperature or separating the fuel from the oxidizer. When finely powdered sodium bicarbonate was found to be capable of inhibiting fire (U.S. Pat. 1,973,420), the liberation of CO₂ was thought to extinguish the fire. Quantitative analysis of the residue, however, indicated that the CO₂ liberated was only about 5 percent of that actually required. Some other mechanism obviously entered into the process.

Kinetic processes of combustion were being studied, and in 1906 Bodenstein and Lind published the empirical value for $d[\text{HBr}]/dt$ in the reaction



Later investigations indicated that combustion processes were a chain reaction of the form



The OH radical was found in hydrogen-oxygen combustion at temperatures above 1000°C. Atomic hydrogen in hydrogen-oxygen mixtures (2.5×10^{-4} mm H in 100 mm H₂) lowered the upper explosion limit in a temperature-pressure diagram. H was found in the hydrogen-oxygen flame in excess of that in normal thermal equilibrium. The combustion kinetics of hydrogen-oxygen flame, therefore, depend on H, OH, and probably O. Triple collision reactions may occur, or a third body may

orient the other two bodies with respect to one another to cause a chain-branching reaction.

Chemical agents inhibit flame most effectively by interrupting the chain reaction. This is the effect, at least in part, of applying dry powder to fire. The inhibiting effectiveness of a low concentration of halides on low-pressure mixtures of hydrogen and oxygen in the neighborhood of 1 mole percent was $\text{Cl} < \text{Br} < \text{I}$, indicating a chain-breaking mechanism. The halides are highly poisonous, however, and could not be used as extinguishing agents.

While the halogenated compound, carbon tetrachloride, was used in fixed fire extinguishing systems for aircraft as early as 1922, the inhibiting process was not understood; functions were believed to be cooling by vaporization and suffocation by cutting off air. Methyl bromide was considered as an agent in 1929 but was abandoned because of extreme toxicity.

The British and the Germans used methyl bromide. The Germans used a mixture of 50% methyl bromide and 50% ethylene bromide, called "Ardexin". This mixture, too, was highly toxic.

The Germans developed bromochloromethane (CB) in 1939-1940 and tested its extinguishing capabilities. CB appeared to be comparable in extinguishing effectiveness and was considerably less toxic than "Ardexin". When "Ardexin" overcame members of the crew of the Graf Spee (during a shelling by British cruisers), the German Navy investigated CB as a possible substitute. CB was adopted in 1941. Junkers engineers conducted wind-tunnel fire tests in 1942 to determine the relative effectiveness of CB and several other agents in extinguishing comparable gasoline fires. These tests indicated that the concentrations of agents in air to put out comparable fires were as follows:

AGENT	% VOLUME
Carbon Dioxide	45
Dichlorodifluoromethane	35
Carbon Tetrachloride	30
Methyl Bromide	15
CB (Bromochloromethane)	15
D-L (50% Dachlaurin CB, 50% CO ₂ by weight)	12-15

In the United States, the CAA began a series of fire tests on DC-3 type nacelles at the National Bureau of Standards in 1939, as a result of several in-flight power plant fires. These tests showed that using methyl bromide instead of carbon dioxide would result in a 20% reduction in agent weight, and that contamination of the air of the aircraft cabin was extremely unlikely. The CAA therefore approved the use of methyl bromide for fixed airborne fire extinguishing systems.

CB was introduced into the United States in June 1945, with the recommendation that it be checked as a possible substitute for CO₂ and methyl bromide. As a result, tests were conducted on a B-29 engine nacelle. Test results indicated agent effectiveness by relative weight requirements, using CO₂ as a base, as follows:

AGENT	RELATIVE REQUIREMENT
Carbon Dioxide	100
Methyl Bromide	75
CB	50
D-L (Dachlaurin)	20

Final results of this study were reported in 1948, with the recommendation that all methyl bromide and CO₂ aircraft fire protection systems be converted to CB systems.

Wind-tunnel fire tests were conducted on a J-35 jet engine nacelle and a modified F-84 nacelle from February to October 1948 at Wright-Patterson Air Force Base. Results of these tests comparing CB with other agents indicated the following order of effectiveness, decreasing from top to bottom:

Methyl Iodide	1
Methyl Bromide	2
CB	2
Water	3
CO ₂	4
F-12 (Dichlorodifluoromethane)	5
F-22 (Chlorodifluoromethane)	6

As a result, CB was recommended for adoption in November 1950.

The first systematic survey of fire extinguishing agents for hydrocarbon fire was conducted from 1947 to 1950. In this research, a number of halogen compounds were examined; physical properties were noted; flammability areas were determined with a 51 mm flame tube and were compared with other agents; and the effects of temperature, pressure, and binary mixtures were studied. The flame-inhibiting properties of the halogen content of the hydrocarbon were found to be $F < Cl < Br < I$. In a given homologous series, it was found that an increase in molecular weight increased flame inhibition.

From this survey, several compounds were found with effectiveness (considering both weight and volume requirements) equal or superior to methyl bromide, including bromochloromethane (CB), bromotrifluoromethane (BT), dibromodifluoromethane (DB), and dibromotetrafluoroethane. Other effective compounds that were neglected because of high toxicity include hydrobromic acid, hydrochloric acid, methyl iodide, ethyl bromide, ethyl iodide, and dibromomethane. Of the nontoxic agents, dibromodifluoromethane appeared to be the most effective.

Subsequent tests were conducted using 1,2-dibromotetrafluoroethane, methyl bromide, carbon dioxide, bromochloromethane, and dibromodifluoromethane to extinguish fires involving air and hydrogen, ammonia, methanol, ethanol, aniline, nitromethane, and elemental fluorine. The most effective agent for all these materials except elemental fluorine was found to be 1,2-dibromotetrafluoroethane. None of these agents was effective with elemental fluorine, however, because of severe reactivity.

Other studies indicated that dibromodifluoromethane and bromotrifluoromethane were more effective in extinguishing JP-4 fires than water, bromochloromethane, or methyl bromide. In subsequent tests to extinguish JP-4 fires in a simulated compartment, dibromodifluoromethane was selected because it, as a liquid, could better penetrate the fire. The amount of agent required was found to decrease with application rate. The Navy, meanwhile, adopted bromotrifluoromethane for fixed airborne fire extinguishing systems because of its inert physiological properties.

Theory of Mechanisms of Flame Extinguishment

The precise mechanisms by which the halogen agents inhibit flames are as yet unknown. A review of pertinent literature has been conducted by Atlantic Research Corporation, and the problem is still being studied. Much is now known about the action of these agents, even though our knowledge is incomplete.

Flames from fuel that does not contain hydrogen may be insensitive to halogen compounds, as shown by recent studies of the action of methyl bromide on carbon monoxide air flames. Stanford Research Institute studied the mechanisms of inhibiting methane-air flames and $\text{CH}_4 - \text{NO}$ and $\text{CH}_4 - \text{NO}_2$ flames. These studies indicate that the halogen inhibitors appear to have little effect on flames involving NO or NO_2 , probably because of a lack of chain-branching in the $\text{CH}_4 - \text{NO}$ and $\text{CH}_4 - \text{NO}_2$ flames.

Since combustion of hydrocarbon and oxygen proceeds by chain-branching reactions, the inhibiting effect of the halogen agents was proposed as due to rapid reaction between the chain carriers H , O , and OH and the halogen acids; the inhibiting mechanism continuously regenerates the inhibitor species and the halogen acids. This conclusion was reached as the result of measurements of flame speed and temperature and limited spectroscopic observations.

One other possible inhibition mechanism has been proposed by the staff of the USAF Flight Accessories Laboratory. Since the limiting factor in chemical extinguishment of flame is apparently reaction rate, consider Eyring's form of the Arrhenius equation:

$$k_a = k_s \frac{RT}{Nh} e^{\frac{\Delta S_a}{R}} e^{-\frac{\Delta H_a}{RT}}$$

where

k_a = reaction rate

k_s = "steric" or orientation factor

R = gas constant

T = temperature

N = Avogadro's constant

h = Planck's constant

ΔS_a = entropy of activation

ΔH_a = heat of activation

If, as proposed in the literature, we assume a given inhibition mechanism involving dissociation products of an agent and a flame carrier species, then ΔS_a , ΔH_a , and T may be considered essentially as constants for that reaction. The inhibiting effect is then a direct function of k_a , which now depends only on k_s . If it is assumed that other inhibiting effects are constant (such as inertion of carrier species by "wall quenching" effect), inhibition can be increased only by increasing the value of k_s . Since k_s is a steric factor, a mechanism which orients the two reacting species preferentially prior to collision would improve extinguishment. Obviously, a third body is needed to absorb excess energy from and to orient the species.

Agent molecules may exist fleetingly together with the dissociation products and flame-carrier species, due to the finite dissociation rate of molecular structures, even in the presence of excess energy. In this case, the orientation might depend on a dipole moment in the undissociated agent molecule. With a large molecular weight for agent as compared with reactable species, the species should be oriented without relocating the dipole molecule sufficiently to interfere with the impending collision.

The fact that agent molecules with zero dipole moment are significantly inferior to those with dipole moment suggests that such a mechanism exists. No correlation has been established between magnitude of dipole moment and extinguishing efficiency; as the molecular weight increases in a given homologous series of halogen compounds, however, the extinguishing efficiency tends to increase. In addition, the instantaneous agent concentration required for extinguishing a diffusion flame is less if the application velocity is increased. With increased velocity, agent molecules would be

driven into the reaction zone; this would increase the possibility of their coexistence with the flame-carrying and flame-inhibiting species.

Dry powder chemicals may involve a similar orientation mechanism; the surface dipole or ionic structures may act as orientation media by either guiding combustion chain carriers to a deactivation center or aiding the reaction between vaporized (and perhaps dissociated) agent species and the carriers.

Toxicity

No fatalities have been reported from using any of the agents discussed in this study. An excellent discussion of relative toxicity and a bibliography on toxicity are available (Ref. 24). It can be concluded that the current agent, CB, presents very little health hazard. The approximate lethal concentrations for guinea pigs exposed for a 15-minute period are as follows:

AGENT	UNDECOMPOSED VAPOR ppm
CBrF_3	834,000
CBrClF_2	270,000
CBr_2F_2	56,000
$\text{CH}_2\text{BrCl}(\text{CB})$	26,500

Since none of the agents are seriously toxic, toxicity need be considered only if the situation requires forced exposure to high concentrations of agent.

Storage

Certain properties of the agents are important for storage, whether in logistic support of maintenance facilities or in the airborne system.

An agent with a high boiling point can penetrate a fire better, producing an extended agent concentration, and can be safely shipped and stored in ordinary steel drums. CB is the only bromine-containing agent studied that has this advantage.

CB appears to be the most corrosive of the agents considered. This problem is not serious, however, if inhibited CB is used and proper materials are chosen for the containers; a steel drum containing inhibited CB that had been stored out of doors for 14 years was intact and had not leaked, although the outside of the drum was very rusty. At temperatures above 250°F, however, CB decomposes, liberating HCl and HBr. Aluminum and its alloys are particularly susceptible to corrosion by moist CB, even at room temperature.

An investigation of the effects of temperature on the agent-container system has been completed.

Figure 10 presents the pressure-temperature relationships for four agents of interest.

Summary of Extinguishant Data

In the practical approach of considering an agent and its container as an entity, all the bromine-containing agents are of the same magnitude in fire extinguishing efficiency. Choosing one agent in preference to another must therefore be based upon other factors. Since each agent has both desirable and undesirable secondary properties, the specific application must be considered in the selection of a particular agent. None of the agents are sufficiently toxic to be excluded from consideration.

Bromochloromethane has by far the best storage qualities; it is the only bromine-containing agent that may be stored and shipped in ordinary steel drums. The airborne agent-container system for bromochloromethane has the lowest dp/dT of the agents considered. Thermal stability of this agent at elevated temperatures is least desirable; it decomposes at temperatures above 250°F even under pressure. Only bromotrifluoromethane appears to be stable at 500°F, but this agent is the least desirable from the standpoint of dp/dT at both high and low temperature extremes.

Choosing an agent, therefore, would depend upon the temperature requirements of the agent-container system. For extended temperatures of -65° to 250°F, bromochloromethane is best; for -65° to 350°F, dibromodifluoromethane is best; for -65° to 400°F, bromochlorodifluoromethane is best; and above 400°F,

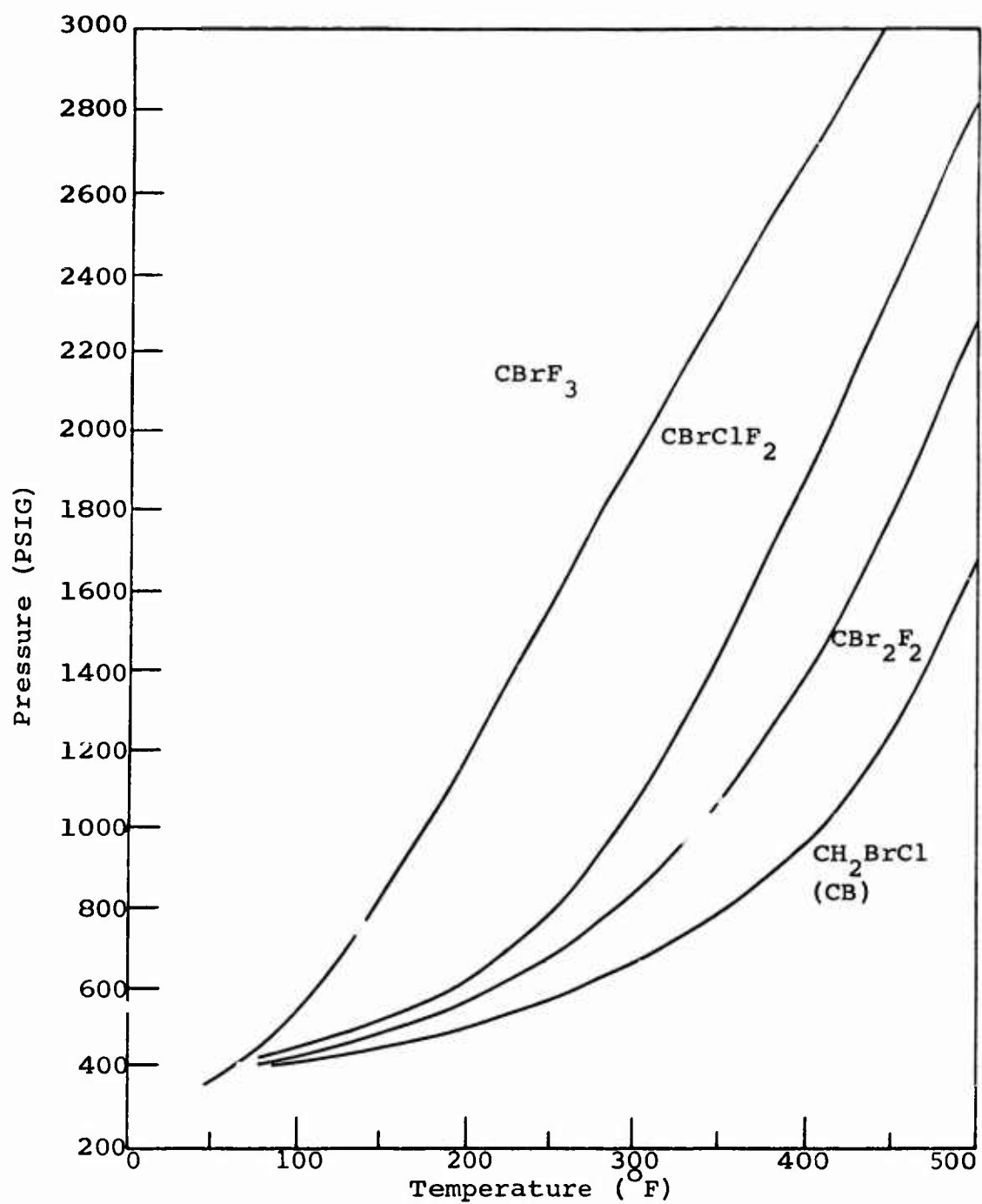


Figure 10. Pressure-Temperature Relationships for Fire Suppression Agents of Interest. (Containers supercharged with N_2 to 400 psig.)

no agent is suitable. Even though bromotrifluoromethane is stable to at least 500°F, pressures become prohibitive when sufficient nitrogen is provided to supercharge and maintain a practical pressure at -65°F.

It is concluded that bromochloromethane (CB) will remain the standard agent for fixed airborne fire extinguishing systems, provided that the agent-container system is protected from temperatures exceeding 250°F. If the agent-container system must be subjected to temperatures ranging from 250° to 400°F, the above order should be used in selecting the agent. The system designer, however, must consider the weight penalty incurred at higher temperatures and pressures. Isolating the container from temperatures above 250°F should be easily accomplished with most Army aircraft fuel tank systems. Physical properties of some major agents are presented in Table IV.

Weight and Cost Estimates of a Chemical Explosion Suppression System

The weight and cost associated with the installation of a chemical explosion suppression system on Army aircraft are estimated from figures provided for the Fenwal system.³ This system is now being installed in the small capacity fuel surge tanks in the vent system of Boeing aircraft and could be adapted for use in Army aircraft.

The components of the Fenwal system operate very similarly to those in an ECA system, and only slight variations exist in their respective physical dimensions and characteristics. The Fenwal system is considered by the authors to be representative of present-day chemical fire suppression systems. The system components have the following maximum weights: the radiation detection unit, 1.10 pounds; the initiator or blasting cap, 0.10 pound; a checkout unit, 0.56 pound; and a checkout indicator lamp assembly, 0.43 pound. A typical Fenwal 250cc capacity cartridge of bromochloromethane weighs 2.38 pounds. Fenwal engineers presently suggest 2 to 4 cc of extinguishant per gallon of fuel capacity as a guide for estimating the initial quantity of extinguishant required by each fuel system.

³Fenwal Division, Walter Kidde Corporation, Ashland, Mass.

TABLE IV
PHYSICAL PROPERTIES OF FIRE SUPPRESSION AGENTS (Ref. 40)

Chemical Name	Bromo- chloro- methane	Dibromo- difluoro- methane	Bromochloro- difluoro- methane	Bromo- trifluoro- methane	Trichloro- fluoro- methane
Chemical Formula	CH ₂ BrCl	CB ₂ F ₂	CB ₂ ClF ₂	CB ₃ F ₃	CCl ₃ F
Molecular Weight	129.4	209.8	165.4	148.9	137.38
Boiling Point, °C °F	67.0 153.0	22.8 73.0	-4.0 24.8	-57.9 -72.0	23.7 74.7
Freezing Point, °C °F	-88.9 -125.4	-141.5 -223.0	-160.5 -257.0	-174.4 -282.0	-111.0 -168.0
Critical Temp., °C °F	296.8 567.0	198.8 390.0	153.8 309.0	67.4 153.5	198.0 388.4
Critical Pressure, psia	953.0	593.0	595.0	574.0	635.0
Density at 70°F, lb/gal g/ml	16.1 1.93	19.0 2.28	15.25 1.83	13.1 1.57	12.36 1.48
Density at 130°F, lb/gal g/ml	15.4 1.85	17.9 2.15	14.15 1.69	10.4 1.25	11.61 1.39
Vapor Pressure at 130°F psig	0.0	25.0	75.0	435.0	26.0
Vapor Pressure at -65°F psig	0.0	0.0	0.0	2.5	0.0

An estimate of 3cc per gallon of fuel has been used to determine the extinguishant requirements for the Army aircraft fuel systems presented in Table V. The smallest initial quantity of extinguishant required by these aircraft is 50cc. It is assumed that the extinguishant cartridge can be economically manufactured in sizes representing each 25cc increment. Accordingly, the extinguishant requirement for each fuel cell has been rounded up to the nearest 25cc incremental value in Table V.

Both bromochloromethane and bromotrifluoromethane are compatible with the Fenwal system and have been considered in this weight analysis. The specific gravities of bromochloromethane and bromotrifluoromethane are 1.93 and 1.58, respectively, at 70°F. The empty 250cc capacity Fenwal cartridge weighs 1.32 pounds; thus the filled cartridges of the two liquids weigh 2.38 and 2.04 pounds, respectively. The weight estimates for the various size cartridges of each extinguishant appearing in Table V are extrapolated values based on the weight of each respective 250cc cartridge. For each fuel cell, the estimated weight of the bromotrifluoromethane cartridge appears first and is followed by the estimated weight of a cartridge containing bromochloromethane in parentheses.

The weight of the detector(s) and detonator has been added to the weight of the extinguishant reservoir, and this sum appears in Table V. The test unit and indicator lamp assembly are required as checkout equipment for each aircraft; thus the total weight of the fire suppression system for each aircraft has been obtained by adding the weight of the checkout equipment to the combined weight of all equipment required in the individual fuel cells. The total weight of the system using the heavier bromochloromethane appears in parentheses in the table.

If the shape index of a fuel cell (see Table XV, page 134) is less than 1.5, it is assumed that the tank is too irregularly shaped to permit adequate visual survey by only one detection unit. These cells then are assumed to require two detectors, and the weight of the additional detector has been added to the system weight.

The price structure for internal fuel cell chemical fire suppression systems is significantly influenced by existing

TABLE V
WEIGHT ESTIMATES FOR A CHEMICAL FIRE SUPPRESSION SYSTEM

Aircraft	Number of Fuel Cells	Capacity of Fuel Cells	Extinguish- ant Require- ment (cc)	Weight* of Extinguish- ant Reser- voir (lb)	No. of Detec- tor Units Per Cell	Total Weight* of Extinguish- ing Unit Per Cell (lb)	Total Weight* of Chem. Suppres- sion Sys. (lb)
(1) UH-1B	2	242.0					9.5 (10.5)
Cargo	(1)	122.0	375	3.06 (3.57)	1	4.26 (4.77)	
Wt.** 2430 lb.	(2)	120.0	375	3.06 (3.57)	1	4.26 (4.77)	
(2) UH-1D	5	220.0					13.1 (14.1)
Cargo	(1)	44.2	150	1.22 (1.43)	1	2.42 (2.63)	
Wt. 3373 lb.	(2)	44.2	150	1.22 (1.43)	1	2.42 (2.63)	
	(3)	34.3	125	1.02 (1.19)	1	2.22 (2.39)	
	(4)	63.0	200	1.63 (1.90)	1	2.83 (3.10)	
	(5)	34.3	125	1.02 (1.19)	1	2.22 (2.39)	

TABLE V (Continued)

Aircraft	Number of Fuel Cells	Capacity of Fuel Cells	Extinguishant Requirement (cc)	Weight* of Extinguishant Reservoir (lb)	No. of Detector Units Per Cell	Total Weight* of Extinguishant Per Cell (lb)	Total Weight* of Chem. Suppression Sys. (lb)
(3) U-1A	4	213.5					11.5 (12.5)
Cargo	(1)	61.2	200	1.63 (1.90)	1	2.83 (3.10)	
Wt.							
2337 lb.	(2)	51.0	175	1.43 (1.67)	1	2.63 (2.87)	
	(3)	51.0	175	1.43 (1.67)	1	2.63 (2.87)	
	(4)	50.3	150	1.22 (1.43)	1	2.42 (2.63)	
(4) U-6A	5	139.8					10.9 (11.5)
Cargo	(1)	35.7	125	1.02 (1.19)	1	2.22 (2.39)	
Wt.							
1286 lb.	(2)	35.6	125	1.02 (1.19)	1	2.22 (2.39)	
	(3)	25.5	75	0.61 (0.71)	1	1.81 (1.91)	

TABLE V (Continued)

Aircraft	Number of Fuel Cells	Capacity of Fuel Cells	Extinguishant Requirement (cc)	Weight* of Extinguishant Reservoir (lb)	No. of Detector Units Per Cell	Total Weight* of Extinguishing Unit Per Cell (lb)	Total Weight* of Chem. Suppression Sys. (lb)
(4) Cont.	(4)	21.5	75	0.61 (0.71)	1	1.81 (1.91)	
(5)	(5)	21.5	75	0.61 (0.71)	1	1.81 (1.91)	
(5) U-8D&F Cargo Wt. 1674 lb.	8	230.0					29.1 (30.3)
(1)	(1)	44.0	150	1.22 (1.43)	1	2.42 (2.63)	
(2)	(2)	44.0	150	1.22 (1.43)	1	2.42 (2.63)	
(3)-(6)	(6)	23.0	75	0.61 ea (0.71) ea	2 ea	2.91 ea (3.01) ea	
(7)	(7)	25.0	75	0.61 (0.71)	2	2.91 (3.01)	
(8)	(8)	25.0	75	0.61 (0.71)	2	2.91 (3.01)	
(6) OH-6	2	66.0					5.0 (5.3)

TABLE V (Continued)

Aircraft	Number of Fuel Cells	Capacity of Fuel Cells	Extinguish- ant Require- ment (cc)	Weight* of Extinguish- ant Reser- voir (lb)	No. of Detec- tor Units Per Cell	Total Weight* of Extinguish- ing Unit Per Cell (lb)	Total Weight* of Chem. Suppres- sion Sys. (lb)
(6) Cont. Cargo Wt. 1206 lb.	(1)	33.0	100	0.82 (0.95)	1	2.02 (2.15)	
	(2)	33.0	100	0.82 (0.95)	1	2.02 (2.15)	
(7) OH-13 Cargo Wt. 571 lb.	2	58.0					5.0 (5.3)
	(1)	29.0	100	0.82 (0.95)	1	2.02 (2.15)	
	(2)	29.0	100	0.82 (0.95)	1	2.02 (2.15)	
(8) Ol-F Cargo Wt. 518 lb.	2	45.0					6.8 (7.0)
	(1)	22.5	75	0.61 (0.71)	2	2.91 (.301)	
	(2)	22.5	75	0.61 (0.71)	2	2.91 (3.01)	
(9) OV- 1A,B&C Cargo Wt. 768 lb.	1	297.0	900	7.34 (8.57)	1	8.54 (9.77)	9.5 (10.8)

TABLE V (Continued)

Aircraft	Number of Fuel Cells	Capacity of Fuel Cells	Extinguish-ant Requirement (cc)	Weight* of Extinguish-ant Reservoir (lb)	No. of Detector Units Per Cell	Total Weight* of Extinguish-ing Unit Per Cell (lb)	Total Weight* of Chem. Suppres-sion Sys. (lb)
(10) CH-34 Cargo Wt. 3475 lb.	11	263.0					30.6 (31.8)
	(1)	15.7	50	0.41 (0.48)	2	2.71 (2.78)	
	(2)	20.0	75	0.61 (0.71)	2	2.91 (3.01)	
	(3)	15.7	50	0.41 (0.48)	2	2.71 (2.78)	
	(4)	25.8	100	0.82 (0.95)	2	3.12 (3.25)	
	(5)	25.8	100	0.82 (0.95)	2	3.12 (3.25)	
	(6)	22.3	75	0.61 (0.71)	2	2.91 (3.01)	
	(7)	28.9	100	0.82 (0.95)	1	2.02 (2.15)	
	(8)	22.3	75	0.61 (0.71)	2	2.91 (3.01)	
	(9)	28.7	100	0.82 (0.95)	1	2.02 (2.15)	

TABLE V (Continued)

Aircraft	Number of Fuel Cells	Capacity of Fuel Cells	Extinguish-ant Requirement (cc)	Weight* of Extinguish-ant Reservoir (lb)	No. of Detector Units Per Cell	Total Weight* of Extinguish-ing Unit Per Cell (lb)	Total Weight* of Chem. Suppres-sion Sys. (lb)
(10)Cont.	(10)	29.1	100	0.82 (0.95)	2	3.12 (3.25)	
	(11)	28.7	100	0.82 (0.95)	1	2.02 (2.15)	
(11) CH-37 Cargo Wt. 7990 lb.	4 (1) (2) (3) (4)	398.0 100.0 99.0 99.0 100.0	300 300 300 300	2.45 (2.86) 2.45 (2.86) 2.45 (2.86) 2.45 (2.86)	1 1 1 1	3.65 (4.06) 3.65 (4.06) 3.65 (4.06) 3.65 (4.06)	15.6 (17.2)
(12) CH-47 Cargo Wt. 16,634 lb.	2 (1) (2)	530.0 315.0 315.0	950 950 950	7.75 (9.04) 7.75 (9.04)	1 1	8.95 (10.24) 8.95 (10.24)	18.9 (21.5)

TABLE V (Continued)

Aircraft	Number of Fuel Cells	Capacity of Fuel Cells	Extinguishant Requirement (cc)	Weight* of Extinguishant Reservoir (lb)	No. of Detector Units Per Cell	Total Weight* of Extinguishing Unit Per Cell (lb)	Total Weight* of Chem. Suppression Sys. (lb)
(13) CH-54	5	1357.0					40.9 (46.7)
Cargo Wt. 14,864 lb	(1)	226.0	700	5.71 (6.66)	1	6.91 (7.86)	
	(2)	226.0	700	5.71 (6.66)	1	6.91 (7.86)	
	(3)	226.0	700	5.71 (6.66)	1	6.91 (7.86)	
	(4)	226.0	700	5.71 (6.66)	1	6.91 (7.86)	
	(5)	453.0	1375	11.22 (13.09)	1	12.24 (14.29)	

*Weight values without parentheses are for CBrF₃ extinguishant, and weight values with parentheses are for CH₂BrCl.

**Cargo weight is defined as the difference between takeoff weight and the weight of the aircraft loaded with fuel and oil but excluding crew, passengers, and any kind of cargo.

patent rights. The authors believe that reliable high-performance types of the basic components of a chemical extinguishant system - the radiation-sensing device, an actuator, a reservoir of extinguishant, and a checkout assembly - could be purchased on an individual basis at a total cost well within \$200.

The Fenwal Division, Walter Kidde Corp., has purchased the rights to the patented Graviner system, the first operational internal fuel cell chemical fire extinguishant system to be used in combat aircraft. The Graviner system patent (Ref. 33) gives broad coverage to possible ways of distributing a chemical extinguishant within a fuel cell. However, there is a considerable amount of uncertainty among companies manufacturing fire detection equipment concerning the extent to which these patent rights protect Fenwal in marketing of the assembled "basic" components as an internal fuel cell fire and explosion suppression system. Fenwal is now supplying a chemical fire suppression system for commercial aircraft. It is sold in a price range of from \$1000 to \$1200. The price includes the system "hardware" as well as the required engineering design to assure a successful fuel cell installation; this price scale also is believed to reflect Fenwal's position of possessing the patent rights to a generally defined internal fuel cell chemical fire suppression system. Thus, it is postulated that the quoted price structure could be revised considerably, if necessary, in order to compete economically with other fuel cell protection measures which might be considered.

Using the \$1000-per-fuel-cell estimate as a price guide, the only estimate now available, the chemical extinguishant system is economically competitive with the other proposed fire suppression measures only when very large fuel cells are considered.

B. FIRE SUPPRESSION THROUGH FUEL ADDITIVES

Adding a halocarbon directly to the fuel rather than injecting it into the vapor space is a relatively new approach to vapor space inerting which is presently under study by the U.S. Navy. This approach, if proven feasible, not only will provide protection against fuel explosions in aircraft fuel tanks

but will also provide protection in fuel storage; thus it may offer potential benefits not found in other fire suppression methods now being considered.

Types of Fuel Additives

The Aeronautical Engine Laboratory at the U.S. Naval Air Engineering Center has been active in the study of fuel additives (Ref. 51). Their findings indicate that by adding a halogenated hydrocarbon to the fuel, in quantities of less than 1 percent by weight, a substantial reduction in the combustibility of the fuel/air mixture existing above the fuel is achieved. The presence of small quantities of a halocarbon in the fuel has not produced significant adverse effects on the combustion of the fuel in the limited testing performed to date. Fuel additives used in experiments reported thus far include CH_2Cl_2 , CBr_2F_2 , CCl_2F_2 , and CBrF_3 . The fluorinated hydrocarbons have been the most effective in these preliminary tests.

The halocarbon must be selected on the basis of certain physical parameters closely related to its degree of volatility and flame extinguishing characteristics. A measure of volatility of several halocarbons can be noted from the boiling points listed in Table IV.

The flammability region of JP-4 is bordered by the limiting extremes of the fuel-to-air mixture ratios, identified as the rich and lean limits. In order to provide a noncombustible vapor, these limits must coincide with each other.

A preliminary evaluation of several halocarbons was conducted by the Naval Air Engineering Center, Philadelphia, Pennsylvania, in order to relate their respective combustion abating capabilities to some physical property. The investigation was conducted using JP-4 fuel with the halocarbon dissolved in it. The combustion tube in which the vapors were ignited was 4 feet in length and 4 inches in diameter. The concentration of the additive in the fuel was increased until combustion was completely eliminated. A high-energy spark was used for ignition. In these tests, the more volatile agents provided the greatest flame extinguishment per given concentration. The most effective fire suppressant of those tested was bromotrifluoromethane.

Reduction of the Flammability Limits

The reduction of the JP-4 combustibility envelope achieved in these laboratory experiments through the addition of varying percentages of bromotrifluoromethane is illustrated in Figure 11. Complete elimination of the JP-4 flammability loop can be obtained from 0.45% by weight of bromotrifluoromethane in the fuel. The same experiment was repeated using JP-5, a kerosene type fuel. Only 0.38% by weight of bromotrifluoromethane completely eliminated the flammability loop of JP-5. From these experiments, it is apparent that small amounts of a fluorinated hydrocarbon dissolved in JP-4 fuel can produce a nonflammable atmosphere in a closed system.

The approach of adding halocarbons to the fuel in order to reduce the combustibility envelope appears to be promising; however, much research is yet to be undertaken before the approach can be proved practical. The study of the compatibility of halocarbon containing fuels with aircraft engines and the ground fueling systems is the most important of the many areas still requiring investigation.

Weight and Cost Estimates for a Fuel Additive System

The weight and cost estimates for the fuel additive system in Table VI have been computed assuming the use of bromotrifluoromethane as the additive halocarbon. A recently quoted price of this agent, purchased in large quantities, is approximately \$2.75 per pound.⁴ Many of the more "standard" fire extinguishants are considerably cheaper (bromochloromethane is \$0.48 per pound, and carbon tetrachloride is \$0.11 per pound⁵); perhaps these will serve as adequate inerting agents when used as fuel additives. As yet, however, no experimental work has been reported which demonstrates that these cheaper agents can be satisfactorily used as fuel additives.

⁴Lot price, 2000-pound quantities, quoted from the Freon Products Division, The DuPont Corporation, Chicago, Illinois, January 1967.

⁵Prices quoted from the Oil, Paint and Drug Reporter, Schnell Publishing Co., New York, January 1967.

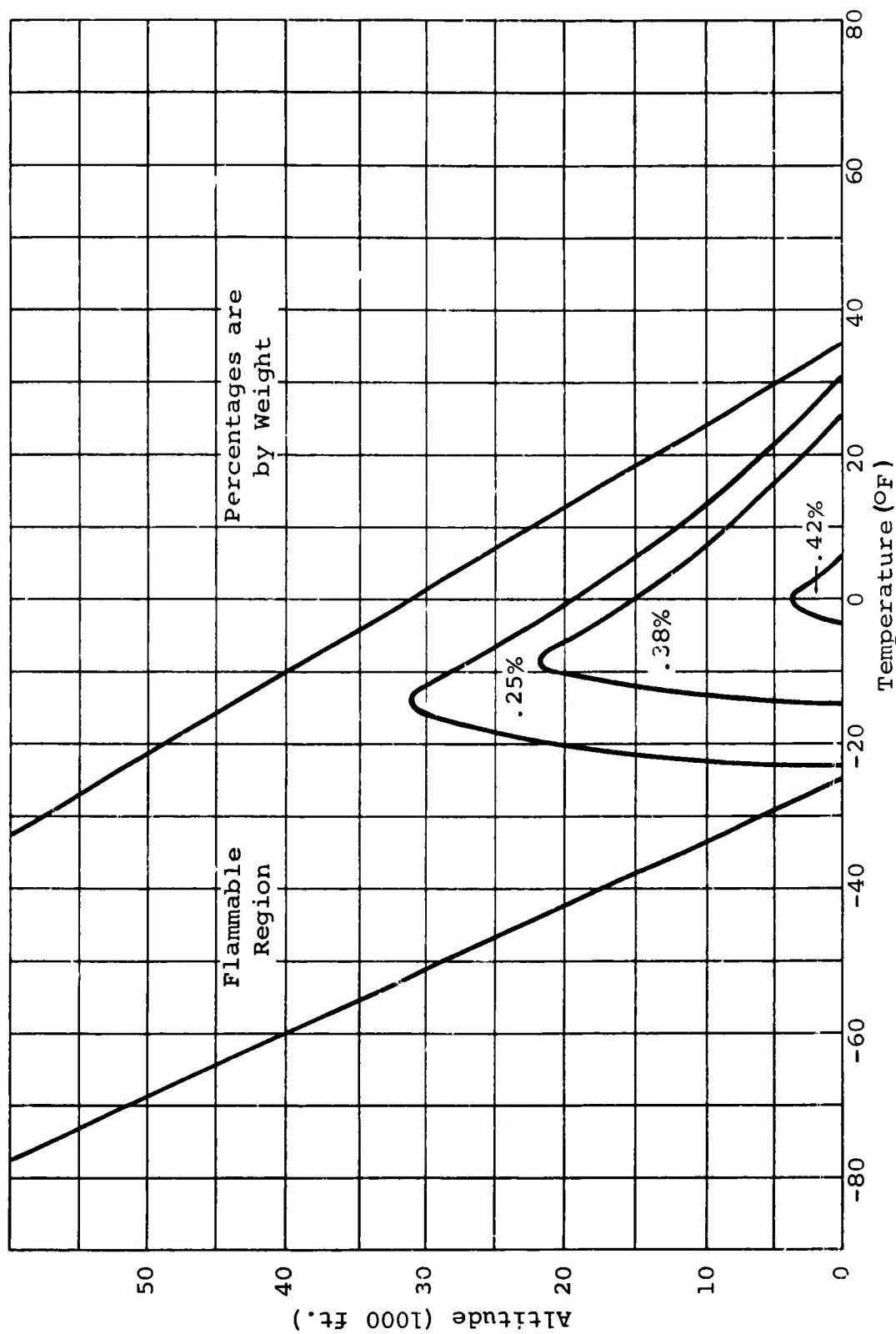


Figure 11. Reduction of Equilibrium Flammability Limits by the Addition of Bromotrifluoromethane to JP-4 (combustion tube tests).

The approximate weight of bromotrifluoromethane is 13.09 pounds per gallon, assuming a specific gravity of 1.57. It is considerably heavier than any of the three types of aircraft fuels listed in Table VI; thus an additional weight penalty is incurred by adding CBrF₃ to fuel or by replacing a small quantity of fuel from a given volume with an equal amount of additive.

To satisfy the requirements of adding 0.45% by weight of additive to the fuels, it has been assumed that the fuel can be treated in 1000-pound lots and that 4.5 pounds of fuel can be replaced with a similar amount of CBrF₃ in each lot. Using Table VI fuel weights, it is seen that a 1000-pound lot of fuel represents 155.67 gallons of JP-4, 173.34 gallons of 115/145 octane gasoline, and 170.17 gallons of 80/87 octane gasoline. The mixture ratios of additive per gallon of fuel can be computed for each type of fuel using these figures and the fact that 4.5 pounds of CBrF₃ represents approximately 0.344 gallon. The calculated volume percentages are 0.221% for JP-4, 0.199% for 115/145 octane gasoline, and 0.202% for 80/87 octane gasoline.

The quantity (gallons) of chemical additive required for one capacity fuel supply of each aircraft has been computed using the appropriate percentage figure and the given fuel capacity of the aircraft. These requirements are shown in Table VI.

The fuel additive weight penalty imposed on each aircraft is estimated as the difference in weights of the quantity of bromotrifluoromethane added to the fuel and the volume of fuel which that quantity of additive replaces.

The halocarbon additive dollar cost estimates for each filling of the aircraft fuel system are easily computed from the estimated quantity of CBrF₃ required and its quoted price, which, when converted to a volume basis, is \$36.00 per gallon. These estimates are also presented in Table VI.

C. INERT GAS PURGE SYSTEMS

Types of Gas Purge Systems

Inert gas purging systems have been studied as a means of protecting aircraft fuel cells from fire and explosion hazards

TABLE VI
WEIGHT AND COST ESTIMATES FOR A FUEL ADDITIVE SYSTEM

Aircraft	Fuel System Capacity		Bromo-trifluoromethane Requirements (gal)	Weight Penalty (lb)	Cost (\$)	Type of Fuel Used
	(gal)	(lb)				
(1) UH-1B	242.0	1551.0	0.535	3.57	19.26	JP-4; 6.409 lb/gal
(2) UH-1D	220.0	1410.0	0.486	3.25	17.50	JP-4
(3) U-1A	213.5	1229.5	0.425	3.11	15.30	115/145 gasoline; 5.769 lb/gal
(4) U-6A	139.8	855.0	0.282	2.04	10.15	80/87 gasoline; 5.85 lb/gal
(5) U-8D&F	230.0	1324.0	0.458	3.35	16.49	115/145 gasoline
(6) OH-6	66.0	423.0	0.146	0.97	5.26	JP-4
(7) OH-13	58.0	348.6	0.117	0.85	4.21	80/87 gasoline
(8) O1-F	45.0	259.0	0.090	0.66	3.24	115/145 gasoline
(9) OV-1A, B&C	297.0	1903.5	0.656	4.38	23.62	JP-4
(10) CH-34	263.0	1525.4	0.523	3.83	18.83	115/145 gasoline
(11) CH-37	398.0	2308.0	0.792	5.80	28.51	115/145 gasoline
(12) CH-47	630.0	4038.0	1.392	9.30	50.11	JP-4
(13) CH-54	1357.0	8832.0	3.003	20.06	108.11	JP-4

since as early as 1940. The British were prominent in the early development of such systems and by 1943 had installed and flight-tested nitrogen gas systems in a number of fighter-bomber aircraft. Since 1950, Great Britain, Russia, and the United States have developed and tested several different kinds of purging systems. These systems may be classified into two general categories: types which are independent of all other aircraft subsystems, and those which depend on engine exhaust as a source of inert gas.

There are two basic types of purging systems, which are classified by their respective method of physically introducing the inert gas into the fuel cell vapor space. These basic types are known as the demand system and the through-flow system.

A demand system is one in which the flow of inert gas into the cell vapor space is regulated by a pressure gage which detects pressure variations within the cell. In the normal operation of this system, small quantities of inert gas are forced into the vapor space as the fuel is consumed. Rapid changes in altitude effect greater pressure variations within the fuel cells. As these conditions occur and the tank pressure variations are detected, greater amounts of inerting gas must be fed into or vented from the vapor space to compensate for pressure differentials.

The through-flow system is one in which the inert gas flows through the fuel vapor space at a relatively constant flow rate and thus is independent of pressure variations within the fuel cells. Much of the fuel vapor is simply "swept out" of the fuel tank in the flow of inert gas.

The through-flow system is obviously very simple and easily adapted; it requires no additional equipment other than the pressurized bottled gas supply and a pressure reduction valve. Conversely, the demand system must incorporate a highly reliable pressure gage within the fuel cell or on the inert gas feed line to detect internal tank pressure variations. In addition, check valves are usually placed in the fuel vent lines to prevent an in-flow of air into the fuel tank vapor space.

The vapor space of a fuel cell can be more uniformly inerted with a demand system, since with this system there is no

constant path of flow through the vapor space which may tend to stratify layers of fuel vapor. A more uniform distribution of inert gas within the vapor space is achieved with the demand system. This system also offers the major advantage of requiring a smaller inert gas supply, thereby reducing the potential weight and space requirements associated with a purge gas system. A substantially smaller quantity of inert gas would be used in the demand system for a long period of aircraft operation.

The major disadvantage of the demand system is its requirement for additional equipment. Another potential disadvantage is associated with its reliability and safety. The demand system is essentially a closed system depending upon reliable operation of pressure gages and vent line check valves. A malfunction of either of these components greatly impairs the efficiency of the purge system. The less complex through-flow system would probably experience fewer operational failures over long periods of aircraft operation and could be more easily maintained.

It is believed that the greater efficiency of the demand type of purging system will more than compensate for its associated additional equipment requirements and its possible reliability problems. Thus, it is considered to be the most suitable type of purge system for U.S. Army aircraft. For comparative analyses of the inert gas purge system and other explosion suppression systems, a nitrogen gas demand type purge system is considered in this study.

Flammability Limits for Nitrogen Gas Diluted Fuel/Air Mixtures

A number of possible sources of the inert gas have been considered in earlier studies. It is possible to extract gas of low oxygen content from a combustion unit such as an aircraft engine, or it is possible to absorb or react the oxygen in air to produce a relatively inert gas. A review of the problems associated with these alternatives has led to the conclusion that the use of bottled inert gas is the only presently practical system which should receive consideration. The introduction of equipment needed to cool, clean, and dehumidify the raw gas produced as engine exhaust would involve major redesign of some components of each of the aircraft fuel systems

considered herein. The complexity of this processing equipment would preclude its economical use on small aircraft.

The flammability limits for the fuels of interest have been studied under various conditions of temperature, pressure, inerting gas composition, and ignition source for several different inerting gases. Figure 12 indicates the findings of a program conducted by the University of California relative to the flammability limits for JP-4 with nitrogen as the inert gas. Figure 13 provides similar data for carbon dioxide inerting. For convenience in applying these flammability limits to specific protection problems, the data are presented in terms of the maximum allowable oxygen concentration in Figure 14 and in terms of the proportion of inerting gas required in Figure 15. These data were all obtained using a multiple, high-energy, spark ignition source.

Other tests have been conducted using caliber .50 and 20 mm incendiary ammunition as the ignition source. These tests used specification self-sealing tanks surrounded by an aluminum enclosure, simulating aircraft structure, and employed a function plate and fiber glass plastic anti-chafe boards to make the test as realistic as possible. The inerting gas was nitrogen for these tests. Figure 16 presents the flammability limits for JP-4 vapor mixtures ignited by caliber .50 armor-piercing incendiary ammunition.

Additional tests were conducted in which a liquid phase was present in the lower portion of the tank. Although all hits were still in the vapor space, a significant widening of the flammability limits was established for this test condition. The additional danger due to the presence of nonequilibrium conditions involving fuel mists created upon impact is shown by Figure 17. These data summarize the potential hazard within the fuel tanks of Army aircraft. These tests have conclusively shown that the presence of liquid fuel in an aircraft fuel tank at sea level markedly extends the zone in which inflammation can take place, as compared to the case in which only a gas phase is present. They have also shown that if the fuel vapor concentration is greater than 11 percent, the tank is inerted, or nonflammable, and that if the oxygen concentration is less than 9 percent, the tank is inerted, or nonflammable. It is important to remember, however, that even though the fuel tank is completely inerted, bay spaces surrounding the tank are hazardous when not inerted.

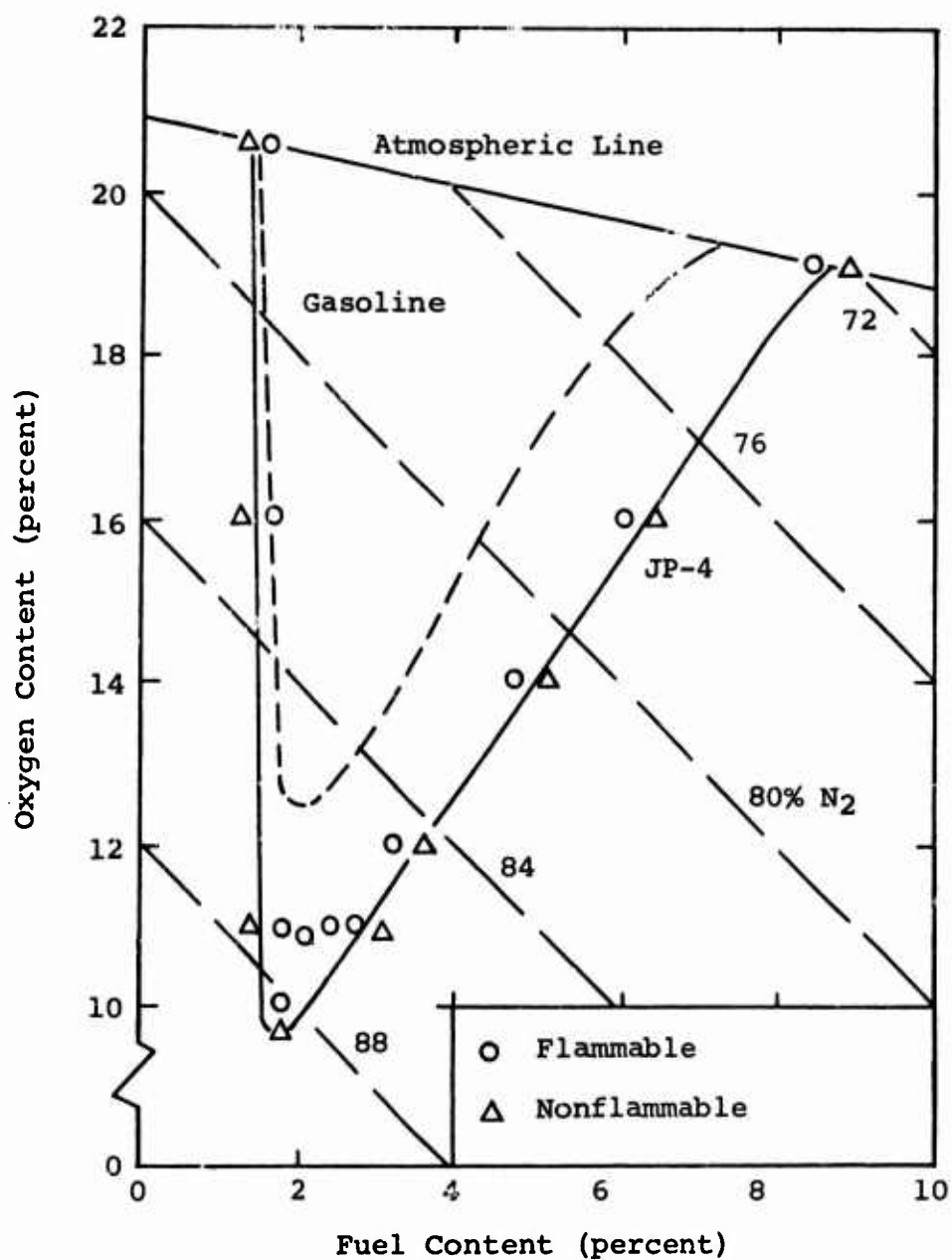


Figure 12. Sea Level Flammability Limits for JP-4 and Gasoline Vapors With Nitrogen Inerting.

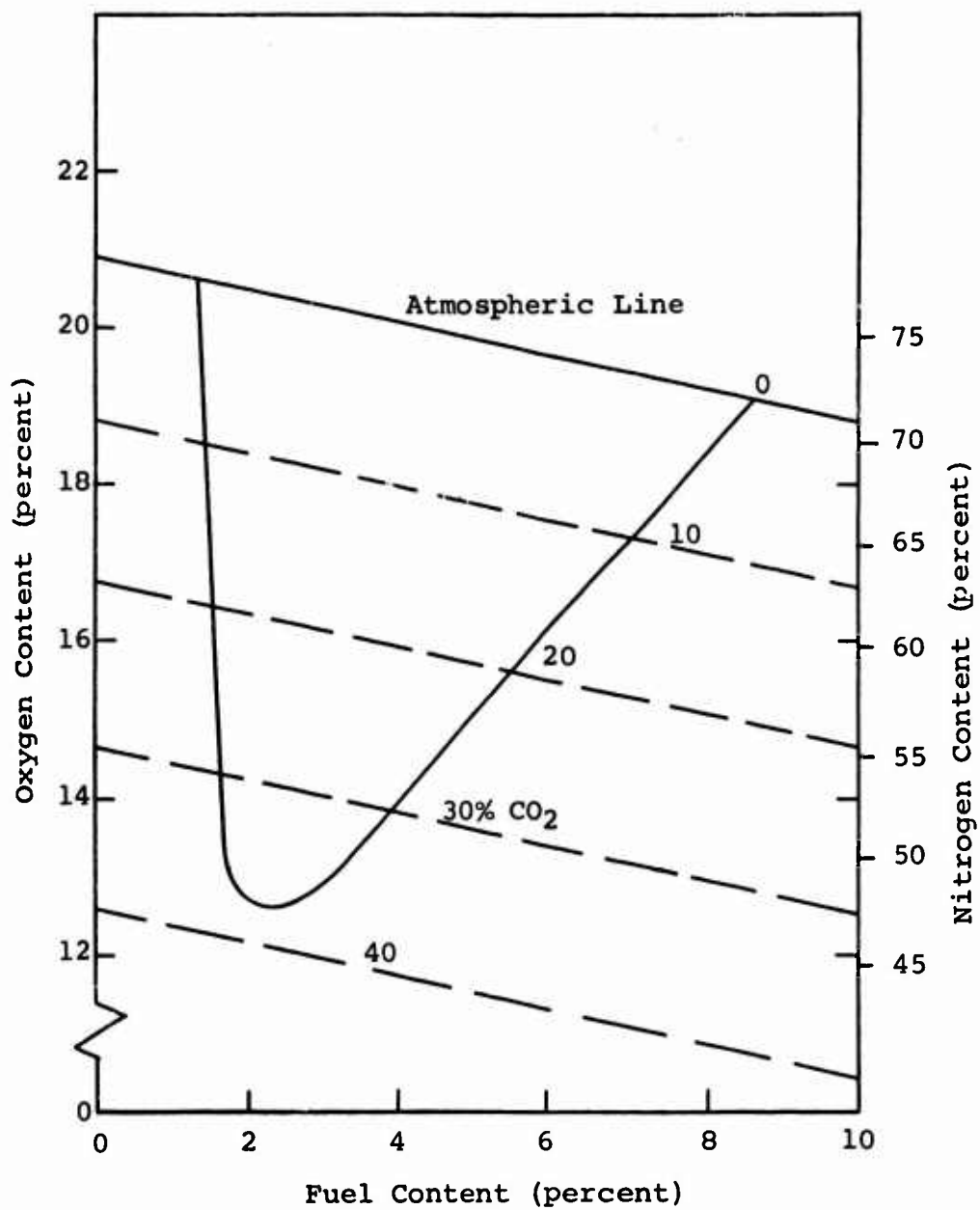


Figure 13. Sea Level Flammability Limits for JP-4 Vapor With Carbon Dioxide Inerting.

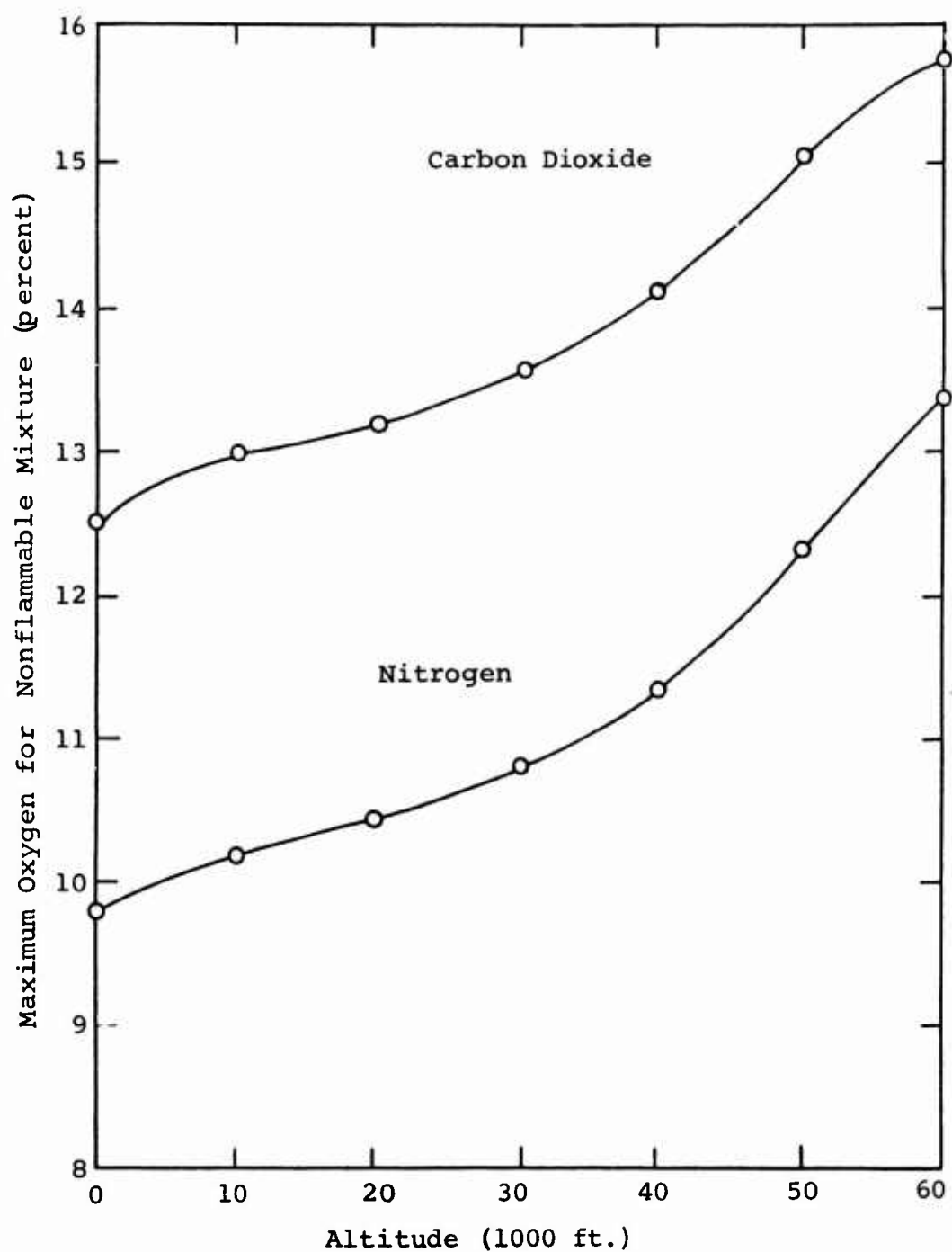


Figure 14. Permissible Oxygen Concentration for CO_2 and N_2 Inerted Fuel/Air Mixtures With JP-4 Vapor.

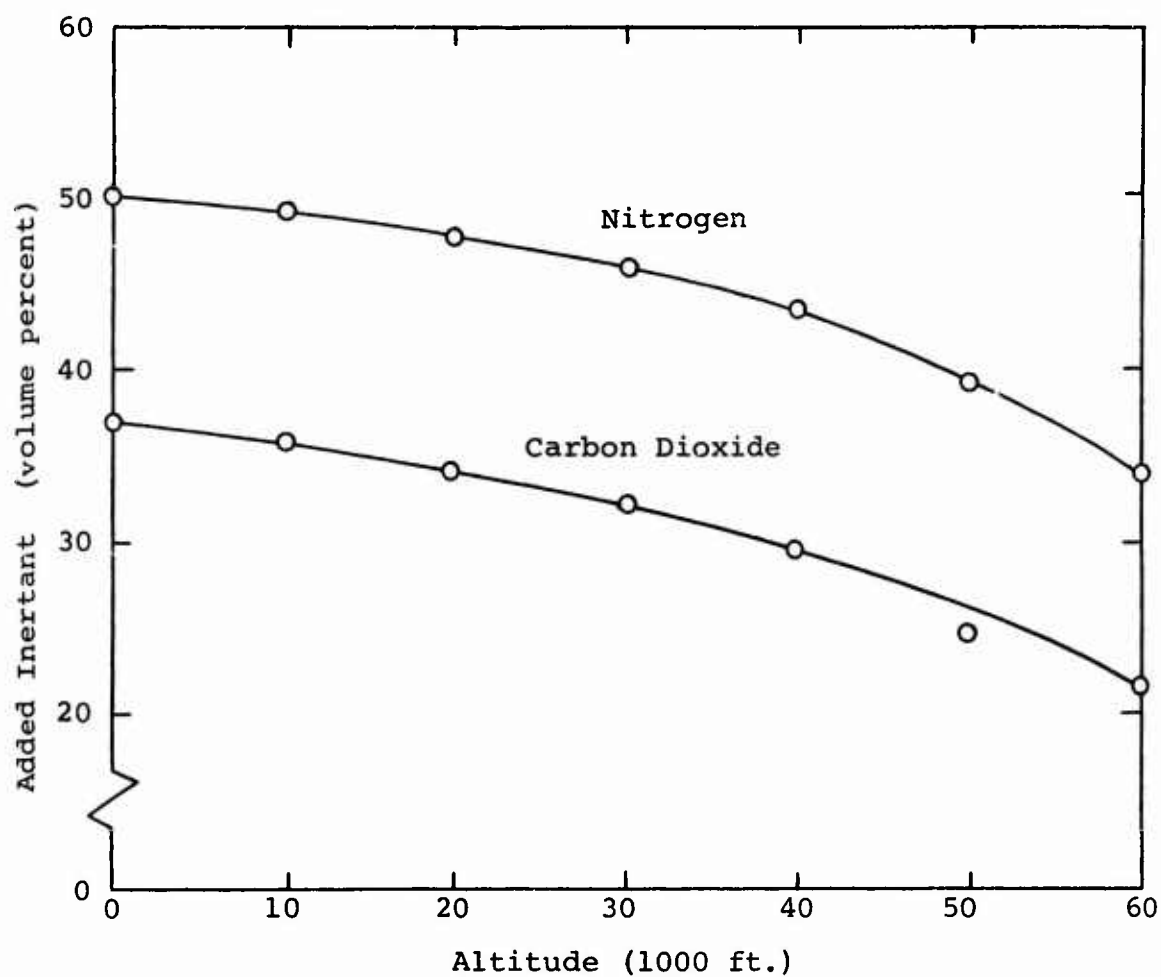


Figure 15. Quantities of Nitrogen and Carbon Dioxide Required for Inerting JP-4 Vapor.

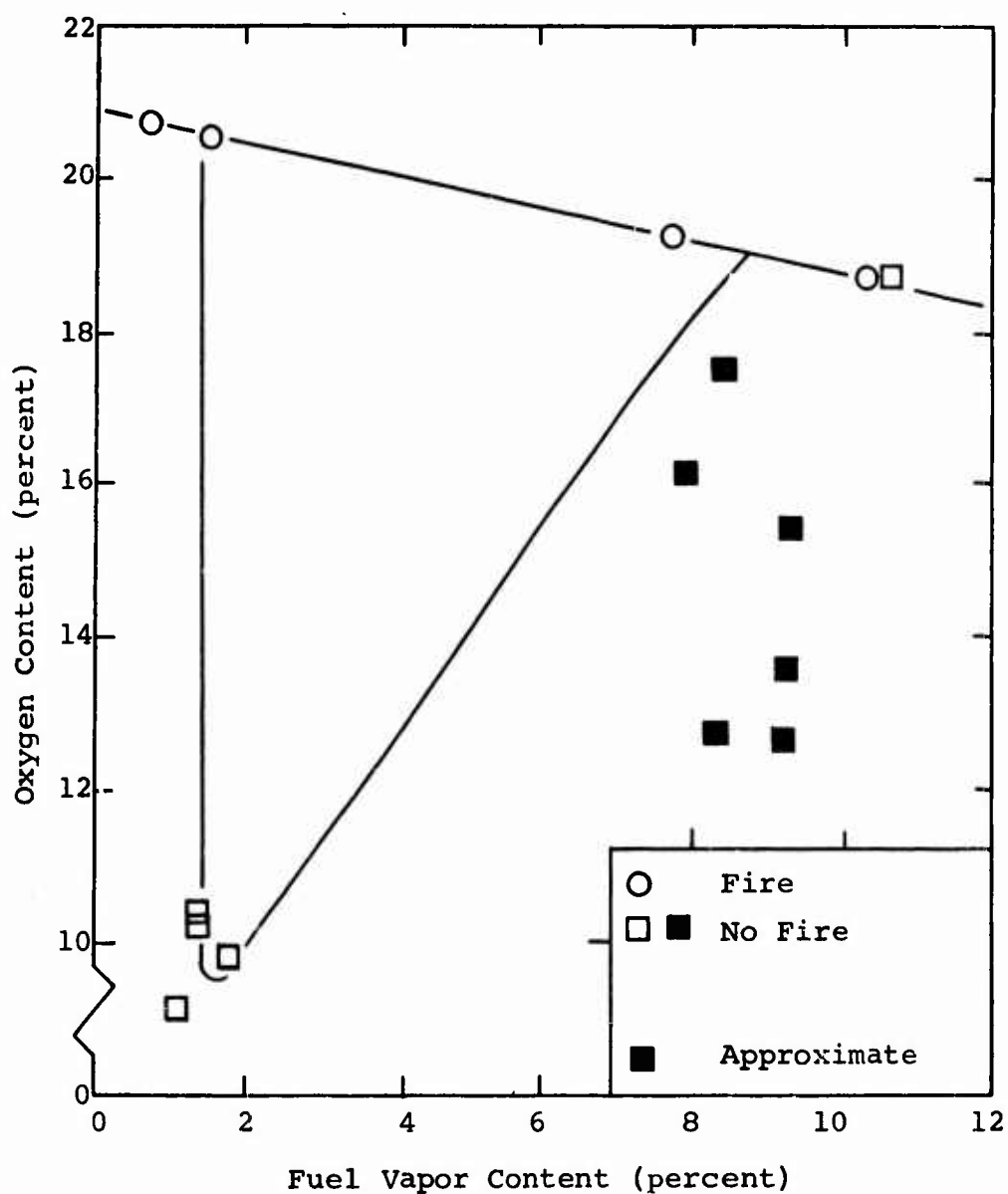


Figure 16. Sea Level Flammability Limits for JP-4 Vapors Under Attack by Caliber 50 Armor Piercing Incendiary Ammunition With Nitrogen Inerting.

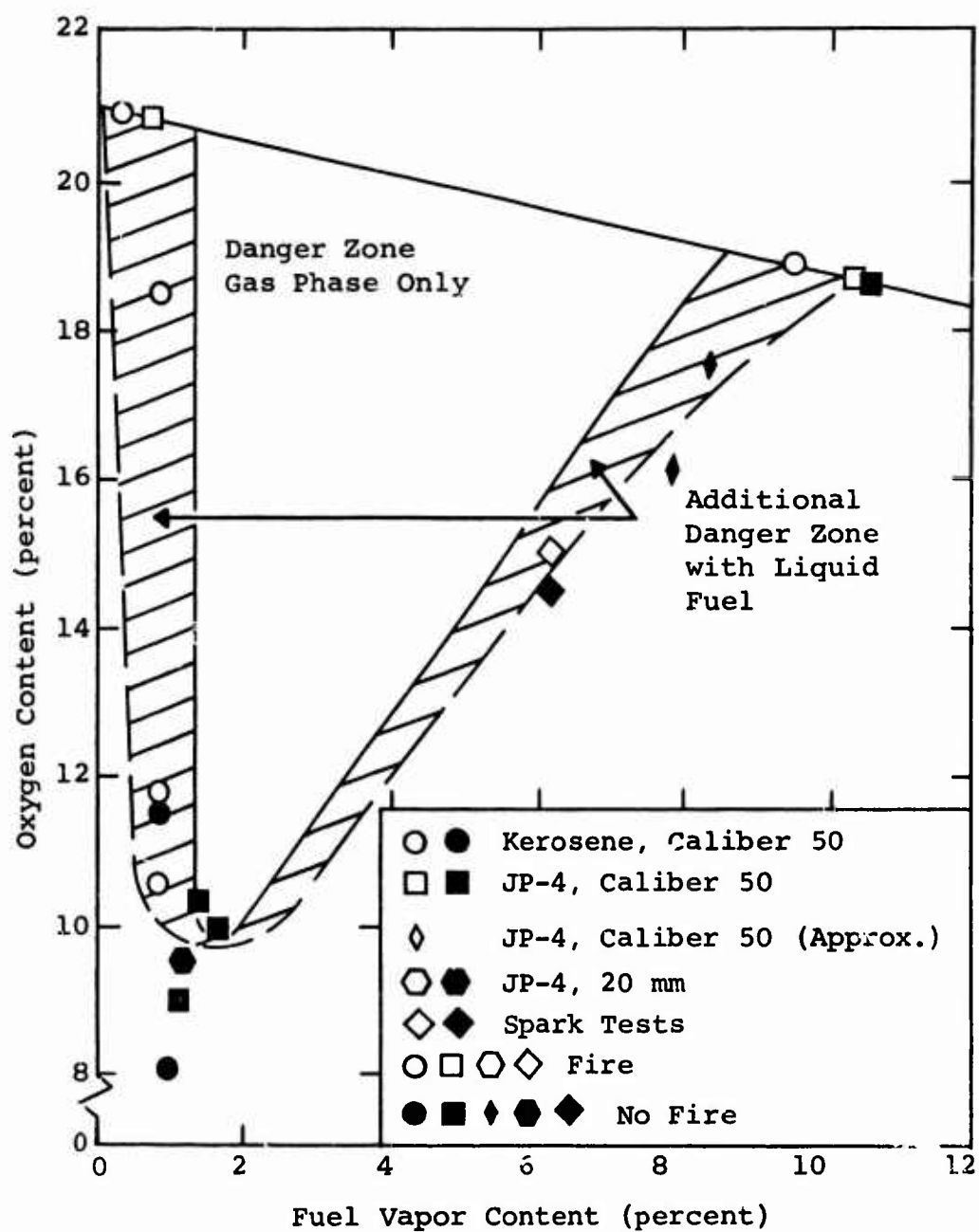


Figure 17. Summary of Available Flammability Data for Gun Fired Incendiary Ammunition.

The weight penalties associated with the use of bottled gas purge systems may be divided into four categories for estimation purposes. First there is the weight of the gas itself; second, the weight of a high-pressure container or "bottle"; third, the weight of a suitable distribution system (aluminum tubing); and finally, the weight of a valve and pressure regulator unit.

The most practical and economical inert gases are nitrogen and carbon dioxide. Either gas could be used in a practical system, but nitrogen has a slight weight advantage and is less apt to form fuel contaminants in a humid or wet fuel mixture. These computations are thus somewhat arbitrarily based on nitrogen as the purge gas. The quantity of nitrogen needed has been established so that the entire fuel tank system of the aircraft can be filled twice during the mission. This provides one system volume of purge gas to replace the liquid fuel as it is used and a second volume to replace nitrogen expelled to the atmosphere during aircraft ascent. This second volume is necessary because the fuel systems normally operate at pressures which are very close to ambient; thus, nitrogen will be expelled through the vent as the aircraft ascends and will be drawn from the storage bottle to equalize tank pressure as the aircraft descends. If an aircraft changes altitude a great many times during a mission, it will be possible to use more than this volume of nitrogen; however, a quantity which is twice the fuel system volume is believed to be adequate for most missions.

Weight Estimates for Nitrogen Gas Purge Systems

Nitrogen is normally stored in steel containers at a pressure of approximately 2,200 psi. Under these conditions it has a density of about 12 pounds per cubic foot. Table VII presents information relative to the weight, estimated cost, and capacity of conventional nitrogen containers.

Estimates of the required steel tank weight for any desired gas volume, based on the data of Table VII, are presented in Figure 18.

For aircraft installation, weight will be an important consideration, and it is probable that the cost of a gas container made of titanium or perhaps even aluminum can be

TABLE VII
NITROGEN GAS CONTAINER DATA*

Bottle Capacity (ft ³ @std. cond.)	Bottle Wt. Empty (lb)	Rated Fill Pressure (psi)	Estimated Retail Cost (\$)
18	12	2200	30
73	65	2200	41
112	116	2200	50
138	80	2200	45
224	133	2200	55
300	143	2640	59

*Supplied by the Linde Division of Union Carbide Corporation

justified. For the purposes of this estimate, a titanium cylinder has been anticipated. It is believed that present titanium technology would permit fabrication of a tank which could take full advantage of the lower density of that metal. Figure 19 presents a plot of weight versus nitrogen capacity for a family of such titanium tanks. Perhaps the use of aluminum or a reduction in the safety factor of the steel tank design could further reduce these weight values. These weight estimates are thus considered to be realistic but perhaps a bit conservative, even though they may imply the design and fabrication of nitrogen cylinders specifically to meet Army requirements.

The fuel tanks of all Army aircraft considered in this study now have vent systems vented to the atmosphere and are designed to meet the maximum flow requirements of anticipated flight profiles for the aircraft. Present venting systems should be compatible with a nitrogen gas purge system, and thus a very minimal allowance for vent line weight is included in this estimate. Three feet of one-inch O.D. aluminum tubing weighs approximately 1-3/4 pounds. It is believed that this will be sufficient material to connect the nitrogen tank to the existing vent system of the aircraft considered. In some instances a smaller size of tubing or a shorter length may be adequate.

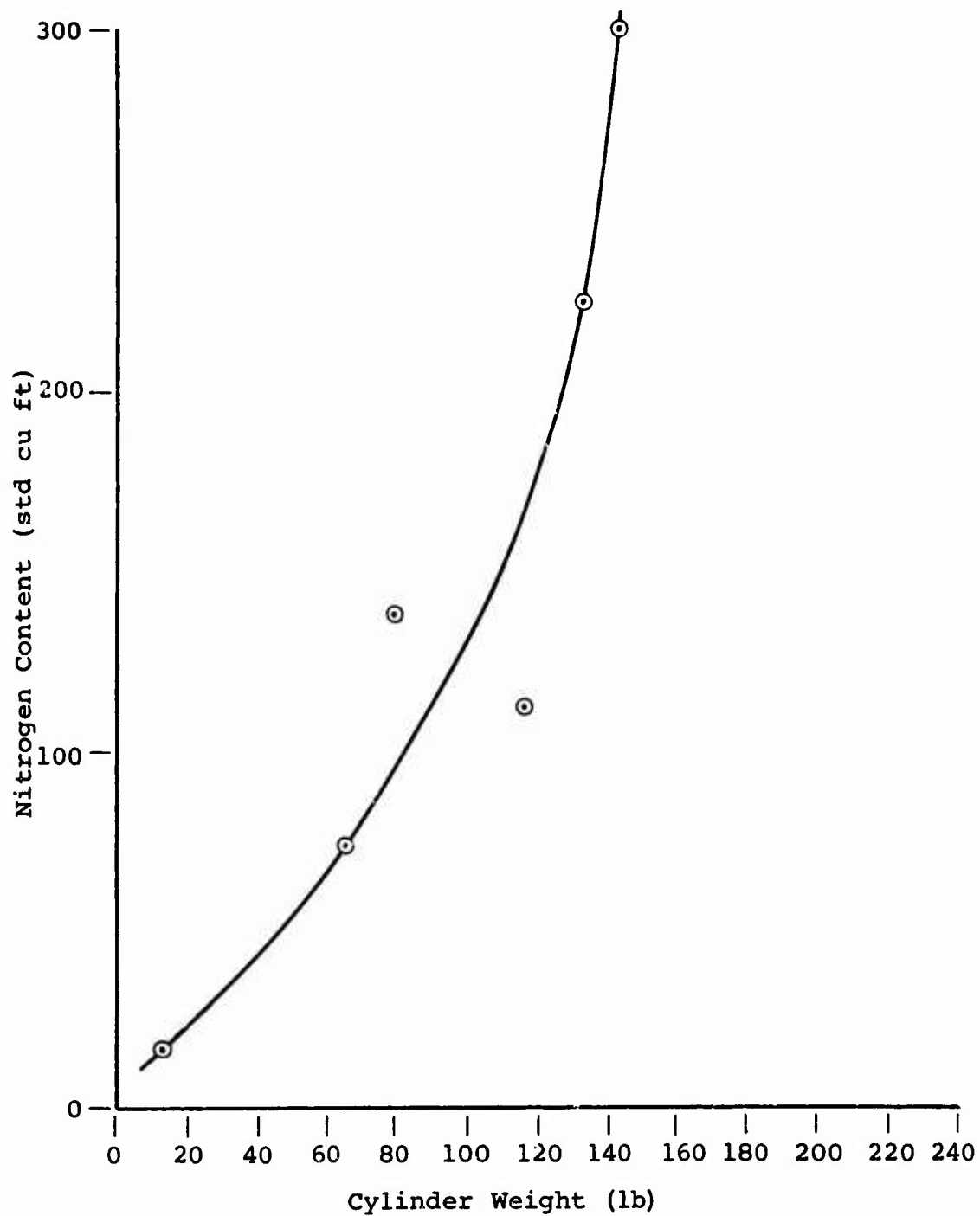


Figure 18. Nitrogen Container Weight for Steel Tanks.

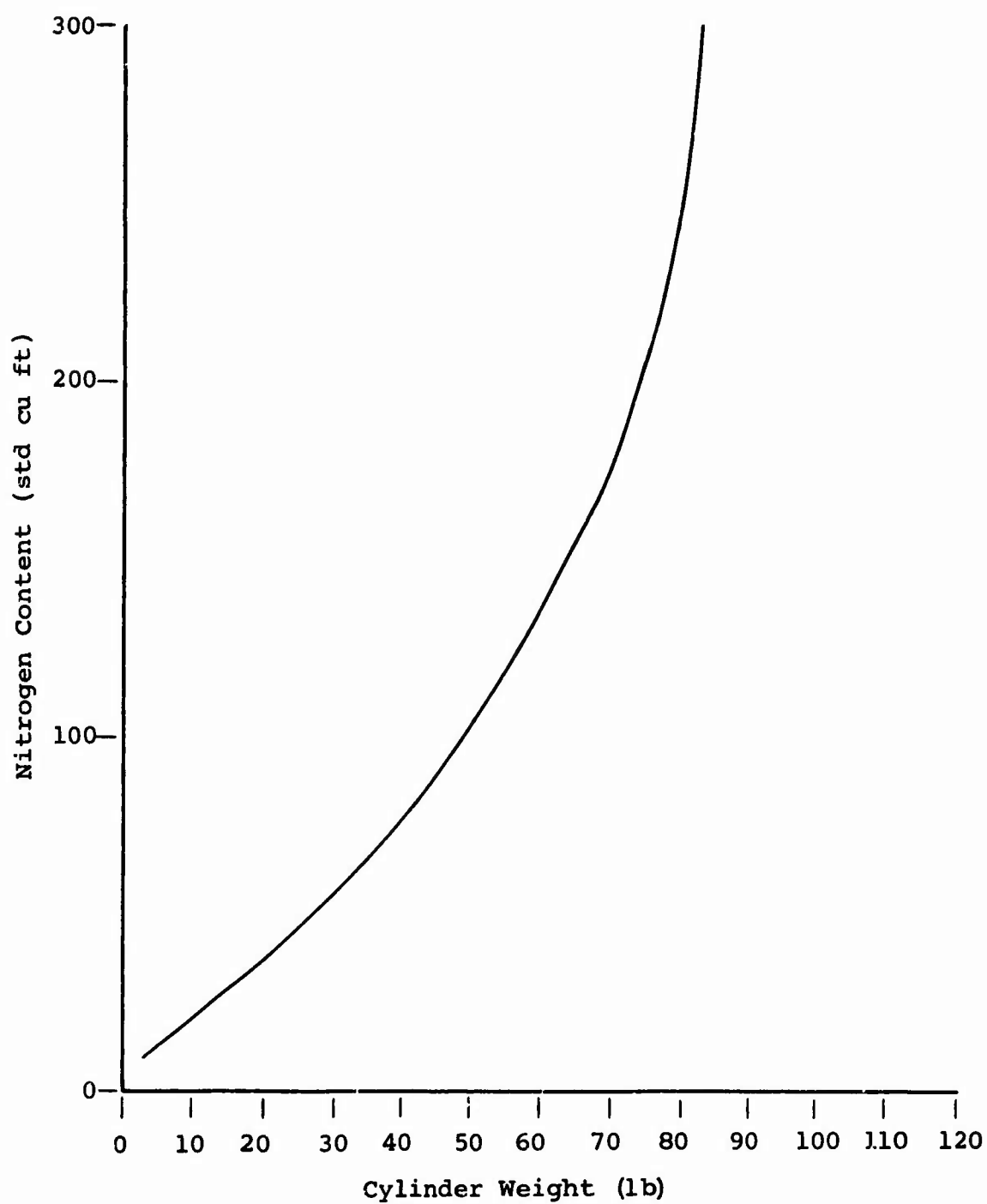


Figure 19. Nitrogen Container Weight for Titanium Tanks.

These weight estimates will reflect the inclusion of a 1-3/4-pound allowance for additional vent tubing on all systems.

The additional components required by a purge gas system for Army aircraft fuel systems include a pressure reducing valve and a pressure regulator for each tank or group of interconnected tanks. Check valves will be required in the vent lines leading to the outside of the aircraft. These valves must prevent air intake and permit nitrogen to be expelled as the aircraft climbs. It has been estimated that a suitable pressure reducing valve can be supplied within a weight factor of 1 pound per unit. For most aircraft, a single nitrogen tank and thus a single pressure reduction valve will be most economical from the standpoint of weight added to the aircraft.

Pressure regulation within the system must be provided for each independent tank or group of interconnected fuel cells. The regulator will consist of a pressure sensor, a flow control valve, and a linkage. These will permit purge gas to flow in response to a drop in pressure. The linkage may be either mechanical or electrical. It is believed that such a pressure regulator can be supplied for a weight penalty of no more than 1-1/2 pounds per unit.

More than one check valve will be required where tank separation within the aircraft has dictated that additional vent points are needed. The estimates included in this report will contain allowances for multiple check valves where this appears to be necessary. An allowance of 4 ounces for each valve is considered to be sufficient for this item.

Weight estimates for the aircraft of interest are presented in Table VIII. Estimates have been shown for both steel nitrogen tanks and titanium tanks.

Cost Estimates for a Nitrogen Gas Purge System

Cost estimates for a demand nitrogen gas purge system for each Army aircraft are presented in Table IX. These estimates are based on retail tank price quotations obtained from the Linde Division of the Union Carbide Corporation. The total cost of the "standard" components of the purge system, i.e., the tubing, the pressure reduction valve, the fuel cell pressure regulator, and a vent line check valve, is estimated as \$93.50.

TABLE VIII
WEIGHT ESTIMATES FOR A NITROGEN GAS PURGE SYSTEM

ESTIMATED WEIGHTS FOR HYDROGEN GAS SYSTEMS									
Aircraft	No. of Fuel Cells	Rated Fuel System Capacity (gal)	Nitrogen Required (ft ³)	Nitrogen Cylinder Weight (lb)		Valves, Regulators, Tubing, Etc. (lb)	Estimated Total		
				Fe	Ti		Steel Tank	Titanium Tank	
(1) UH-1B	2	242	65	5.1	60	34.8	4.7	69.8	44.6
(2) UH-1D	5	220	59	4.7	55	31.8	4.7	64.4	41.2
(3) U-1A	4	214	57	4.5	53	30.6	4.7	52.2	39.8
(4) U-6A	5	140	37	2.9	34	19.7	7.5	44.4	30.1
(5) U-8D & 8F	8	230	62	4.9	57	33.0	5.3	67.2	43.2
(6) CH-6	2	66	18	1.4	15	8.7	4.7	21.1	14.8
(7) OH-13	2	58	15	1.2	10	5.8	4.7	15.9	11.7
(8) O1-F	2	45	12	1.0	8	4.6	4.7	13.7	10.3
(9) OV-1A,B,C	1	297	80	6.3	70	40.5	4.5	80.8	51.6
(10) CH-34	11	263	70	5.5	63	36.5	7.0	75.5	49.0
(11) CH-37	4	398	106	8.4	87	50.4	6.7	102.1	65.5
(12) CH-47	2	630	168	13.2	117	67.7	6.7	136.9	87.6
(13) CH-54	5	1357	363	28.6	150	86.8	8.7	187.3	124.1

TABLE IX
COST ESTIMATES FOR A NITROGEN GAS PURGE SYSTEM

Aircraft	Number of Fuel Cells	Capacity of Fuel System (gal)	Nitrogen Requirements (ft ³)	Estimated Costs of Nitrogen, Tubing Pressure Regulator, and Check Valves	Estimated Costs of Steel Nitrogen Container	Total Estimated System Costs
(1) UH-1B	2	242	65	\$ 97	\$40	\$137
(2) UH-1D	5	220	59	95	39	134
(3) U-1A	4	214	57	94	39	133
(4) U-6A	5	140	37	101	37	138
(5) U-8D&8F	8	230	62	99	42	141
(6) OH-6	2	66	18	96	32	128
(7) OH-13	2	58	15	95	30	125
(8) O1-F	2	45	12	95	30	125
(9) OV-1A,B,C	1	297	80	98	45	143
(10) CH-34	11	263	70	111	43	154
(11) CH-37	4	398	106	112	50	162
(12) CH-47	2	630	117	112	58	173
(13) CH-54	5	1357	363	118	72	190

The additional costs of the nitrogen gas itself and the pressurized gas container vary with each aircraft, since the total nitrogen requirements differ for each aircraft. Under the assumptions previously stated, the quantity of nitrogen required and the size of the bottle container are determined from the fuel capacity of the respective aircraft.

The retail cost of nitrogen is approximately \$.025 per cubic foot. After the quantity of nitrogen required for each aircraft was determined, the total cost of the nitrogen was added to the cost estimate of the standard components. This sum is presented in Table IX. The estimated cost of the empty nitrogen container is presented separately in the table and has been estimated from the cost data presented in Table VIII. Finally, the total system cost estimate is presented as a sum of these two cost estimates in the table. It is emphasized that the costs are associated with one maximum-range mission for each aircraft. Additional costs will be involved in replacing used nitrogen and in servicing the system during maintenance procedures.

No dollar estimates of titanium tanks have been included because of the development work which will be required before specifications for such a tank can be fully established.

D. COLLAPSIBLE INTERNAL TANK BLADDERS

This approach to the passive defense of Army aircraft fuel tanks is based upon the recent work with expulsion bladders which is being pursued for the handling of liquid fuels in a zero-gravity space environment. By containing aircraft fuel in a collapsible bladder, all mixing of fuel vapor with the air in the tank can be eliminated; thus an explosive or flammable mixture would never be formed.

A preliminary review of the work thus far accomplished in expulsion bladder development clearly indicates that there are a number of potential bladder materials which can meet the physical requirements of an aircraft fuel tank application. The operating environment for Army aircraft is much less demanding than the space environment for which bladders are under development. The very low temperatures (below -300°F) which must be expected in a space mission involving the

storage of very reactive fuels such as hydrazine present particularly difficult conditions in which polymeric materials must survive and retain strength and flexibility.

It is recognized that a number of design problems would have to be met in applying the collapsible bladder concept to existing aircraft fuel systems. Present tanks contain a variety of plumbing and fuel measuring devices which would have to be located outside the bladder or outside the tank, or their functions would have to be accomplished in a new way. Tank filling and tank venting systems would require modification, and of course a reliable bladder design would have to be developed for each fuel cell so that fuel capacity would not be significantly altered. These design problems are not beyond the state of the art at the present time, and it is the considered opinion of the authors that practical bladder systems can and should be fabricated if their value can be conclusively shown.

Results of Experimental Test Programs

Preliminary tests were undertaken at an early point in this program to provide data relative to the potential value of collapsible bladders inside fuel tanks. Three types of tests were conducted. Briefly summarized, these tests involved placing a well-functioned caliber .30 M-14 API incendiary round within the vapor space of a test fuel cell under the following conditions:

1. Fuel cells containing only an explosive (near stoichiometric) fuel/air mixture.
2. Fuel cells containing liquid gasoline in a collapsible bladder with air above and the line of fire through the vapor space only.
3. Fuel cell conditions as in No. 2, but with the line of fire through the liquid and then into and through the vapor space.

These conditions are illustrated in Figure 20.

A light-gage steel container of approximately 5-gallon capacity was used as the test cell in each instance. Figure 21 shows the test cell and function plates ready for firing.

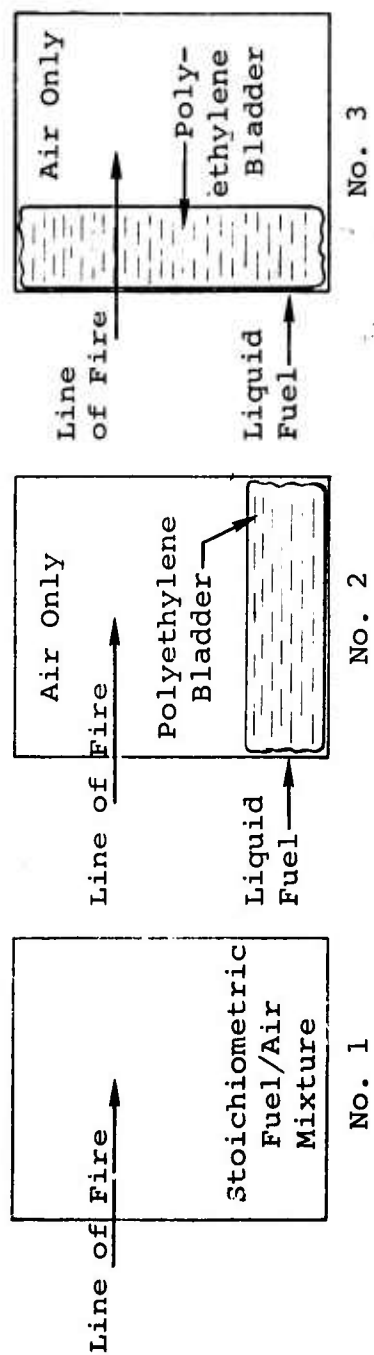


Figure 20. Fuel Cell Arrangements for Collapsible Bladder Testing.

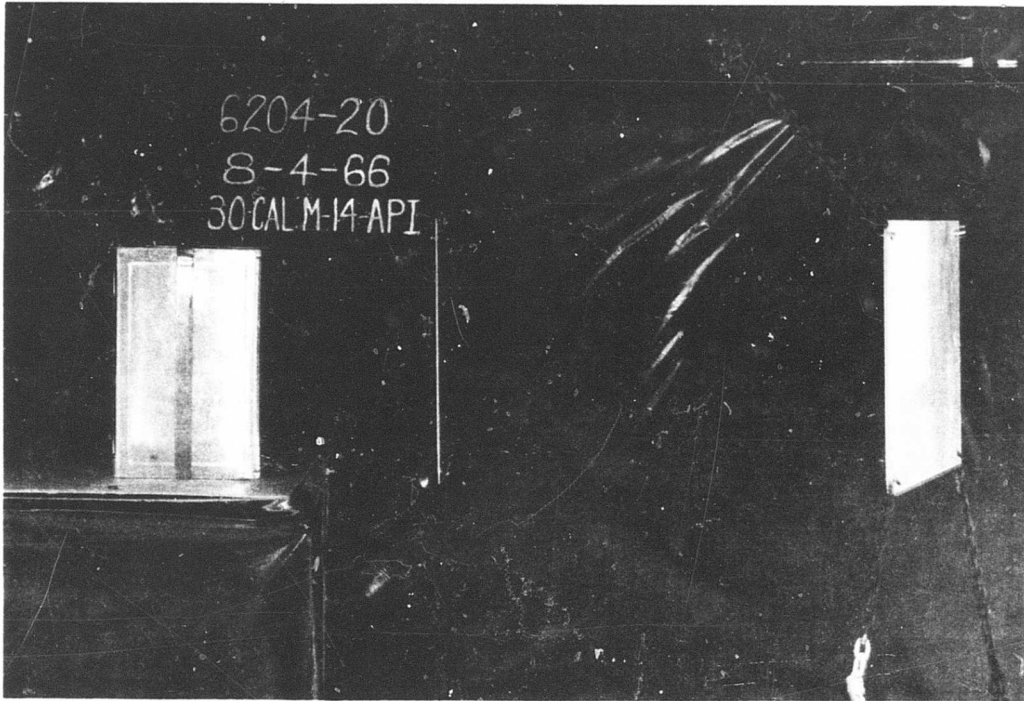


Figure 21. Test Cell and Function Plates in Position for Vapor Space Tests.

Figure 22 shows the size and location of the incendiary bursts resulting from caliber .30 M-14 API impacts at full velocity upon this target. It is important to note that there was a strong incendiary burst on the front side of the test fuel cell which carried into the cell in all cases and in some cases carried through the tank and out the exit side.

Figure 23 shows the results of a shot into an explosive fuel/air mixture (test condition No. 1). This was the most catastrophic damage to any test cell; however, other similar tests threw containers 25 feet in the air and left the cells very severely bulged or with torn seams. In the instance shown in Figure 23, the rolled and soldered seams of the can came entirely apart and the can was literally turned inside out by the force of the explosion. These tests were included in this preliminary firing program to provide a comparative basis for the other tests to be performed and to demonstrate the power of a fuel vapor/air explosion. This cell contained 2 milliliters of liquid gasoline, well vaporized and mixed with the air in the 5-gallon container.

Three tests under condition No. 2 produced no explosions and no fires. For these tests, 1 gallon of 80/87 octane aviation gasoline was enclosed in a polyethylene bag. The mouth of the bag was gathered and sealed around a piece of rubber tubing. Once gasoline was added to the bladder and all air expelled, the tubing was sealed with a stopper.

The bladder was placed in the bottom of the 5-gallon container and vapor space, then checked with a MSA Model 2A Combustible Gas Indicator to assure that the concentration of the combustible vapor in the cell was less than 20 percent of the lower explosive limit. After this check, the container was immediately sealed and the test was fired.

Figure 24 shows the appearance of the entrance and exit holes in the tank under these test conditions. Note that there is evidence of the incendiary burst on both entrance and exit surfaces. In some instances, fragments from the bullet or from the function plates perforated the light bladder, but no fires resulted. These were single-shot tests, and it is possible that fires might have been produced within the tank by subsequent shots, although some time would be required for the leakage, vaporization, and diffusion processes to produce an explosive mixture.

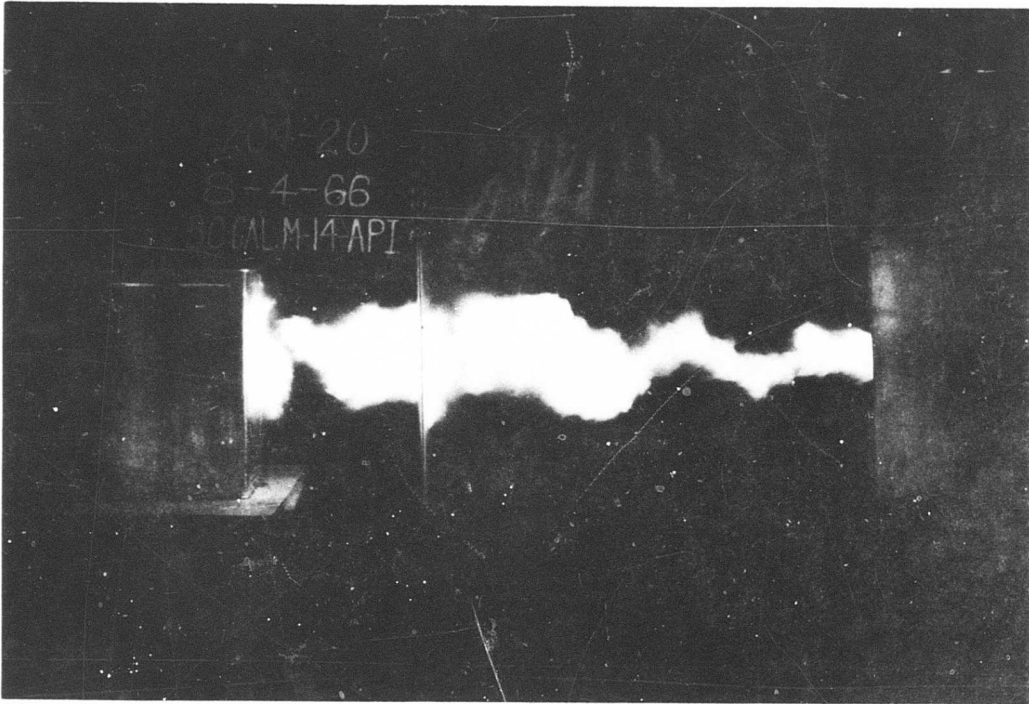


Figure 22. Caliber .30 M-14 Armor-Piercing Incendiary Burst
Location Within the Test Target.

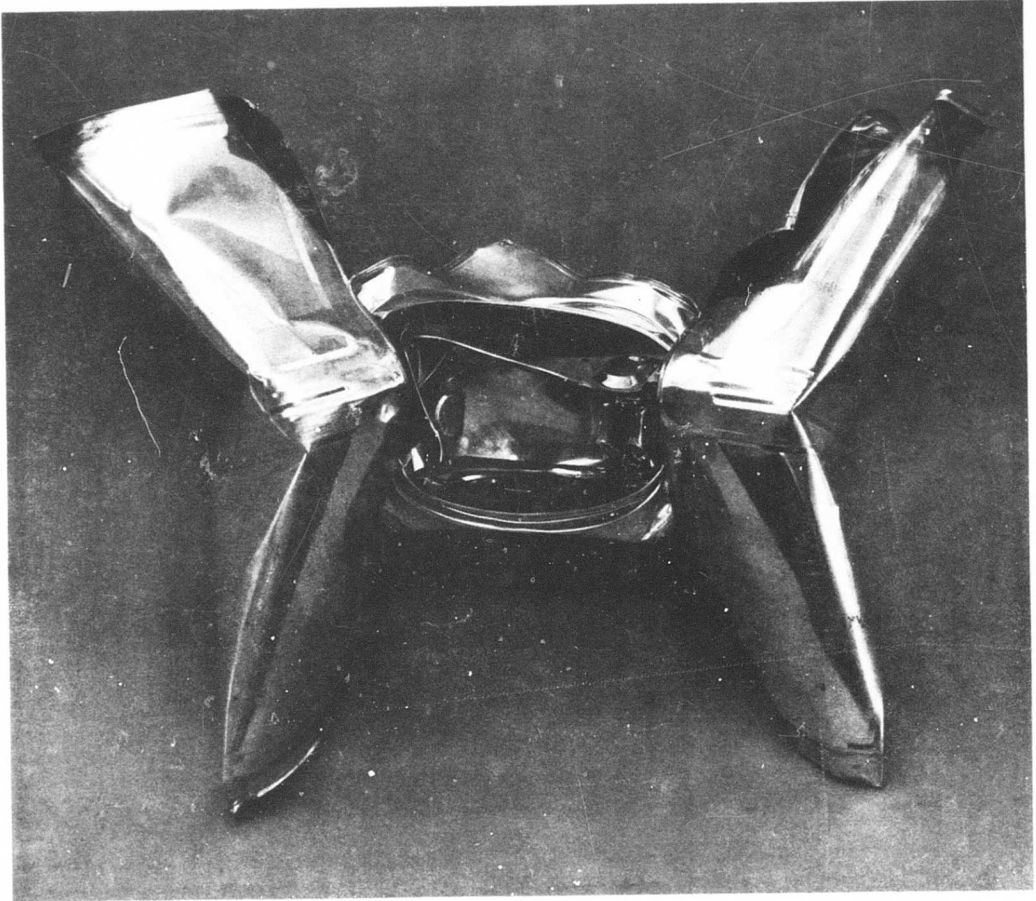


Figure 23. Test Cell After Firing Caliber .30 M-14 Armor-Piercing Incendiary Through Explosive Fuel/Air Mixture.

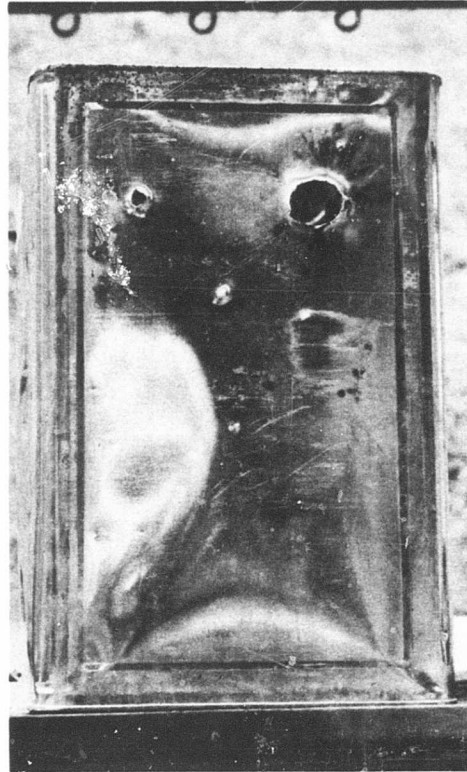
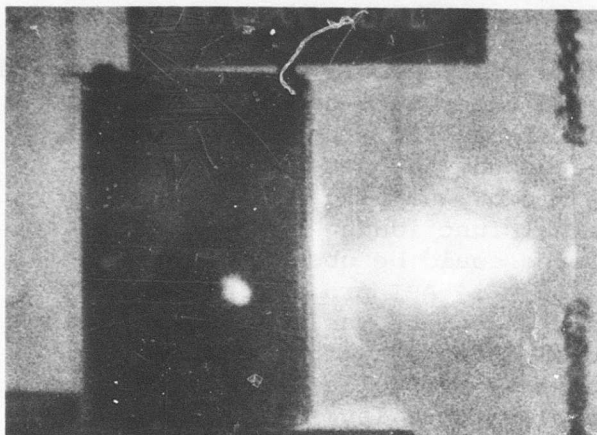


Figure 24. Entrance and Exit Holes After Firing Caliber .30 M-14 Armor-Piercing Incendiary Through Vapor Space.

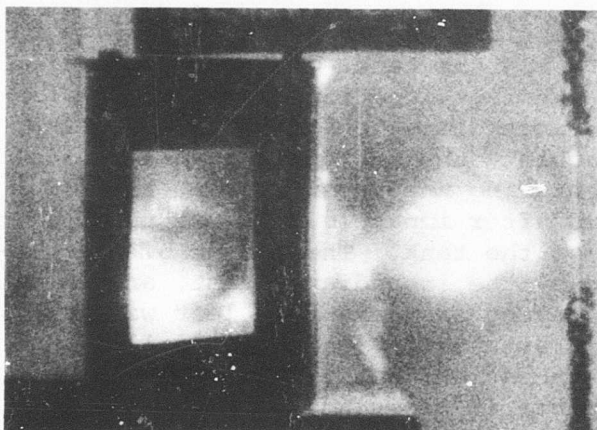
The significant frames of the high-speed motion picture record of one of the tests conducted under fuel cell condition No. 3, Figure 20, are presented as Figure 25. The target was a 5-gallon metal container preceded by the necessary aluminum function plates. A Lucite window was placed in the side of the container so that internal functioning of the incendiary round and resulting fuel fires could be observed. The ignition source was a caliber .30 M-14 API projectile fired at full velocity. One gallon of gasoline was contained within a sealed bladder which had been located against the internal container face first impacted by the bullet. The gasoline-filled bladder was held in place by a layer of open-cell plastic honeycomb.

The first frame of the series is taken at about 1/3 millisecond after bullet impact upon the tank. The incendiary burst can be seen between the last function plate and the tank, and the start of the incendiary action within the tank is just visible. At this point, the bullet is just emerging from the liquid fuel and entering the vapor space. Frame 2 is taken at 2/3 millisecond after impact but before the bullet has reached the back face of the tank. The inside of the container is well illuminated by the incendiary burst, and the liquid fuel can be seen spraying from right to left within the tank. The fuel appears as a shadow which partially blocks the light from the incendiary burst. The third frame is 1 millisecond after impact; it shows both fuel and parts of the incendiary burst leaving the back surface of the tank. It appears that the AP core passed directly through the tank but that a portion of the bullet jacket separated and was leaving through the lower edge of the tank. This is a common occurrence with jacketed incendiary ammunition. Note that the front surface of the tank is not yet bulged at this point in time and thus no fuel has yet sprayed from the front of the tank. A spray of fuel appears to have followed the bullet out the back of the tank, but it has not yet been ignited in this frame. The fourth frame is 1 millisecond after the third and 2 milliseconds after initial impact. It appears that some of the fuel spilling or spraying from the back of the tank has been ignited and that the front of the tank is now seriously bulged. Note that the incendiary burst which resulted from the impact on the function plate in front of the tank is little changed from its appearance in the earlier frames and it is thus "waiting" for the fuel spray which is now beginning



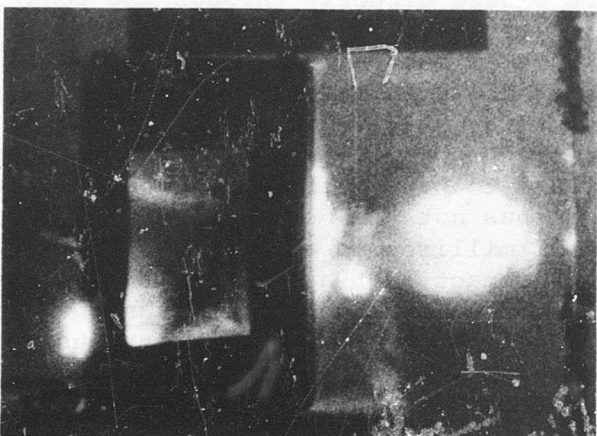
+0.3 Millisecond
After Impact

1



+0.7 Millisecond

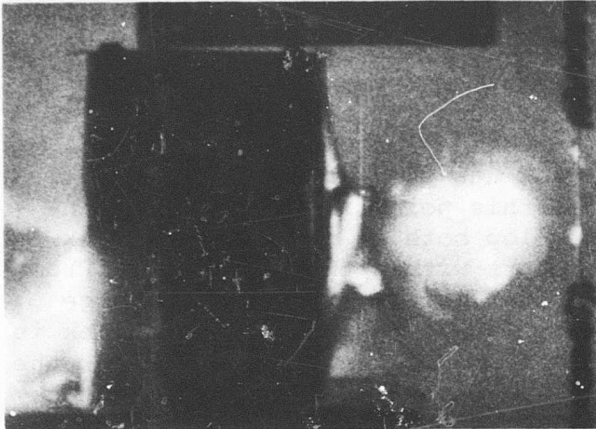
2



+1.0 Millisecond

3

Figure 25. Test of the Collapsible Bladder Concept for Internal Fuel Tank Passive Defense.



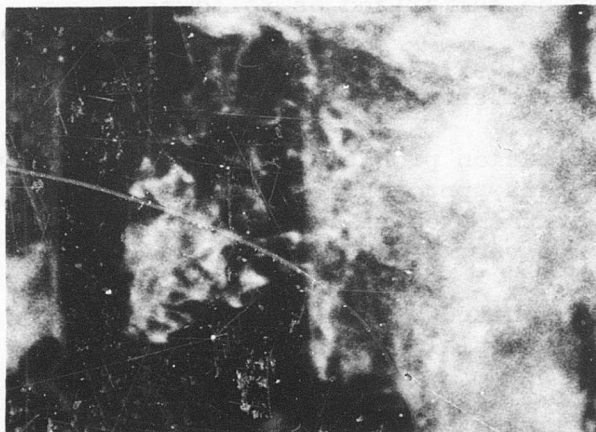
+2.0 Milliseconds

4



+78 Milliseconds

5



+120 Milliseconds

6

Figure 25 (Continued)

to flow from the front surface of the tank. Note also that the incendiary burst within the tank has been almost completely extinguished. The quenching action of the spray of liquid gasoline within the tank has probably been responsible for this rapid cooling. From this point in time, a substantial fuel fire is seen to develop both in front of the tank and behind it, but no fire occurs within the container. Frame 5 was taken 78 milliseconds after bullet impact. The large external fuel fires are visible, but the inside of the tank is dark. Fuel coming out of the front of the tank has struck the aluminum function plate and is now rebounding toward the tank as it burns. The last frame in the sequence is at 120 milliseconds after impact and shows the rebounding flame in front of the tank window but clearly on the outside of the tank. This flame is moving at a speed of 15 to 20 feet per second between this frame and frame 5.

These tests, plus the results of firings previously reported, show quite conclusively that a collapsible bladder can be employed to eliminate the formation of fuel/air mixtures within tank vapor spaces. Fires and explosions within the tank are prevented from all bullet impact directions, even when the functioning round passes through the liquid before entering the vapor space. The collapsible bladder, of course, does nothing to reduce the occurrence or severity of fires outside the fuel tank.

The data now available on the collapsible bladder approach to internal tank protection may be summarized as follows:

1. Present polymer technology can provide the basis for selecting a suitable material for such a bladder.
2. The design and fabrication problems associated with the application of this approach to Army aircraft are substantial, but the probability of eventual success appears to be very high.
3. Fuel/air explosions ignited by incendiary burst have a very destructive potential, as shown by Figure 23.
4. Collapsible bladders are clearly effective in eliminating this explosion hazard for single hits when the line of fire is through the vapor space.

5. Collapsible bladders appear to prevent internal tank fires and explosions for hits passing through the liquid and entering the vapor space. The massive fire existing outside the fuel tank has obscured internal tank performance for the tests conducted.
6. The collapsible bladder approach appears to have merit and deserves further study and investigation.

Weight and Cost Estimates for Internal Tank Bladders

Estimation of the weight of collapsible bladders suitable for present-day Army aircraft and the dollar costs associated with installing them is vastly complicated by the uncertainties surrounding bladder design and fuel cell modification. As previously noted, the methods of fuel pumping and measuring and of tank filling and venting presently used in Army aircraft fuel cells must be modified in order to utilize the collapsible bladder concept. In addition, a reliable bladder is yet to be developed.

The fabrication costs for developing small quantities of expulsion bladders are very high. In one reported case, the tooling for one spherical bladder approximately 8 inches in diameter was about \$3,000. It may be possible to build bladders around an inflatable form or to form them in other less expensive ways; however, in any case, a development program is involved.

For comparative purposes, a theoretical weight penalty imposed on each aircraft by the use of collapsible bladders has been estimated in Table X. Each fuel cell bladder is assumed to fit against the interior surface walls of the cell when filled to capacity. Each bladder is assumed to be made of 0.025-inch material having a specific gravity of 2.0. An additional weight penalty is computed in Table X to account for the additional equipment associated with the use of a collapsible bladder. These include fill pipes and connectors. It has been assumed for estimation purposes that this equipment will impose a 1 pound per 50 gallons of fuel capacity weight penalty in each fuel cell. The total estimated weight and the individual estimated weight of the collapsible bladder system appear in Table X.

TABLE X
WEIGHT ESTIMATES FOR COLLAPSIBLE BLADDER FUEL SYSTEMS

Aircraft	Number of Fuel Cells	Fuel Cell Capacity (gal)	Surface Area of Each Cell (ft ²)	Collapsible Bladder (lb)	Weight of Associated Equipment (lb)	Total Wt. of System (lb)
(1) UH-1B	2	242.0				22.9
	(1)	122.0	39.0	8.45	3.0	(11.45)
	(2)	120.0	39.0	8.45	3.0	(11.45)
Earlier models of the UH-1B	2	165.0				17.0
	(1)	82.0	30.0	6.50	2.0	(8.50)
	(2)	83.0	30.0	6.50	2.0	(8.50)
(2) UH-1D	5	220.0				29.4
	(1)	44.2	22.1	4.79	1.0	(5.79)
	(2)	44.2	22.1	4.79	1.0	(5.79)
	(3)	34.3	18.5	4.01	1.0	(5.01)
	(4)	63.0	26.6	5.76	2.0	(7.76)
	(5)	34.3	18.5	4.01	1.0	(5.01)
(3) U-1A	4	213.5				27.4
	(1)	61.2	26.1	5.65	2.0	(7.65)
	(2)	51.0	25.8	5.59	1.0	(6.59)
	(3)	51.0	25.8	5.59	1.0	(6.59)
	(4)	50.3	25.8	5.59	1.0	(6.59)

TABLE X (Continued)

Aircraft	Number of Fuel Cells	Fuel Cell Capacity (gal)	Surface Area of Each Cell (ft ²)	Collapsible Bladder (lb)	Weight of Associated Equipment (lb)	Total Wt. of System (lb)
(4) U-6A	5	139.8				21.7
	(1)	35.7	21.0	4.55	1.0	(5.55)
	(2)	35.6	21.0	4.55	1.0	(5.55)
	(3)	25.5	16.0	3.47	1.0	(4.47)
	(4)	21.5	9.4	2.04	1.0	(3.04)
	(5)	21.5	9.4	2.04	1.0	(3.04)
(5) U-8D&F	8	230.0				40.1
	(1)	44.0	20.0	4.33	1.0	(5.33)
	(2)	44.0	20.0	4.33	1.0	(5.33)
	(3) -	23.0	21.0; (2)	4.55; (2)	1.0 ea	(5.55); (2)
	(6)		15.0; (2)	3.25; (2)		(4.25); (2)
	(7)	25.0	18.0	3.90	1.0	(4.90)
	(8)	25.0	18.0	3.90	1.0	(4.90)
(6) OH-6	2	55.0				10.2
	(1)	33.0	19.0	4.12	1.0	(5.12)
	(2)	33.0	19.0	4.12	1.0	(5.12)
(7) OH-13	2	58.0				7.6

TABLE X (Continued)

Aircraft	Number of Fuel Cells	Fuel Cell Capacity (gal)	Surface Area of Each Cell (ft ²)	Collapsible Bladder (lb)	Weight of Associated Equipment (lb)	Total Wt. of System (lb)
(7) Cont.	(1)	29.0	12.9	2.79	1.0	(3.79)
	(2)	29.0	12.9	2.79	1.0	(3.79)
(8) OI-F	2	45.0				10.7
	(1)	22.5	20.1	4.35	1.0	(5.35)
	(2)	22.5	20.1	4.35	1.0	(5.35)
(9) OV-1A,B,C	1	297.0	84.0	18.19	6.0	24.2
(10) CH-34	11	263.0				52.5
	(1)	15.7	13.2	2.86	1.0	(3.86)
	(2)	20.0	15.8	3.42	1.0	(4.42)
	(3)	15.7	13.2	2.86	1.0	(3.86)
	(4)	25.8	20.5	4.44	1.0	(5.44)
	(5)	25.8	20.5	4.44	1.0	(5.44)
	(6)	22.3	14.9	3.23	1.0	(4.23)
	(7)	28.9	16.8	3.64	1.0	(4.64)
	(8)	22.3	14.9	3.23	1.0	(4.23)
	(9)	28.7	18.9	4.09	1.0	(5.09)
	(10)	29.1	22.5	4.87	1.0	(5.87)

TABLE X (Continued)

Aircraft	Number of Fuel Cells	Fuel Cell Capacity (gal)	Surface Area of Each Cell (ft ²)	Collapsible Bladder (lb)	Weight of Associated Equipment (lb)	Total Wt. of System (lb)
(10) Cont.	(11)	28.7	18.9	4.09	1.0	(5.09)
(11) CH-37	4	498.0				44.8
	(1)	100.0	45.4	9.83	2.0	(11.83)
	(2)	99.0	39.5	8.56	2.0	(10.56)
	(3)	99.0	39.5	8.56	2.0	(10.56)
	(4)	100.0	45.4	9.83	2.0	(11.83)
(12) CH-47	2	630.0				56.5
	(1)	315.0	98.0	21.23	7.0	(28.23)
	(2)	315.0	98.0	21.23	7.0	(28.23)
(13) CH-54	5	1357.0				116.3
	(1)	226.0	71.4	15.47	5.0	(20.47)
	(2)	226.0	73.5	15.92	5.0	(20.92)
	(3)	226.0	73.5	15.92	5.0	(20.92)
	(4)	226.0	71.4	15.47	5.0	(20.47)
	(5)	453.0	113.3	24.54	9.0	(34.54)

A number of design problems would have to be solved in applying the collapsible bladder concept to existing Army aircraft fuel tanks. Present tanks, containing internal pumping and fuel measuring equipment, would have to be redesigned so as to locate this equipment outside the tank, or otherwise fulfill its functions without interfering with the bladder. Tank filling and venting systems would require modification, and of course a reliable bladder design must be developed for each fuel cell so that the fuel capacity is not significantly altered. These design problems are probably not beyond the present state of the art, and a research and development program could lead to an operational design in a reasonable length of time.

In the limited testing accomplished to date, the collapsible bladder has not appeared to offer any special or unique benefits over the other proposed systems, nor does it seem to be any more reliable. With respect to these conclusions, the considerable costs which would arise from a research and development program to fully develop the collapsible bladder for specific Army aircraft do not seem to be justified at this time.

E. RETICULATED FOAM FUEL TANK FILLERS

Background and Status of Foam Applications to Aircraft

Reticulated or open-cell polyurethane foam has been commercially available for 5 years or more. It has been widely used as a filter medium and can be supplied in almost any pore size. It is produced by techniques similar to other foam products and is first a closed-cell foam. The thin membranes between cells are then removed by either chemical action or fire to produce the unique open-cell material.

The U.S. Air Force has actively pursued a program to apply reticulated foam to the passive defense of aircraft fuel tanks during the past 2 years. The work has advanced rapidly and is still in progress at several facilities at this time (March 1967). Reference 5 presents an excellent summary of the work which has been accomplished, and the paragraphs which follow present sections of that work which are particularly applicable to this study and to Army aircraft requirements.

Reticulated foam's first vehicle application was by Firestone Tire & Rubber Company in Indianapolis race-car fuel tanks in 1964 and 1965 to reduce sloshing and in conjunction with heavy bladders to improve crashworthiness.

At the request of an engineer from the Research and Technology Division of Wright-Patterson Air Force Base (USAF RTD), Firestone, in mid-1965, conducted small-scale "flame tube" and gunfire tests to determine if the "10-pore-per-inch" material packed in fuel tanks would render them "explosion proof". These tests were totally successful, and in the judgement of RTD engineers promised an immediate solution to a pressing operational problem in Southeast Asia.

In late 1965, six HH-3E "Jolly Green Giant" Combat Rescue Helicopters were being deployed in Southeast Asia. They carried an F-100, 200-gallon external fuel tank on each side, which was mandatory for their long-range mission requirements. Unfortunately, supply of these tanks was limited because of requirements for the F-100, and it appeared necessary for the helicopters to retain these tanks when empty of all but residual JP-4 fuel during "pickup" and the return leg. Because of their size, exposed location, and 98% ullage, they were deemed to be a severe compromise of the HH-3E's survivability.

Thus, USAF RTD (SEG) advocated a program which, in November 1965, was funded and managed by the ASD Deputy for Limited War. It was to provide for qualification of the foam material for use in fuel tanks of aircraft operating in Southeast Asia, full-scale testing and qualification of the HH-3E external tanks with the foam material installed, and delivery of 12 "explosion proof" tanks for use on the 6 HH-3E's. The laboratory tests proved compatibility of the foam with JP-4 and acceptable environmental performance. Full-scale slosh and vibration, functional, weight and CG, and contamination tests were acceptable. They indicated a loss in usable fuel of 4.5% and a weight increase between a filled tank with the foam of 14 pounds compared with a filled tank without the foam. Full-scale gunfire tests on an unmodified tank with residual JP-4 fuel confirmed the explosion and catastrophic break-up of the HH-3E external tank when hit by a caliber .30 tracer round. Shots into a tank that was identical except for addition of the foam demonstrated the explosion proofing

available, even with multiple hits of caliber .30 tracer rounds through the tank filled with explosive vapors.

The Air Force Aero Propulsion Laboratory, supported by contracts with the U.S. Bureau of Mines, performed tests sufficient to prove that the explosion proofing capabilities of the foam material were far beyond the requirements of this first-generation application. The program has been extended in an effort to define a "cored" foam configuration which will provide acceptable explosion proofing but may cut weight and volume penalties by as much as one-half. Alternate materials provided by the Air Force Materials Laboratory are also being evaluated.

The HH-3E tanks were delivered in April 1966, and were in use in May 1966. Sump samples from the tanks with the foam were analyzed periodically. Used fuel filter elements were shipped to WPAFB (APFL) for contaminant analysis, which revealed no significant number of foam-associated particles. Fortunately, the supply situation on F-100, 200-gallon tanks eased, and jettison from the HH-3E's of the external tanks upon emptying became permissible. This is greatly preferred due to the critical need to reduce all possible weight and drag on long-range missions. The "explosion proof" tanks, their purpose fulfilled, were eventually all jettisoned.

Follow-on effort included compatibility testing of the foam material with JP-5 and aviation gasoline, and environmental and functional testing which included high-performance aircraft and world-wide deployment. All testing was successful, and is reported in ASJ-TM-66-1, dated November 1966.

Chemical lab testing had conclusively demonstrated that fuel did not adversely affect the foam. Also, JP-4 fuel was found to be unaltered by its exposure to foam under simulated service conditions. These findings permitted immediate modification of auxiliary tanks without the delay of full-scale engine and/or flight testing. However, due to the tremendous range of potential internal tank applications, turbine engine manufacturers were briefed in a joint meeting at WPAFB in April 1966 on the application of the reticulated polyurethane foam and were requested to propose testing which they considered necessary to confirm engine compatibility. This effort has resulted in satisfactory performance of a J-75

engine at Pratt & Whitney Aircraft Company under severe test conditions. The contractor recommended that foam-modified internal tanks be flight tested.

The program for installation of the reticulated polyurethane foam in all internal tanks of the F-105 is proceeding successfully. The full-scale F-105 fuel system simulator, the "Iron Bird", was performance calibrated; then the tanks were packed with the material and extreme functional testing was conducted. This and other testing have resulted in high confidence in the foam configuration by Republic Aviation.

The foam material is now an Air Force requirement for explosion proofing fuel tanks in all O-2, A-37, and C-142 aircraft, along with one special SEA mission C-130 and a flight test B-52. The foam material is being recommended by manufacturers of the F-100, F-101, F-105, and F-4 in a vulnerability study managed by ASD. An Army UH-1B is flying with internal tanks modified with the foam.

The FAA is conducting comparative crashworthiness testing of tanks with unmodified fuels and thickened fuels and tanks that are foam filled. Boeing Aircraft Company is actively investigating the foam material for application to explosion proofing and arresting flame propagation in vent lines and vent surge tanks of commercial and military aircraft.

An early hypothesis was that the foam packed in a self-sealing fuel tank might improve its leakage protection by its ability to absorb hydraulic shock. Continuous cell wall support is provided by the foam when installed under slight compression. The Air Force reports that after the usual military specification qualification of a caliber .30 self-sealing cell in a full-scale OV-10 aircraft center wing tank structure, the foam material was installed under 2% to 5% compression. The modified configuration was subjected to caliber .50 gunfire qualification. The results were phenomenal, in that caliber .50 tumbled exits from the caliber .30 cell were sealing "dry"; i.e., without any significant external flow of test fluid. This would be excellent performance even for a caliber .50 cell, which is far thicker and heavier than a caliber .30 cell. Subsequent testing of another caliber .30 self-sealing cell in the same cavity and without the

foam resulted in total failure under caliber .50 gunfire. This success has inspired the self-sealing cell manufacturer to initiate Phase I qualification of lightweight caliber .50 self-sealing tanks which are to perform satisfactorily provided they are packed with the foam material.

At the direction of Headquarters, USAF, Air Force Logistics Command (AFLC) has funded a program with Republic Aviation Division to assess the comparative performance under caliber .50 and 20 mm gunfire of various-weight self-sealing fuel cells with and without the foam material installed in a fixture simulating critical F-105 fuel tank support structure. The testing is complete, and reports and narrated movies are being prepared. It is reported that each time incendiary rounds were fired into test tank vapor spaces unprotected by the foam, an explosion occurred. No explosions or significant pressure rises were ever encountered with incendiary shots into tanks fully packed with foam or with the foam cored 30% to 40% by volume. The data support the desirability of providing caliber .50 protection for the F-105 fuel tanks by installing caliber .30 self-sealing fuel cells and packing them with the reticulated polyurethane foam. Conventional caliber .50 self-sealing fuel cells cannot be installed in the F-105 without increasing the size of the tank cavity access openings, which is far too costly and time-consuming.

In summary, the Air Force has found reticulated polyurethane foam to be an "off-the-shelf" material which is qualified and considered acceptable for immediate retrofit and use in aircraft fuel tanks, provided installation criteria and performance limits are followed. The material has been successfully retrofitted in aircraft fuel tanks of many types, and appears to be limited only in the case of restricted or impossible access to the fuel tank's interior.

This method of explosion proofing is advantageous in that it is effective at all times; has unsurpassed reliability; requires no electronic or moving parts, no power, and no replenishment or control of gaseous or liquid media; and can be readily installed or removed without wiring or plumbing of any kind. The basic disadvantages are the loss of usable fuel, 5% or less, and the added weight, about 0.24 pound per gallon of tank capacity. Augmentation of self-sealing tank performance is a proven fact and is highly significant, since

lighter, thinner cells providing adequate protection can offset the weight and volume penalties of the foam. Material cost is less than \$1.50 per gallon of tank volume in small quantities, and can be reduced by 50% or more by quantity purchasing. Material cutting and installation do not require high accuracy, special equipment, or a high skill level, but may require a substantial number of man-hours. Design is simple and straightforward. Qualification and flight testing of each modified system is more costly.

Firestone has applied for an application patent for the internal tank use of foam materials for both slosh reduction and explosion suppression. It is reported that a secrecy restriction has been placed on this patent application by the DOD; therefore, it is probable that no such patent will issue in the immediate future. Firestone has an exclusive agreement with the Scott Paper Company for this use of the foam material. Scott in turn has purchased the rights from another developer for the thermal "zap" process. Firestone is having Scott develop a lighter weight foam material; some samples of this material received at Firestone weigh from .75 to .88 pound per cubic foot. Testing of this material is in process.

Staff engineers at Wright-Patterson Air Force Base have postulated that the fire extinguishing action of the foam is a mechanical process in which the flame front is interrupted by the turbulence introduced by the foam obstruction. This mechanical approach to the quenching action seems to be quite well accepted within the Air Force.

The Air Force and Firestone Tire and Rubber Company have achieved some very dramatic explosions involving JP-4 which have been vaporized within tanks; both 200-gallon Air Force drop tanks and 55-gallon steel drums have been used in these tests. Good explosions in the steel drums were achieved by adding 5 pints of JP-4 to the drum and allowing some of the more volatile components to vaporize before the incendiary or tracer round was put through the tank.

The U.S. Bureau of Mines, Explosives Research Center, Pittsburgh, Pennsylvania, is performing work for the Air Force relative to the fire propagation inhibiting effects of reticulated foam. Sections of foam have been placed in a chamber,

and an ignition source has been used to set off a stoichiometric mixture of hydrocarbon (N-pentane) vapor. The temperature rise and pressure rise at various points in the chamber were noted. The distance from the ignition point to the surface of the foam is referred to as the run-up distance. This is quite significant, since this distance permits the flame front to intensify and accelerate. The strength of the flame striking the foam is directly proportional to this distance.

It has been shown that the foam has an effective flame suppression action, but it has also been demonstrated that the flame can penetrate several inches of the foam material. It has been observed that the foam itself ignites and burns; some of the rather high temperature increase that has been observed by Bureau of Mines investigators, at some distance into the foam, has been attributed to actual burning foam particles. Perhaps the most important aspect of the foam's ability to burn is that it can serve as a source of reignition for an explosive mixture. This type of behavior has been observed. Thus, the foam at times can act as a wick to preserve an ignition source until a new region of fuel and oxygen reaches the wick. The staff at the Bureau of Mines do not seem to feel that a straightforward quenching action can adequately explain the mechanism of the foam's behavior; if it were a typical flame arrestor, the flame should stop in a very short distance and should not be able to penetrate more than one or two layers of cells of the foam material.

The investigators at the Explosives Research Center have observed that the foam material does melt under some circumstances, and they agreed that this may play a part in the foam's action. It is also possible that the combustion of the foam material may use up available oxygen or that products of the foam combustion may act on the remaining flame in a detrimental way.

The contract work at the Bureau of Mines is continuing with work which involves higher than ambient pressures and work in which the oxygen content of the atmosphere is above the normal 20%. It seems quite clear that at any significant increase in pressure or oxygen content, the foam will fail to perform as it does under ambient conditions. The Bureau of Mines has investigated the possibility of using large voids within layers of 10-pore foam; however, their tests indicate

that this approach presents problems and may not be satisfactory.

Table XI presents recent performance data for foam barriers under varying conditions of thickness, initial pressure, and run-up distance. These tests of 10-pore-per-inch foam were conducted for the Air Force by the U.S. Bureau of Mines Explosives Research Center, and the data reported are taken from Reference 68.

These data show that flame or at least some type of combustion propagating mechanism can penetrate at least 3 inches of 10-pore foam under ambient sea-level conditions and can penetrate 30 inches of foam under elevated pressures. It is important to note, however, that the run-up distance is 18 inches in these instances and that the foam has reduced the pressure rise even where it failed to interrupt the flame completely.

Table XII presents similar data for foam of 20- and 40-pore-per-inch types. These data are from Reference 69. These data show that the reticulated foam materials with finer pore sizes have increased effectiveness as flame arrestors but that elevated initial pressures make the flame blocking job of the barrier increasingly difficult.

Firestone is continuing to make contamination studies with foam-filled tanks involving race-car applications. It has been stated that one car now has over a hundred thousand miles on it while using the foam-filled tank, and no difficulty has been experienced which could be attributed to the foam material.

The foam is not satisfactory for alcohol fuels and is less than fully satisfactory for the very highly aromatic fuels which are sometimes used in race cars; however, no difficulty whatsoever has been experienced with any type of straight-chain hydrocarbon fuel such as gasoline or JP-4.

Firestone staff members indicate that some tests have been performed using foam materials as external backing boards for fuel tank installation. These have generally been quite successful except that in some instances where the aircraft skin was very light, enough energy had been transferred from

TABLE XI
10-PORE FOAM BARRIER PERFORMANCE UNDER VARIOUS CONDITIONS WITH A 2.4%
N-PENTANE-AIR MIXTURE

Initial Pressure (psig)	Barrier Thickness L ₂ (inches)	Run-up Distance L ₁ (inches)	Cal.* Observed Press. Rise (psi)	Press. Rise (psi)	Flame in L ₃ **	Foam Melting or Burning (inches)
0	None	--	--	85.2	--	--
0	27	6	4.5	8.5	No	Upstream end - 1/8
0	30	18	1.67	25.6	No	Upstream end - 1/2
0	18	18	1	25.6	No	Upstream end - 3/8
0	9	18	0.5	25.5	No	Upstream end - 3/8
0	9	18	0.5	25.6	No	Upstream end - 1/8
0	6	18	0.33	25.6	No	Upstream end - 3/8
0	4.5	18	0.25	25.6	No	Upstream end - 1/4
0	3	18	0.17	25.6	Yes	Downstream end - 2
5	30	18	1.67	34.3	Yes	Downstream end - 1
10	None	--	--	155	--	--
10	30	18	1.67	42.9	Yes	Downstream end - 1-1/2
15	30	18	1.67	51.6	Yes	Downstream end - 1-1/2

*Corresponds to expected pressure rise for combustion of gas only in the run-up void of length, L₁.

**Observations made visually and by flame sensors (thermocouple or photovolt multiplier).

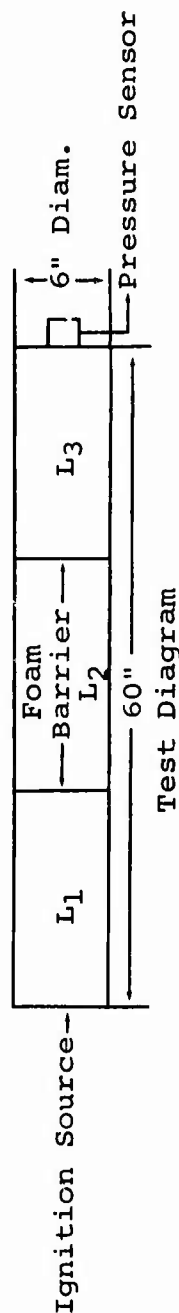
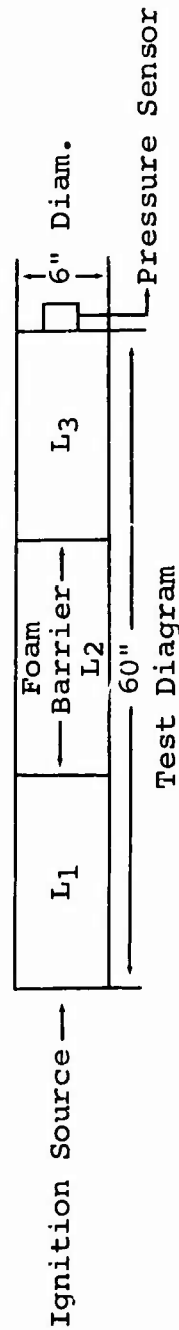


TABLE XII
20-PORE AND 40-PORE FOAM BARRIER PERFORMANCE UNDER VARIOUS CONDITIONS WITH
A 2.4% N-PENTANE-AIR MIXTURE

Initial Pressure (psig)	Barrier Thickness L ₂ (inches)	Run-up Distance L ₁ (inches)	Cal.* Observed Press. Rise (psi)	Observed Pressure Rise (psi)	Flame in L ₃ **	Foam Melting or Burning (inches)
Reticulated Foam (40 pores/inch)						
0	30	18	1.67	25.6	No	Upstream end - 1/8
5	30	18	1.67	34.3	No	Upstream end - 1/4
10	30	18	1.67	42.9	No	Upstream end - 3/4
15	30	18	1.67	51.6	No	Upstream end - 2
Reticulated Foam (20 pores/inch)						
0	30	18	1.67	25.6	No	Upstream end - 3/4
5	30	18	1.67	34.3	No	Upstream end - 1/8
10	30	18	1.67	42.9	Yes	Downstream end - 2-1/2
15	30	18	1.67	51.6	Yes	Downstream end - 3

*Corresponds to expected pressure rise for combustion of gas only in the run-up void length, L₁.

**Observations made visually and by flame sensors (thermocouple or photovolt multiplier).



the hydraulic ram in the fuel tank to the aircraft skin to buckle the skin.

The Monsanto Research Corporation (Ref. 32) has completed an extensive study for the Air Force of the compatibility of aircraft fuels with reticulated foam under extreme environmental conditions.

Static exposure of the foam and fluids for 28 days at 158°F (110°F for aviation gasoline) and at -65°F causes no significant changes in compression load deflection, tensile strength, or elongation. A simulated field exposure consisting of a cyclic temperature environment (70° to 130°F) and high humidity did not adversely affect the foam. Tumbling tests on foam in fuel at -65°F resulted in slight weight loss due to fragmentation; however, similar testing in the absence of fuel to cushion the foam resulted in appreciable foam fragmentation. Washing action of the fluids removed particulate matter from the matrix of the foam. This washing also extracted a very low percentage of an alkyl phthalate ester from the foam which had a tendency to increase the gum content of the fuel.

The foam material appeared to have no corrosive effects on two aluminum alloys; MIL-C-6529 corrosion preventive oil remained effective and had no detrimental effect on the foam.

(U) The various parameters affecting vent icing in a foam-filled tank were studied. Each parameter, including void area, foam condition, and inlet air velocity, as well as inlet air and foam temperatures, was systematically varied throughout realistic extremes, and vent icing conditions were measured. Conditions favoring vent icing were developed, as well as tank vent voiding criteria for the foam.

The observed icing on the foam appeared to be very similar to that noted in a similar type stainless steel flame arresting screen; however, complete icing or flow restriction was never obtained under any extreme flight conditions. Vent inlet voiding of the foam was shown to eliminate any possibility of complete flow restriction, and use criteria for voiding were defined for fuel tank applications. Conditions found which favor vent ice formation include maximum airflow for long durations, saturated air below 25°F, and foam

temperature at or below the air temperature to initiate early ice formation. Results also showed that inlet air above 25°F tends to reduce rather than enhance ice formation, and once the foam in a tank has been fuel-wetted, it tends to stay wetted regardless of the amount or condition of air imposed on it.

Fluid retention by the foam was experimentally measured to be 0.95 volume percent with JP-4, 1.1 volume percent with aviation gasoline, and 4.3 volume percent with water.

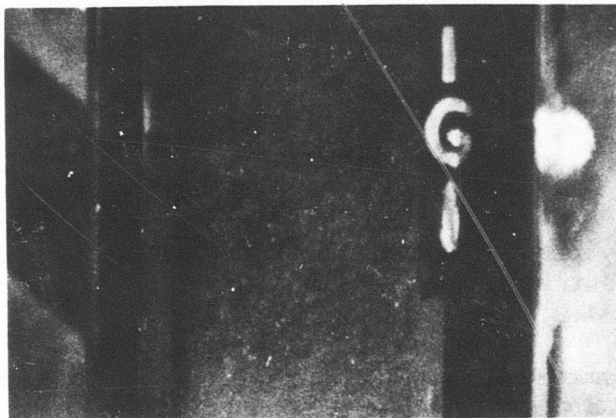
The following recommendations resulted from the work at Monsanto (Ref. 32) and are significant to Army aircraft applications.

1. The material should not be allowed to fit loosely in an aircraft tank, in order to avoid erosion or fragmentation of the foam at low temperatures.
2. Voiding of the foam during tank installation should be maintained in areas such as boost pumps, tank vent outlets, and sumps, and any other area of conceivable flow restriction.
3. For maximum utilization of foam around a tank vent, voiding should be restricted to a volume corresponding to a cube with sides three times the inside diameter of the vent.

Experimental Test Program Under the Current Project

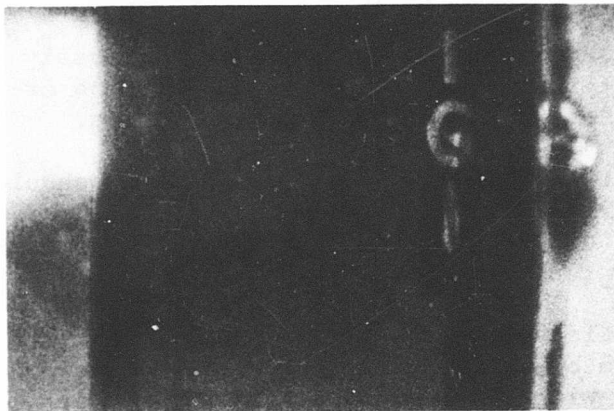
Experimental work which has been accomplished at Falcon Research under this contract has generally confirmed the findings of earlier investigators. Figure 26 presents three frames of the high-speed motion picture documentation for one of these tests. The target is a 5-gallon metal container filled with 10-pore reticulated foam. A Lucite window has been fitted to the tank so that the foam is visible in these pictures.

The first frame is taken 0.3 millisecond after bullet impact upon the container. A small incendiary burst is visible on the front surface of the tank. The functioning caliber .30 M-14 API is inside the foam mass at this time.



+0.3 Millisecond
After Impact

1



+0.7 Millisecond

2



+42 Milliseconds

3

Figure 26. Test of a Reticulated Foam-Filled Fuel Tank
Impacted by a Caliber .30 M-14 API
Projectile

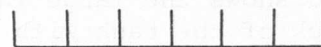
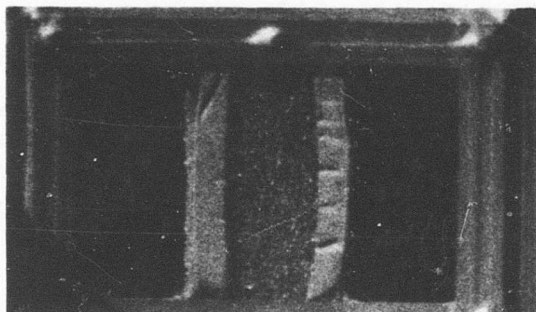
Frame 2 is taken at about 0.7 millisecond after bullet impact and shows the large incendiary burst which emerges from the back of the tank with the bullet. The third and final frame is taken 42 milliseconds after bullet impact, after all traces of the incendiary burst have faded away. No fire or explosion occurred during this test or during any other tests of a similar nature. All test chambers contained combustible or explosive gasoline/air mixtures within the foam.

These tests clearly demonstrate that reticulated foam can greatly reduce, if not entirely eliminate, the explosion hazard arising from incendiary ammunition hits on fuel tank vapor spaces.

Additional tests have been performed in an effort to gain greater insight into the nature of the foam's action when exposed to fire in a fuel tank. Figure 27 presents selected frames from the high-speed motion picture documentation for one of these tests. These pictures show a 5-gallon chamber which has been divided into two parts by a barrier of 10-pore foam about 3 inches thick. The strips on either side of the foam are tape which was used to provide the best seal possible between the foam and the walls and window of the test chamber. Both sides of the compartments contain a combustible gasoline/air mixture which is free to diffuse through the foam barrier. The chamber on the right is fitted with a high-energy spark which can be fired to initiate the mixture. The dark area in the lower left of the pictures is merely a shadow and has no significance to the test.

Frame 1 is taken at zero time, just ahead of the firing of the spark. Frame 2 occurs 2/3 millisecond later and shows the right-hand chamber filled with reflected light from the spark. The spark itself is not visible and is to the right and in the center of the end of the container. It should be emphasized that this is light from the spark only, since no significant fuel combustion has taken place at this point in time. Frame 3 is taken 3 milliseconds after the spark firing and shows that the energy from the spark is of short duration. Still no fuel combustion is visible, and little if any has taken place.

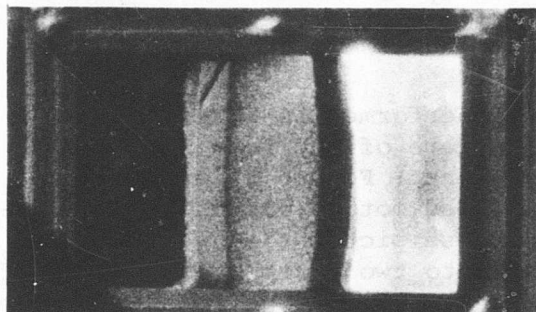
Frame 4 is about 11 milliseconds after spark firing and shows the first visible evidence of fuel combustion appearing at the right edge of the window in the chamber. Frame 5 is



Scale 6 Inches

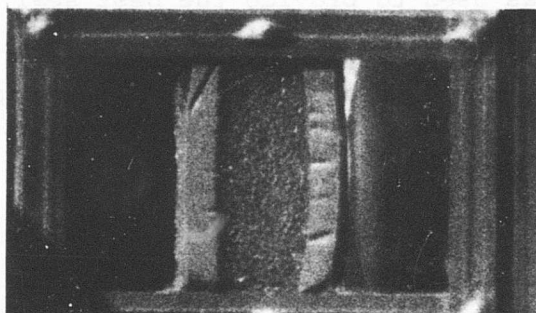
0 Time

1



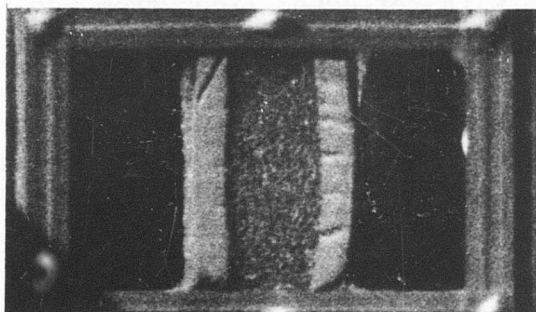
+0.7 Millisecond

2



+3.0 Milliseconds

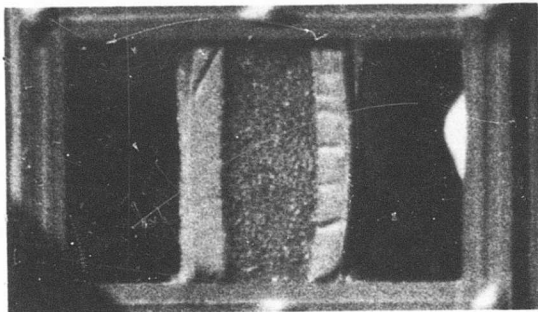
3



+11.3 Milliseconds

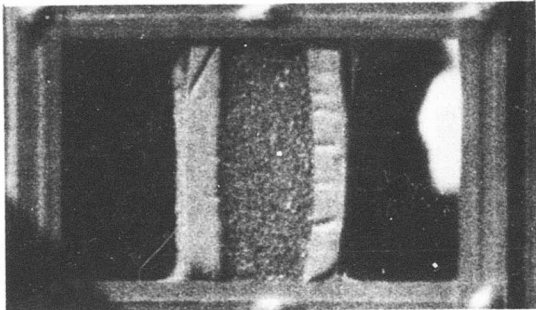
4

Figure 27. The Interaction of a Reticulated Foam Barrier With a Burning Fuel/Air Mixture .



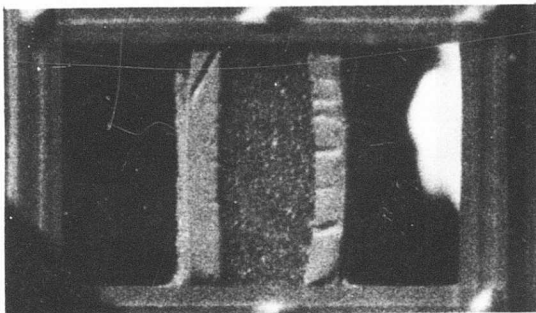
+16.3 Milliseconds

5



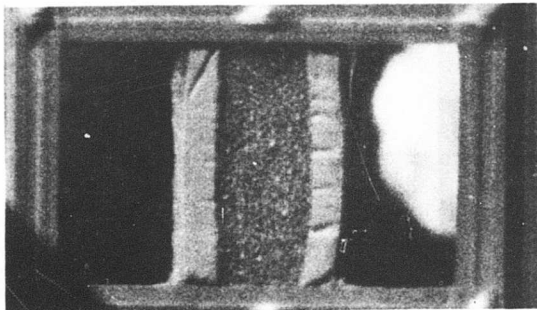
+26.7 Milliseconds

6



+33 Milliseconds

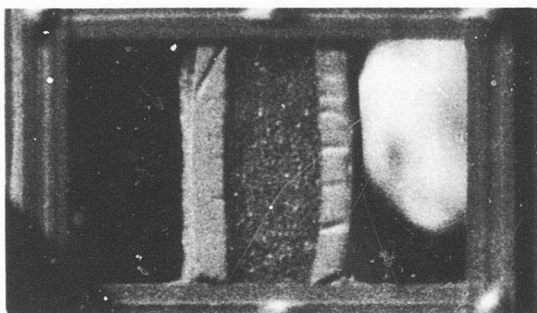
7



+50 Milliseconds

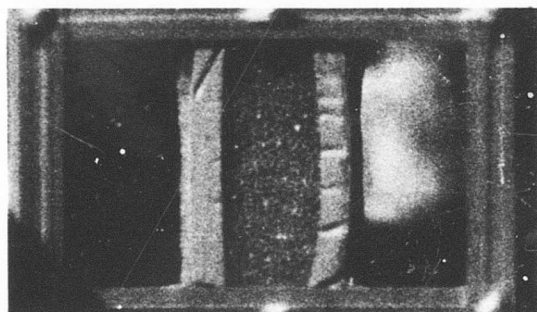
8

Figure 27. (Continued)



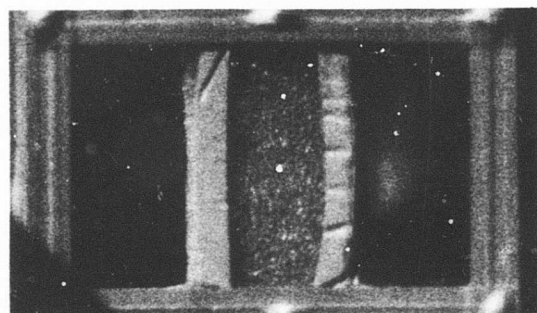
+60 Milliseconds

9



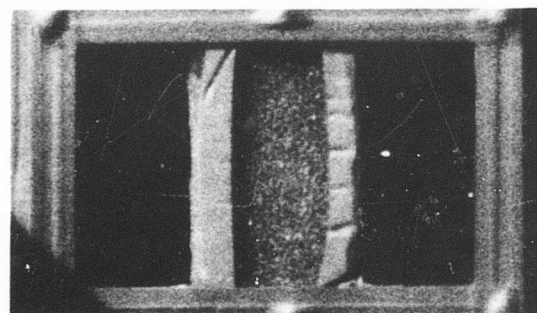
+73 Milliseconds

10



+83 Milliseconds

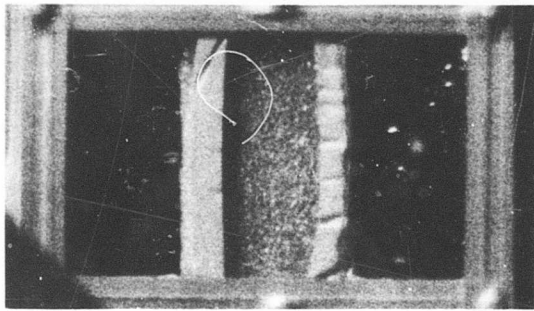
11



+166 Milliseconds

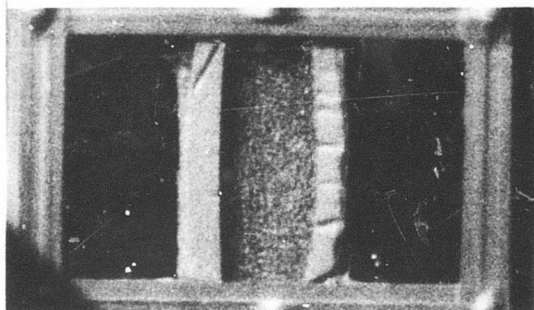
12

Figure 27. (Continued)



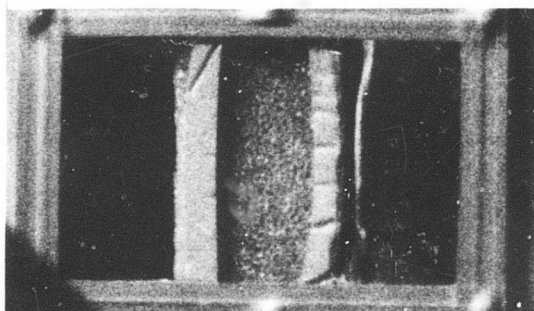
+200 Milliseconds

13



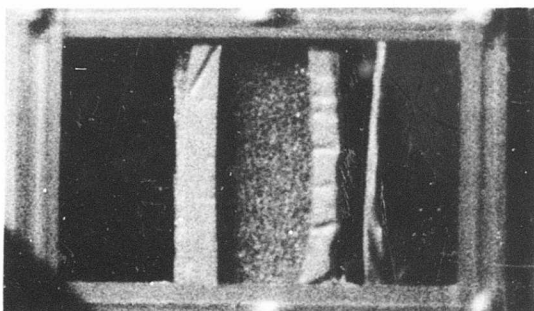
+247 Milliseconds

14



+267 Milliseconds

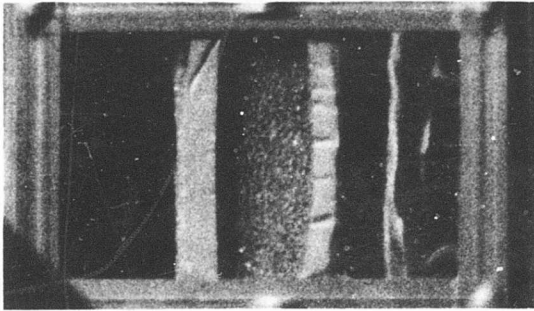
15



+283 Milliseconds

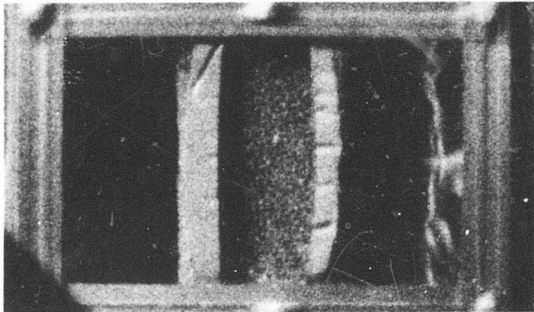
16

Figure 27. (Continued)



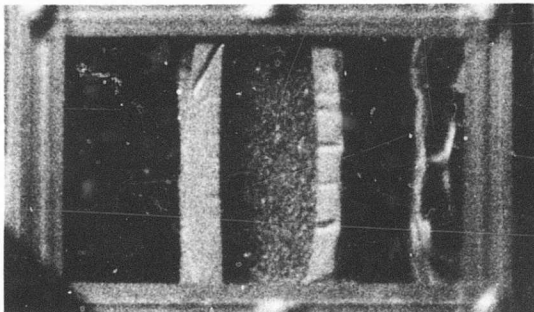
+300 Milliseconds

17



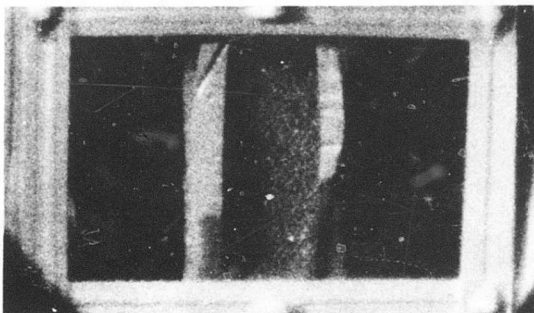
+317 Milliseconds

18



+333 Milliseconds

19



+367 Milliseconds

20

Figure 27. (Continued)

taken 5 milliseconds later and shows the growth of the region where combustion is taking place. Frames 6 through 9 show the further development of this fireball. Several points of importance may be noted from these frames. First, the flame front expands rather slowly, perhaps 5 to 10 feet per second, over the distance of importance here. An induction period of nearly 10 milliseconds was required to get the flame really moving. Note also that the flame never penetrated the lower region of the tank. This is probably due to a poor mixing of the vapors in the tank. The gasoline was originally placed on the bottom of the container as a liquid and thus a "too rich" condition appears to have persisted until the time of the test. This is a very realistic condition as far as an aircraft fuel tank is concerned, since a "too rich" condition will almost always exist close to the liquid surface.

Frame 10 shows the fireball literally being consumed by the foam barrier. Frame 11 shows the last vestiges of the fuel/air reaction as the flame front moves deeper into the foam, if it still exists, and the combustion products continue to cool.

Frame 12, taken some 80-plus milliseconds after frame 11, shows what appears to be burning fragments of foam. These sparks continue to occur in a somewhat haphazard fashion during the next 100 milliseconds, as may be noted by frames 13 and 14. It is possible that these are hot particles which are above their ignition temperature but which glow only as they find regions containing enough oxygen to support their combustion. Remember that most of the oxygen in the chamber was used up in reacting with the fuel during the first 60 to 80 milliseconds.

An examination of the interior of the chamber after the test showed clearly that droplets of molten polyurethane had been splattered about.

Frame 15 is taken at about 267 milliseconds after the firing of the spark. At this point in time, the luminous combustion reaction has been gone for nearly 200 milliseconds and most of the "spark" action has also subsided, although some smoldering fragments are visible. Note the layer of smoke or vaporized foam which is moving from left to right in this frame and in those which follow. It appears that the

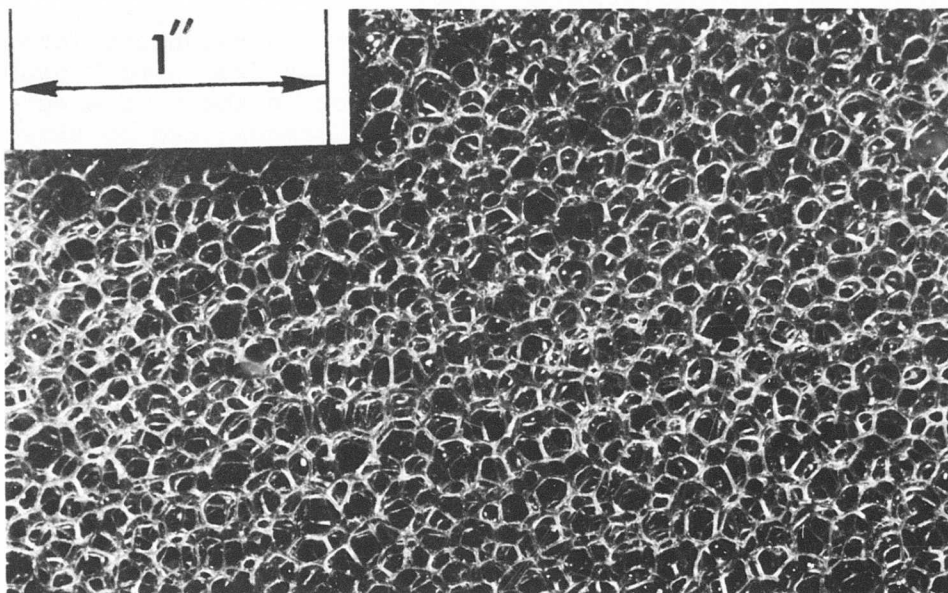
foam has absorbed both the thermal energy of the flame and the kinetic energy of the expanding combustion products. What we see here, then, is the vaporized (or partially burned) foam being propelled backward by the elastic rebound of the foam mass. Note also the shadow at the left of the foam barrier. This has been increasing since slightly after the fireball went into the foam and seems to indicate that the foam toward the left side is pulling away from the container in tension while the right side is still held tightly.

Through frame 17, at about 300 milliseconds, no sign of any action of any sort is noted in the left chamber. Even the back surface of the foam is not noticeably moved. Frames 18 and 19 show what appear to be particles of polyurethane which have finally gotten through the foam. These may be more in the nature of vapor or smoke, since they did not ignite the fuel/air mixture which still existed in the left chamber at this time.

The final frame shows the initial stages of the failure of the test chamber. The observation window is being blown out, as shown by the separation of the tape from the window. Beyond this point in the film record, results cannot be considered to be significant.

(S) In reviewing the more than 1100 frames of 16 mm film between the firing of the spark and container failure, one gets the impression that a great deal of action and interaction has taken place, and it is sometimes difficult to remember that only about one-third of a second separates the first event from the last.

It is possible that these pictures may offer the basis of a working hypothesis for reticulated foam behavior, since they suggest some alternatives and additions to a mechanical disruption of the flame front or a thermal quenching of the flame through the "wall effect". It may be that the greatest contribution to the process of flame extinguishment which the foam makes is through its heat of fusion. It may remove a substantial amount of energy from the flame front by simply melting. That the foam melts when exposed to the flame is indicated by the data presented in Figure 28 and is confirmed by an examination of the foam barrier after the test. Figure 28 shows the appearance of a fresh cut foam surface and the



BEFORE

AFTER

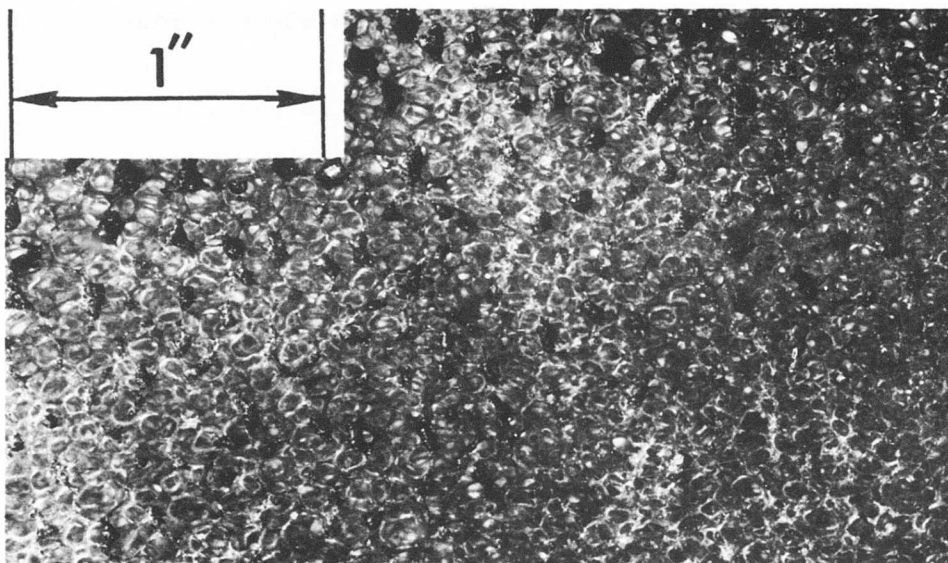


Figure 28. Reticulated Foam Surface Before and After Exposure to the Fire Shown in Figure 27.

surface of the barrier used in this test. A rough estimate of the change in foam volume indicates that from 5 to 7 grams were melted or vaporized from the surface in the test specimen which was photographed. The energy represented by this phase change is at least of the right order of magnitude to cool the flame front below a temperature which favors further propagation. The very low mass of the foam, of course, favors the very rapid heat transfer needed to make this type of cooling work. It is the suggestion of this preliminary study that the most important single effect which reticulated polyurethane foam has on a flame front is the dissipation of energy through its melting and vaporization. It is aided by the mechanical turbulence and radiant quenching, but if the foam had a much higher melting point, 10-pore foam might not be very effective.

A theoretical understanding of foam behavior is quite important, since foam has been shown to be very effective for fuel tank applications. It does impose substantial weight penalties, and its dollar costs are rather high. Through an understanding of its behavior, it should be possible to optimize the foam installation with at least significant weight reductions. Some attempts along these lines are now underway; i.e., the testing of new 10-pore foam of lower density at Firestone and the testing of 20-pore and 40-pore foam at the U.S. Bureau of Mines.

Weight Estimates for Reticulated Foam Protection

The quantity and weight of the reticulated foam filler required in fuel cells of each aircraft fuel system are presented in Table XIII. The quantity of foam filler is considered as being equivalent to the fuel cell volume which has been calculated for each fuel cell in the table. The weight of the reticulated foam required for each tank has been calculated for each fuel cell in the table. The weight of the reticulated foam required for each tank has been calculated based on an estimated foam weight of 1.80 pounds per cubic foot and the calculated tank volume. Other types of lighter weight foams are presently under study but are not yet available for aircraft use.

The weight penalty introduced by the addition of reticulated foam to the empty fuel systems has been computed for

TABLE XIII
RETICULATED FOAM REQUIREMENTS AND WEIGHT PENALTIES FOR SPECIFIC U.S. ARMY AIRCRAFT

Aircraft Type	No. of Fuel Cells	Fuel Cell Capacity		Fuel Cell Volume (ft ³)	Empty Wt. of Fuel Cells (lb)	Foam Requirements for Fuel Cells (lb)	Percentage Increase in wt. of Fuel Cells	Net Fuel Loss (gal)
		(gal)	(lb)					
(1) UH-1B	2	242.0	1551.0	32.351	73.0	58.08	74.5	7.26
	(1) (2)	(122.0) (120.0)	(781.9) (769.1)	(16.309) (16.042)	(40.0) (33.0)	(29.28) (28.80)	(75.1) (73.8)	
Earlier models of this aircraft have 165 gal. cap. fuel system.	2	165.0	1057.0	22.057	60.0	39.60	66.0	4.95
	(1) (2)	(82.0) (83.0)	(525.0) (531.5)	(10.962) (11.095)	(30.0) (30.0)	(19.68) (19.92)	(65.6) (66.4)	
(2) UH-1D	5	220.0	1410.0	29.410	74.5	52.78	70.8	6.60
	(1) (2) (3) (4) (5)	(44.2) (44.2) (34.3) (63.0) (34.3)	(283.3) (283.3) (219.8) (403.8) (219.8)	(5.909) (5.909) (4.585) (8.422) (4.585)	(27.5) (28.0) (4.5) (9.0) (8.5)	(10.61) (10.61) (8.23) (15.02) (8.23)	(38.6) (37.9) (182.89) (166.89) (149.64)	
(3) U-1A	4	213.5	1229.5	28.541	35.0	51.24	146.40	6.41
	(1) (2) (3) (4)	(61.2) (51.0) (51.0) (50.3)	(352.4) (293.7) (293.7) (289.7)	(8.181) (6.818) (6.818) (6.724)	(9.5) (8.5) (8.5) (8.5)	(14.69) (12.24) (12.24) (12.07)	(154.63) (144.00) (144.00) (142.00)	

TABLE XIII (Continued)

Aircraft Type	No. of Fuel Cells	Fuel Cell Capacity		Fuel Cell Volume (ft ³)	Empty Wt. of Fuel Cells (lb)	Foam Requirements for Fuel Cells (lb)	Percentage Increase in wt. of Fuel Cells	Net Fuel Loss (gal)
		(gal)	(lb)					
(4) U-6A	5	139.8	855.0	18.688	61.0	33.55	55.0	4.19
	(1)	(35.7)	(208.8)	(4.772)	(14.0)	(8.57)	(61.2)	
	(2)	(35.6)	(208.8)	(4.759)	(14.0)	(8.54)	(61.0)	
	(3)	(25.5)	(186.3)	(3.409)	(11.0)	(6.12)	(55.6)	
	(4)	(21.5)	(125.8)	(2.874)	(11.0)	(5.16)	(46.9)	
	(5)	(21.5)	(125.8)	(2.874)	(11.0)	(5.16)	(46.9)	
(5) U-8D and U-8F	8	230.0	1324.0	30.746	51.80	55.20	106.15	6.90
	(1)	(44.0)	(253.0)	(5.882)	(6.1)	(10.56)	173.11	
	(2)	(44.0)	(253.0)	(5.882)	(6.1)	(10.56)	173.11	
	(3) -							
	(6)	(23.0)	(132.5)	(3.075)	{(6.2); (2)}	(5.52)	{(89.0); (2)}	
		each	each	each	{(6.0); (2)}	each	{(92.0); (2)}	
	(7)	(25.0)	(144.0)	3.342	(7.6)	(6.00)	(78.9)	
	(8)	(25.0)	(144.0)	3.342	(7.6)	(6.00)	(78.9)	
(6) OH-6	2	66.0	423.0	8.822	21.3	15.84	74.3	1.98
	(1)	(33.0)	(211.5)	(4.411)	(10.8)	(7.92)	(73.3)	
	(2)	(33.0)	(211.5)	(4.411)	(10.5)	(7.92)	(75.4)	
(7) OH-13	2	58.0	348.6	7.754	10.4	13.92	123.85	1.74
	(1)	(29.0)	(174.3)	(3.877)	5.2	(6.96)	(123.85)	
	(2)	(29.0)	(174.3)	(3.877)	5.2	(6.96)	(123.85)	

TABLE XIII (Continued)

Aircraft Type	No. of Fuel Cells	Fuel Cell Capacity		Fuel Cell Volume (ft ³)	Empty Wt. of Fuel Cells (lb)	Foam Requirements for Fuel Cells (lb)	Percentage Increase in wt. of Fuel Cells	Net Fuel Loss (gal)
		(gal)	(lb)					
(8) OI-F	2	45.0	259.0	6.016	21.9	10.80	49.3	1.35
	(1)	(22.5)	(129.5)	(3.008)	(10.95)	(5.40)	(49.3)	
	(2)	(22.5)	(129.5)	(3.008)	(10.95)	(5.40)	(49.3)	
(9) OV-1A, B, and C	1	297.0	1903.5	39.703	100.8	71.28	70.7	8.91
(10) CH-34	11 Fwd Cells	263.0	1525.4	35.158	233.6	63.12	27.0	7.89
	(1)	(15.7)	(91.1)	(2.099)	(19.1)	(3.77)	(19.7)	
	(2)	(20.0)	(160.0)	(2.673)	(23.0)	(4.80)	(20.9)	
	(3)	(15.7)	(91.1)	(2.099)	(19.1)	(3.77)	(19.7)	
	(4)	(25.8)	(149.6)	(3.449)	(29.8)	(6.19)	(20.8)	
	(5)	(25.8)	(149.6)	(3.449)	(29.8)	(6.19)	(20.8)	
	Aft Cells							
	(6)	(22.3)	(129.3)	(2.981)	(15.8)	(5.35)	(33.9)	
	(7)	(28.9)	(167.6)	(3.863)	(17.7)	(6.94)	(39.2)	
	(8)	(22.3)	(129.3)	(2.981)	(15.8)	(5.35)	(33.9)	
	(9)	(28.7)	(166.5)	(3.837)	(19.9)	(6.89)	(34.6)	
	(10)	(29.1)	(168.5)	(3.890)	(23.7)	(6.89)	(29.5)	
	(11)	(28.7)	(166.5)	(3.837)	(19.9)	(6.89)	(34.6)	

TABLE XIII (Continued)

Aircraft Type	No. of Fuel Cells	Fuel Cell Capacity		Fuel Cell Volume (ft ³)	Empty Wt. of Fuel Cells (lb)	Foam Requirements for Fuel Cells (lb)	Percentage Increase in wt. of Fuel Cells	Net Fuel Loss (gal)
		(gal)	(lb)					
(11) CH-37	4	398.0	2308.0	53.204	218.0	95.52	43.8	11.94
	(1)	(100.0)	(580.0)	(13.368)	(66.0)	(24.00)	(36.4)	
	(2)	(99.0)	(574.0)	(13.234)	(43.0)	(23.76)	(55.3)	
	(3)	(99.0)	(574.0)	(13.234)	(43.0)	(23.76)	(55.3)	
(12) CH-47	(4)	(100.0)	(580.0)	(13.368)	(66.0)	(24.00)	(36.4)	
	2	630.0	4038.0	84.218	110.0	151.20	137.45	18.90
	(1)	(315.0)	(2019.0)	(42.109)	(55.0)	(75.60)	(137.45)	
(13) CH-54	(2)	(315.0)	(2019.0)	(42.109)	(55.0)	(75.60)	(137.45)	
	5	1357.0	8832.0	181.403	344.1	325.68	94.6	40.17
	(1)	(226.0)	(1472.0)	(30.211)	(71.4)	(54.24)	(96.5)	
	(2)	(226.0)	(1472.0)	(30.211)	(73.5)	(54.24)	(89.6)	
	(3)	(226.0)	(1472.0)	(30.211)	(73.5)	(54.24)	(89.6)	
	(4)	(226.0)	(1472.0)	(30.211)	(71.4)	(54.24)	(95.2)	
	(5)	(453.0)	(2944.0)	(60.559)	(113.3)	(108.72)	(98.9)	

each individual cell in the form of an absolute weight increase (pound) and as a percentage increase in the weight of the empty cell. As seen in Table XIII, the weight of the quantity of foam required to fill certain types of tanks is greater than the empty cell weight. For instance, the empty weight of each OH-13 fuel cell is 5.2 pounds, yet 6.96 pounds of reticulated foam are required to fill each 29-gallon tank. The situation just illustrated is rather typical of all light-weight non-self-sealing fuel tanks. However, the weight penalties attributable to the introduction of foam filler are insignificant when compared to the overall cargo weight of each aircraft.

Some fuel loss due to reduction in tank fuel capacities may be introduced by use of foam filler. Estimates of the actual fuel loss are considerably varied, as previously discussed. These estimates of fuel losses are based on 3% of the total tank capacity, and they appear in Table XIII.

Cost Estimates of Reticulated Foam Protection (U)

The cost of 10-pore reticulated foam presently quoted for purchases in large quantities is \$6.72 per cubic foot⁶. The costs of foam sufficient to fill the internal volume of each fuel cell of the aircraft considered are presented in Table XIV. The space within each fuel cell occupied by fuel pumping equipment has been disregarded in these calculations.

Next to fuel additives, reticulated foam is the most easily implemented explosion suppression system of those considered. Discussions with personnel of the Sargent-Fletcher Company⁷, who have had considerable experience in installing foam in Air Force aircraft fuel tanks, have indicated that a significant amount of labor is involved in cutting and fitting the foam to each fuel cell. Estimate of the man-hour requirements for foam installation in a typical 200-gallon Air Force combat aircraft drop tank is approximately 16 man-hours.

⁶Based on a \$0.56-per-board-foot price estimate from the Firestone Corporation, Akron, Ohio, January 1967.

⁷A division of A. J. Industries, El Monte, California.

TABLE XIV
COST ESTIMATES FOR RETICULATED FOAM SYSTEMS IN ARMY AIRCRAFT

Aircraft	Number of Fuel Cells	Fuel Cell Capacity (gal)	Foam Requirements (ft ³)	Cost of Foam (\$)	Implementation Costs (\$)	Total Costs (\$)
(1) UH-1B	2	242.0				333.55
	(1)	122.0	16.31	109.60	58.56	168.16
	(2)	120.0	16.04	107.79	57.60	165.39
Earlier Models of UH-1B	2	165.0				227.44
	(1)	82.0	10.96	73.65	39.36	113.01
	(2)	83.0	11.10	74.59	39.84	114.43
(2) UH-1D	5	220.0				303.32
	(1)	44.2	5.91	39.72	21.22	60.94
	(2)	44.2	5.91	39.72	21.22	60.94
	(3)	34.3	4.59	30.85	16.46	47.31
	(4)	63.0	8.42	56.58	30.24	86.82
	(5)	34.3	4.59	30.85	16.46	47.31
(3) U-1A	4	213.5				294.27
	(1)	61.2	8.18	54.97	29.38	84.35
	(2)	51.0	6.82	45.83	24.48	70.31
	(3)	51.0	6.82	45.83	24.48	70.31

TABLE XIV (Continued)

Aircraft	Number of Fuel Cells	Fuel Cell Capacity (gal)	Foam Requirements (ft ³)	Cost of Foam (\$)	Implementation Costs (\$)	Total Costs (\$)
(3) Cont.	(4)	50.3	6.72	45.16	24.14	69.30
(4) U-6A	5	139.8				192.64
	(1)	35.7	4.77	32.05	17.14	49.19
	(2)	35.6	4.76	31.98	17.09	49.07
	(3)	25.5	3.41	22.92	12.24	35.16
	(4)	21.5	2.87	19.29	10.32	29.61
	(5)	21.5	2.87	19.29	10.32	29.61
(5) U-8D and U-8F	8	230.0				317.10
	(1)	44.0	5.88	39.51	21.12	60.63
	(2)	44.0	5.88	39.51	21.12	60.63
	(3) - (6)	23.0 each	3.08 each	20.70 each	11.04 each	31.74 each
	(7)	25.0	3.34	22.44	12.00	34.44
	(8)	25.0	3.34	22.44	12.00	34.44
(6) OH-6	2	66.0				90.96
	(1)	33.0	4.41	29.64	15.84	45.48
	(2)	33.0	4.41	29.64	15.84	45.48

TABLE XIV (Continued)

Aircraft	Number of Fuel Cells	Fuel Cell Capacity (gal)	Foam Requirements (ft ³)	Cost of Foam (\$)	Implementation Costs (\$)	Total Costs (\$)
(7) OH-13	2	58.0				79.98
	(1)	29.0	3.88	26.07	13.92	39.99
	(2)	29.0	3.88	26.07	13.92	39.99
(8) O1-F	2	45.0				62.06
	(1)	22.5	3.01	20.23	10.80	31.03
	(2)	22.5	3.01	20.23	10.80	31.03
(9) OV-1A,B,C	1	297.0	39.70	266.78	142.56	409.34
(10) CH-34	11	263.0				362.50
	(1)	15.7	2.10	14.11	7.54	21.65
	(2)	20.0	2.67	17.94	9.60	27.54
	(3)	15.7	2.10	14.11	7.54	21.65
	(4)	25.8	3.45	23.18	12.38	35.56
	(5)	25.8	3.45	23.18	12.38	35.56
	(6)	22.3	2.98	20.03	10.70	30.73
	(7)	28.9	3.86	25.94	13.87	39.81
	(8)	22.3	2.98	20.03	10.70	30.73
	(9)	28.7	3.84	25.80	13.78	39.58

TABLE XIV (Continued)

Aircraft	Number of Fuel Cells	Fuel Cell Capacity (gal)	Foam Requirements (ft ³)	Cost of Foam (\$)	Implementation Costs (\$)	Total Costs (\$)
(10) Cont.	(10)	29.1	3.89	26.14	13.97	40.11
	(11)	28.7	3.84	25.80	13.78	39.58
(11) CH-37	4	398.0				555.28
	(1)	100.0	13.87	93.21	48.00	141.21
	(2)	99.0	13.23	88.91	47.52	136.43
	(3)	99.0	13.23	88.91	47.52	136.43
	(4)	100.0	13.87	93.21	48.00	141.21
(12) CH-47	2	630.0				868.36
	(1)	315.0	42.11	282.98	151.20	434.18
	(2)	315.0	42.11	282.98	151.20	434.18
(13) CH-54	5	1357.0				1870.36
	(1)	226.0	30.21	203.01	108.48	311.49
	(2)	226.0	30.21	203.01	108.48	311.49
	(3)	226.0	30.21	203.01	108.48	311.49
	(4)	226.0	30.21	203.01	108.48	311.49
	(5)	453.0	60.56	406.96	217.44	624.40

In the present procedure for foam installation, the foam is first cut into several sections, each section fitted to fuel cell contours; these sections then are hand-fitted to their respective portion of the fuel cell. Sargent-Fletcher's experience in foam installation has shown that a considerable amount of handling is required in the fitting process. Two adjacent pieces of reticulated foam demonstrate a "clinging" effect which definitely hinders the manipulation of adjacent sections of foam.

The labor and overhead costs involved in the foam implementation process are estimated at \$6.00 per man-hour. On the basis of Sargent-Fletcher's man-hour estimate, implementation costs on a per-gallon-of-fuel basis may be approximated at \$0.48 per gallon. This figure has been used to calculate foam installation costs for each aircraft in Table XIV.

IV. TARGET DESCRIPTION AND ANALYSIS

A. AIRCRAFT CHARACTERISTICS

In this study, the fuel systems of the 16 models of U.S. Army aircraft listed in the Introduction are considered as potential targets for incendiary ammunition in the caliber .30 to 20 mm size range. The gross takeoff weights of the different aircraft vary from 2400 pounds for the O-1F to approximately 38,000 pounds for the CH-47 and CH-54. Three types of listed aircraft, the OH-6, OH-13, and Ol-F, have a total fuel capacity of less than 100 gallons. Nine other models have total fuel system capacities of between 100 and 300 gallons. These are the UH-1B, UH-1D, U-1A, U-6A, U-8D, U-8F, OV-1A, OV-1B, and OV-1C. The number of fuel cells in the aircraft varies from the single cell in the OV-1 series to 11 separate tanks in the CH-34.

Descriptive data pertaining to the U.S. Army aircraft fuel systems are presented in Figures 29 through 42 and are summarized in Table XV. These data have been developed from investigation of the respective fuel system drawing and organizational maintenance manuals and/or the information obtained from personal interviews. The tabular data thus represent the "best estimates" of the pertinent characteristics of aircraft fuel systems available to this project.

The weight characteristics of each aircraft are presented in Table XV along with the following fuel system characteristics: the number of fuel cells in the system, the type of fuel used, the fuel capacities of the total system and each respective cell, and the respective surface areas (square feet) and empty cell weight of each cell in the fuel system. A description of the material used to construct the fuel cells, the protection level of the self-sealing cells, and the military standard to which they are tested are also presented.

Two qualitative indices, relating indirectly to the geometric shape of each fuel tank, have been developed for comparative analyses in Table XV. A fuel cell "shape index", S. I., defined as the number of gallons of fuel per square foot of surface area, has been computed for each fuel cell. Calculated values of a "weight index", W. I., analogously defined

as the number of gallons of fuel per pound of empty cell weight, are also presented. Numerical values of the S. I. vary in an approximate range of 1.00 to 4.00 gallons per square foot for these fuel cells. The relative magnitude of the numeric S. I. values serves as an indicator of the degree of irregularity in the geometric shape of a fuel cell. Compared with fuel cells of an equal fuel capacity, those cells of relatively small variations in their height, width, and length dimensions are characterized by higher S. I. values. The shape index decreases as the variation between one physical dimension and the other two or among all three dimensions increases, since such patterns of variation generally increase the total fuel cell surface area. Thus, a direct comparison of S. I. values between tanks of relatively equal fuel capacities will, in general, indicate the more symmetric or cubic tank. The lower S. I. values characterize fuel tanks with considerable variations in their physical dimensions. The long, shallow wing tanks of the U-8D aircraft (S. I. = 1.39) are typical examples of such cells.

As seen from a review of Figures 29 through 42, those fuel cells with higher S. I. values are those possessing two nearly equal dimensions with only a slight variation in the third dimension. Examples of such cells are the fuel tanks of the UH-1B helicopter (S. I. = 3.0), the single cell of the OV-1 series of aircraft (S. I. = 3.54), and the large rectangular tanks of the CH-54 (S. I. = 3.0).

Twenty-one of the 43 different types of fuel cells within the various models of aircraft have a fuel capacity in the range of 20.0 to 35.0 gallons. By considering these as one class and ranking their respective S. I. values, it is seen that the most irregularly shaped fuel cells, i.e., the wing tanks of the O-1F, the wing tanks Nos. 3, 5, 7, and 8 of the U-8D, and the shallow floor tanks of the CH-34, all have S. I. values of approximately 1.0. These tanks, having a larger tank surface area than other tanks in this class, offer a greater "presented area" to ground-fired incendiary ammunition. The tanks of higher S. I. values, such as the elliptical exterior tanks of the OH-13 helicopter, present smaller "presented areas" and thus are smaller targets to ground fire. With all other factors equal, the lower S. I. valued cells of any fuel capacity then represent the largest targets.

Fuel capacity (gallons) of each cell
given in parentheses.

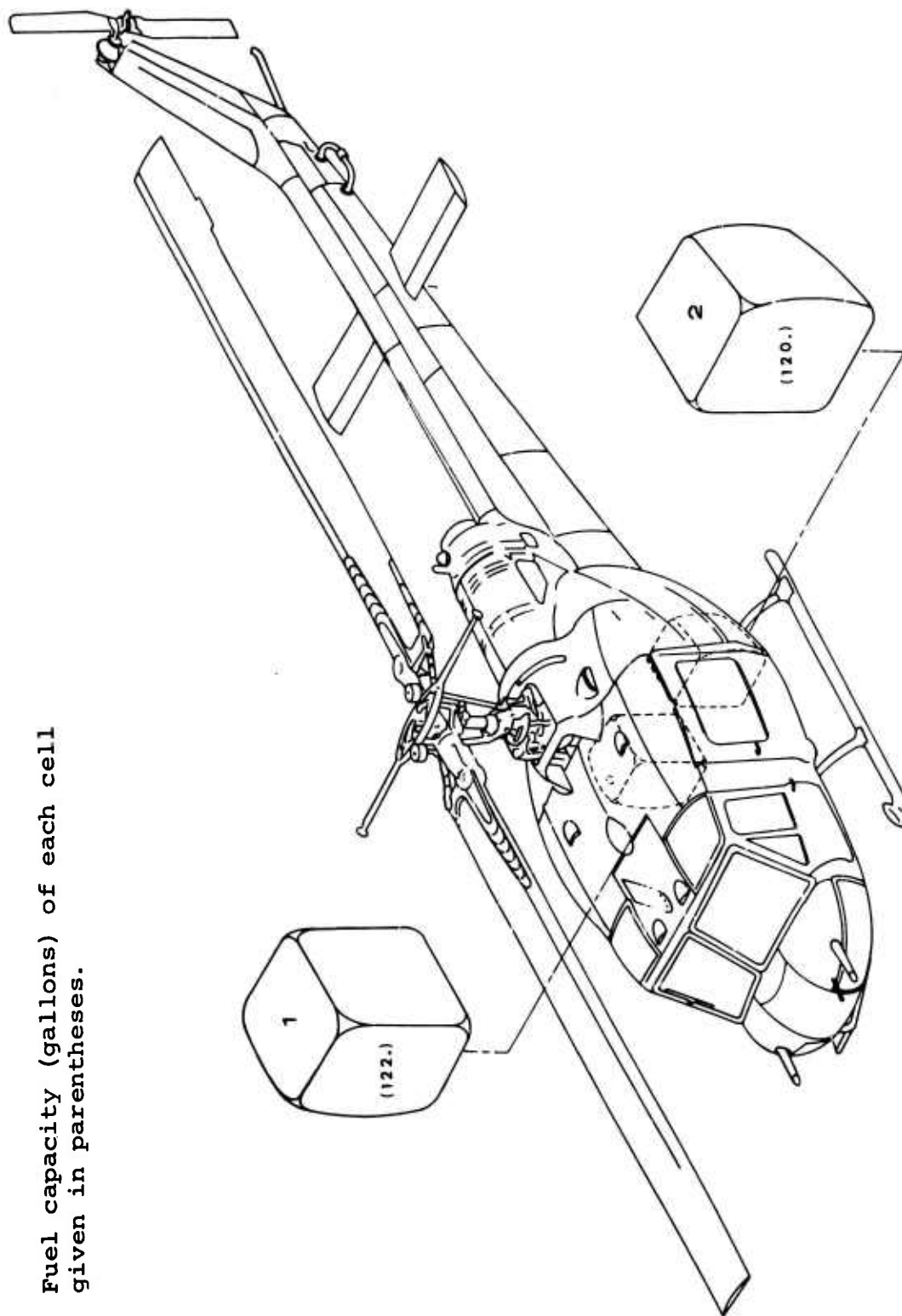


Figure 29. Fuel Tank Configuration and Location for the UH-1B Aircraft.

Fuel capacity (gallons) of each cell
given in parentheses.

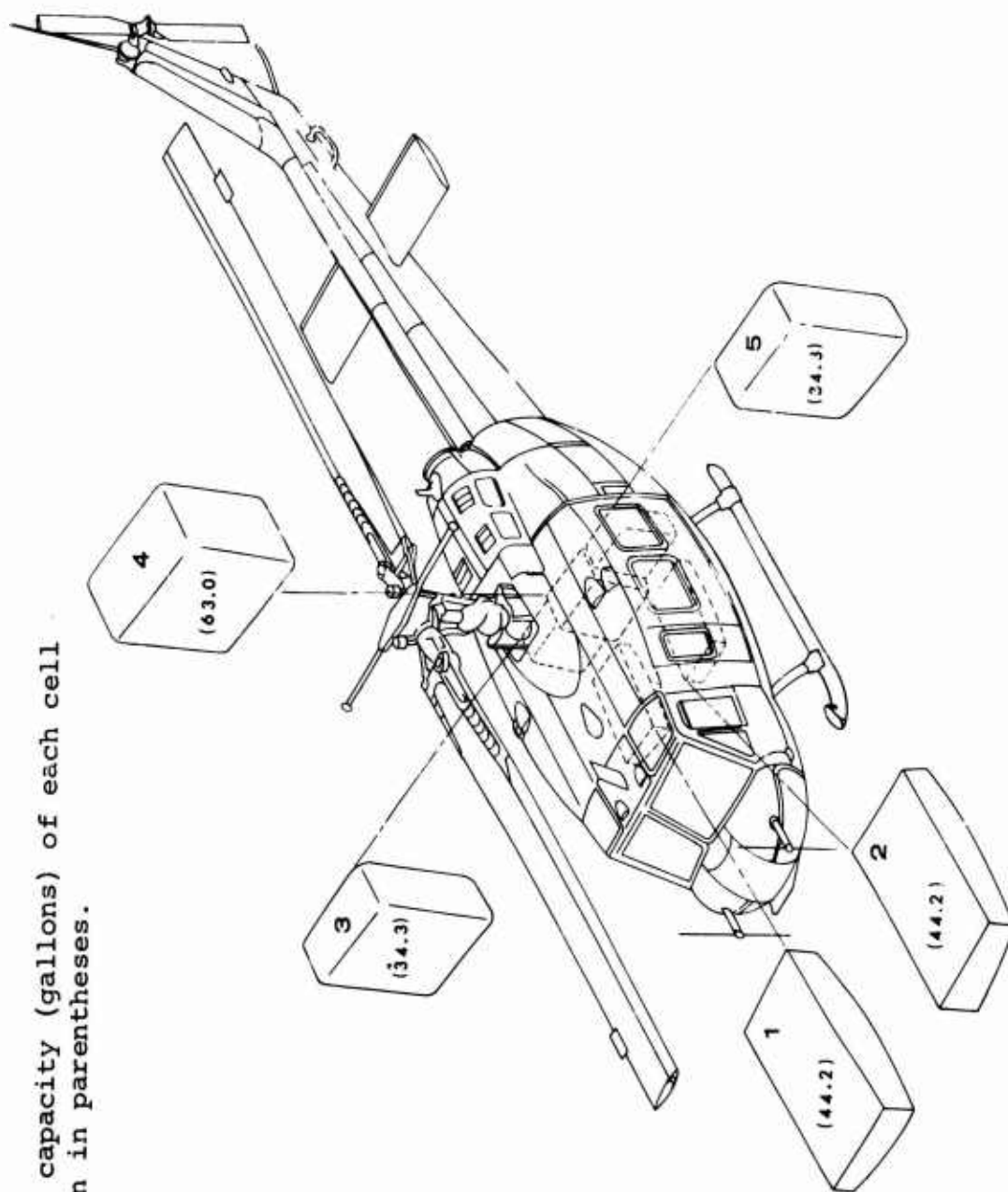


Figure 30. Fuel Tank Configuration and Location for the UH-1D Aircraft.

Fuel capacity (gallons)
of each cell given in
parentheses.

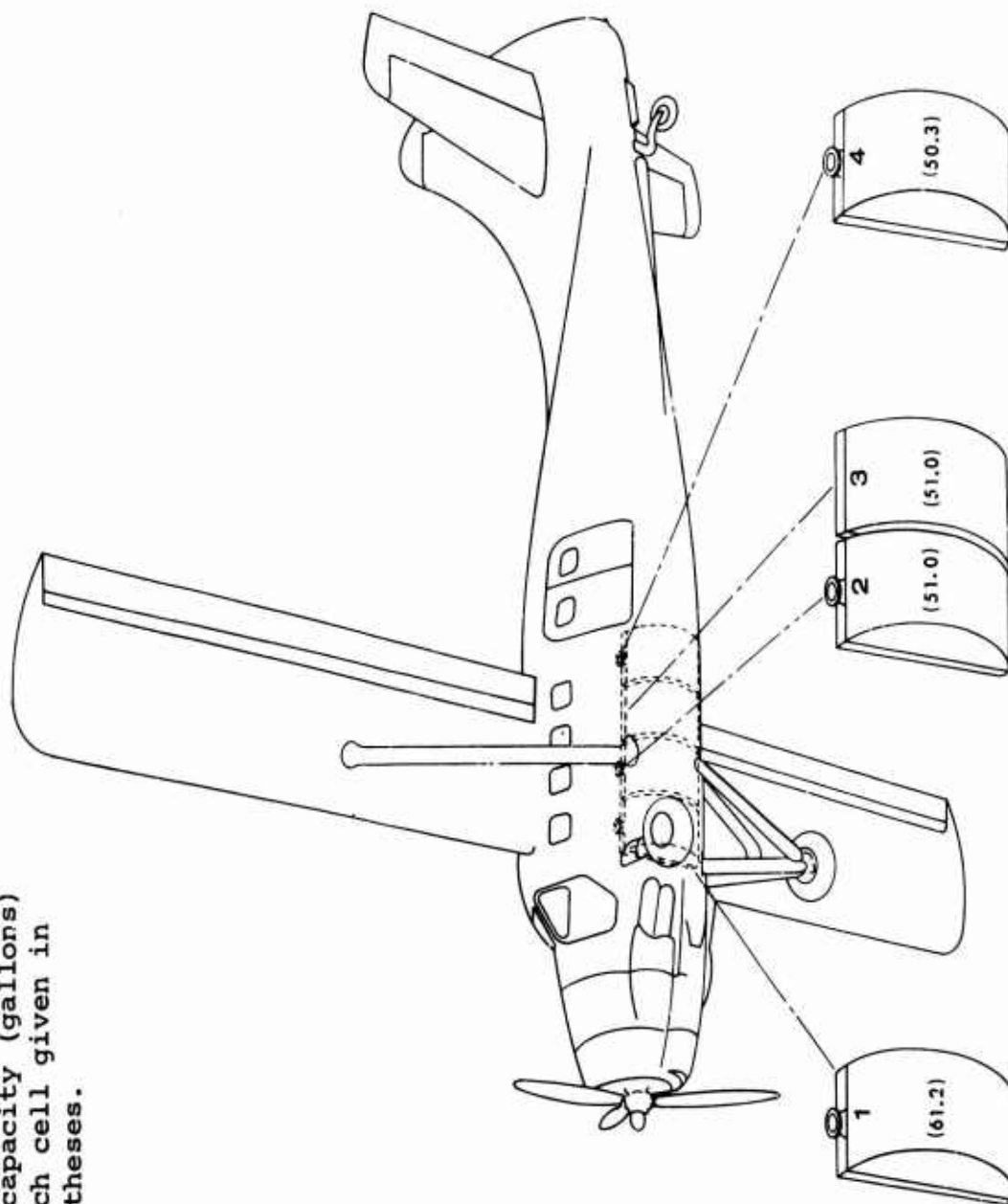


Figure 31. Fuel Tank Configuration and Location for the ULA Aircraft.

Fuel capacity (gallons)
of each cell given in
parentheses.

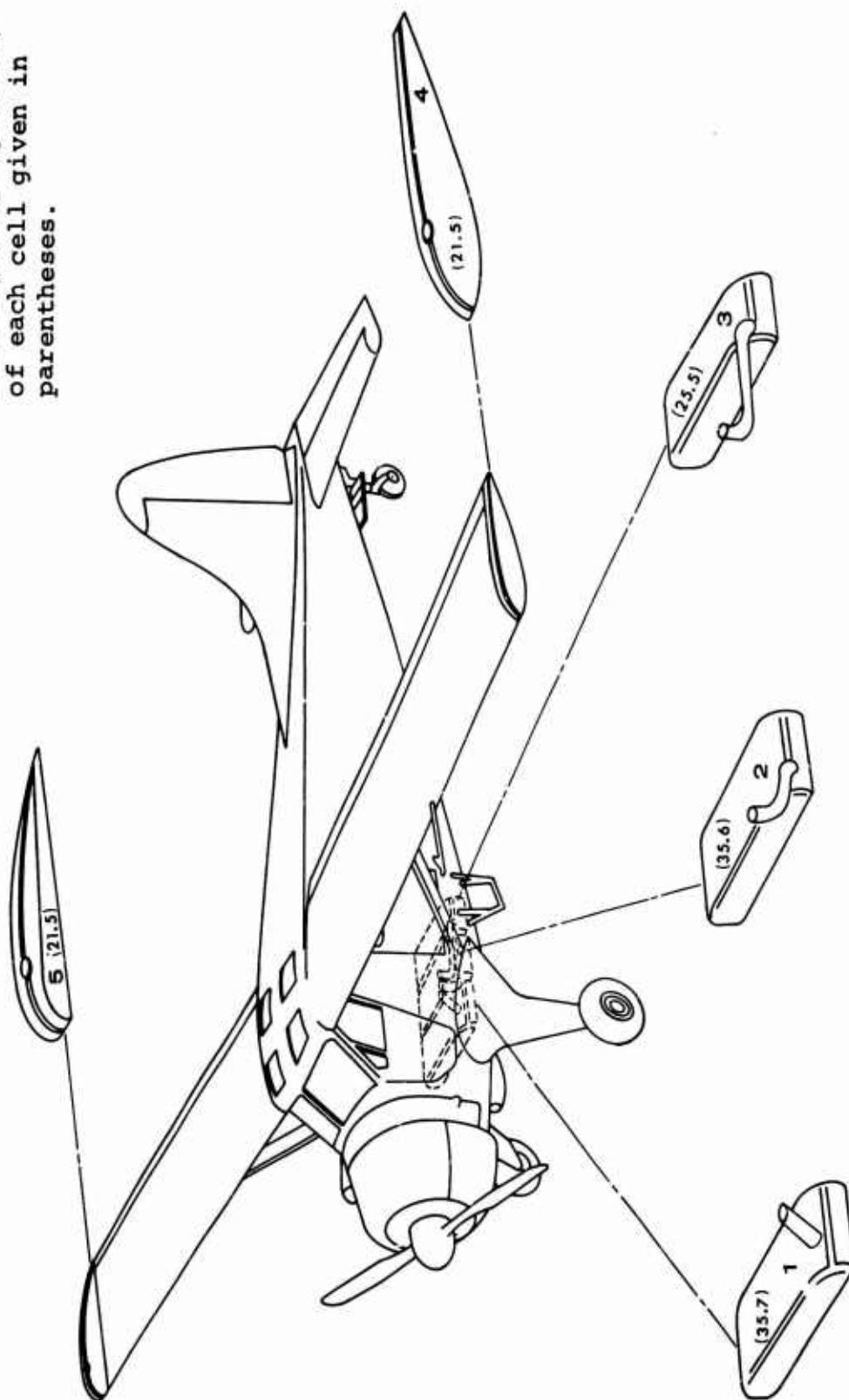


Figure 32. Fuel Tank Configuration and Location for the U-6A Aircraft.

Fuel capacity (gallons)
of each cell given in
parentheses.

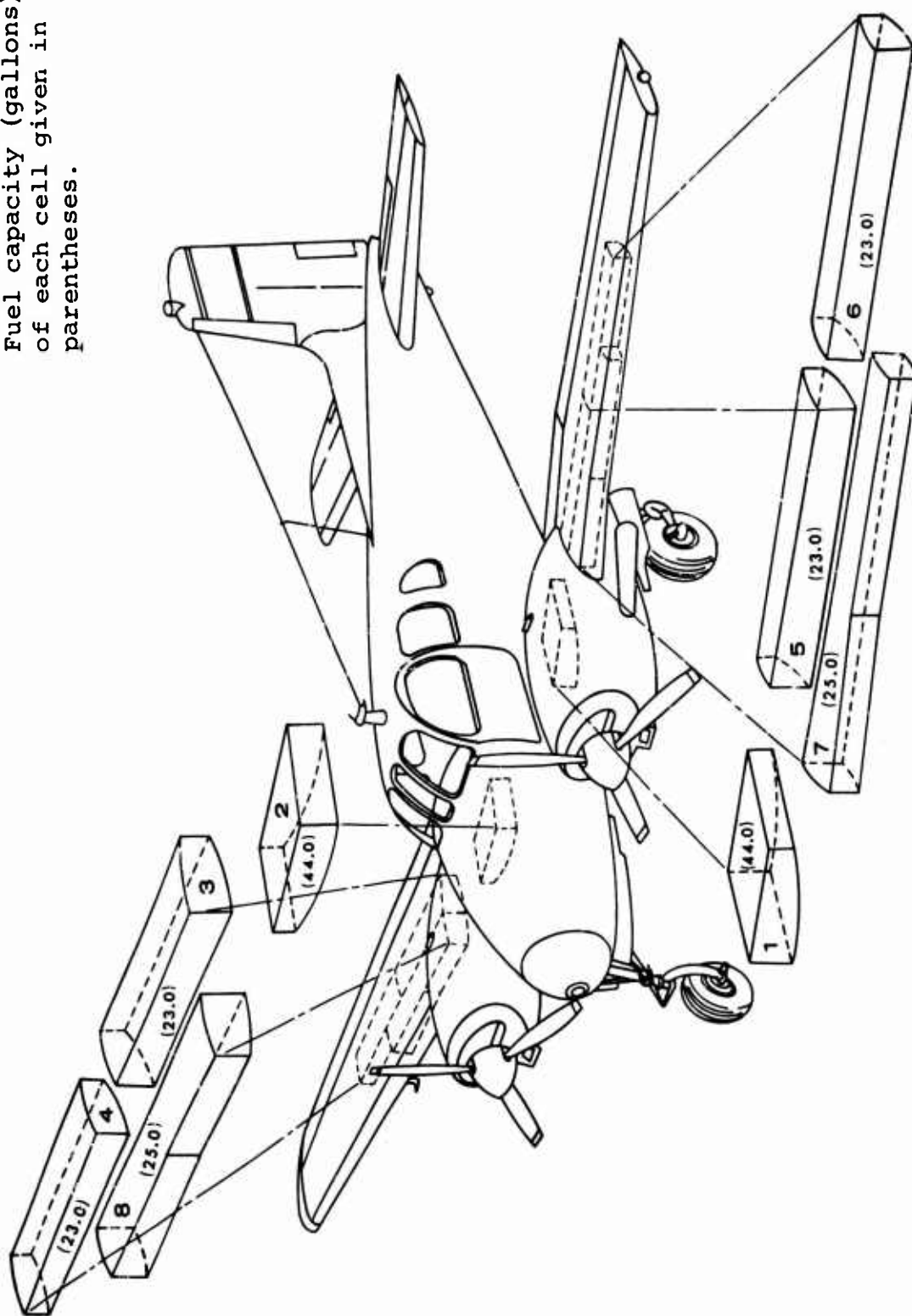


Figure 33. Fuel Tank Configuration and Location for the U-8D Aircraft.

Fuel capacity (gallons)
of each cell given in
parentheses.

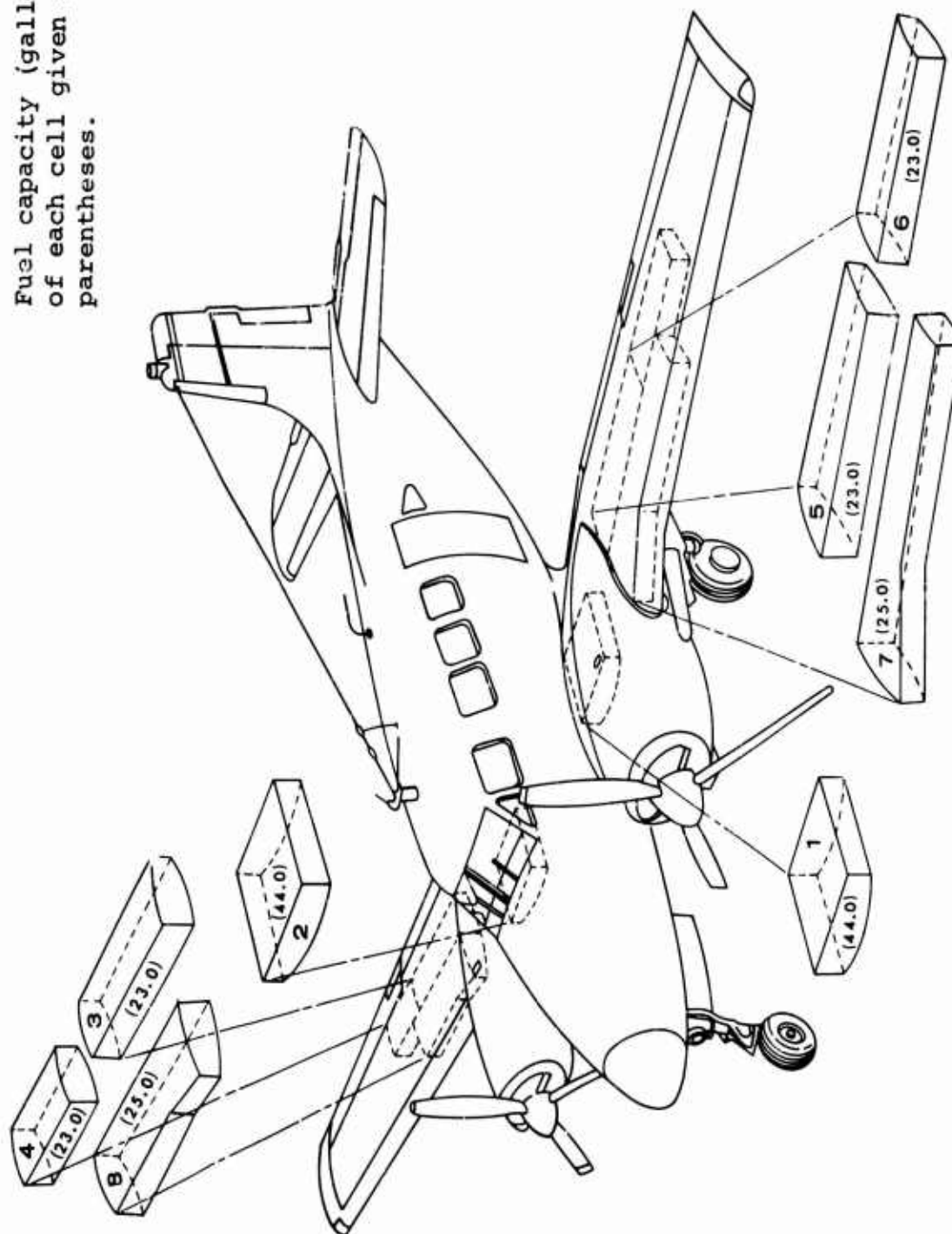


Figure 34. Fuel Tank Configuration and Location for the U-8F Aircraft.

Fuel capacity (gallons) of each cell given in parentheses.

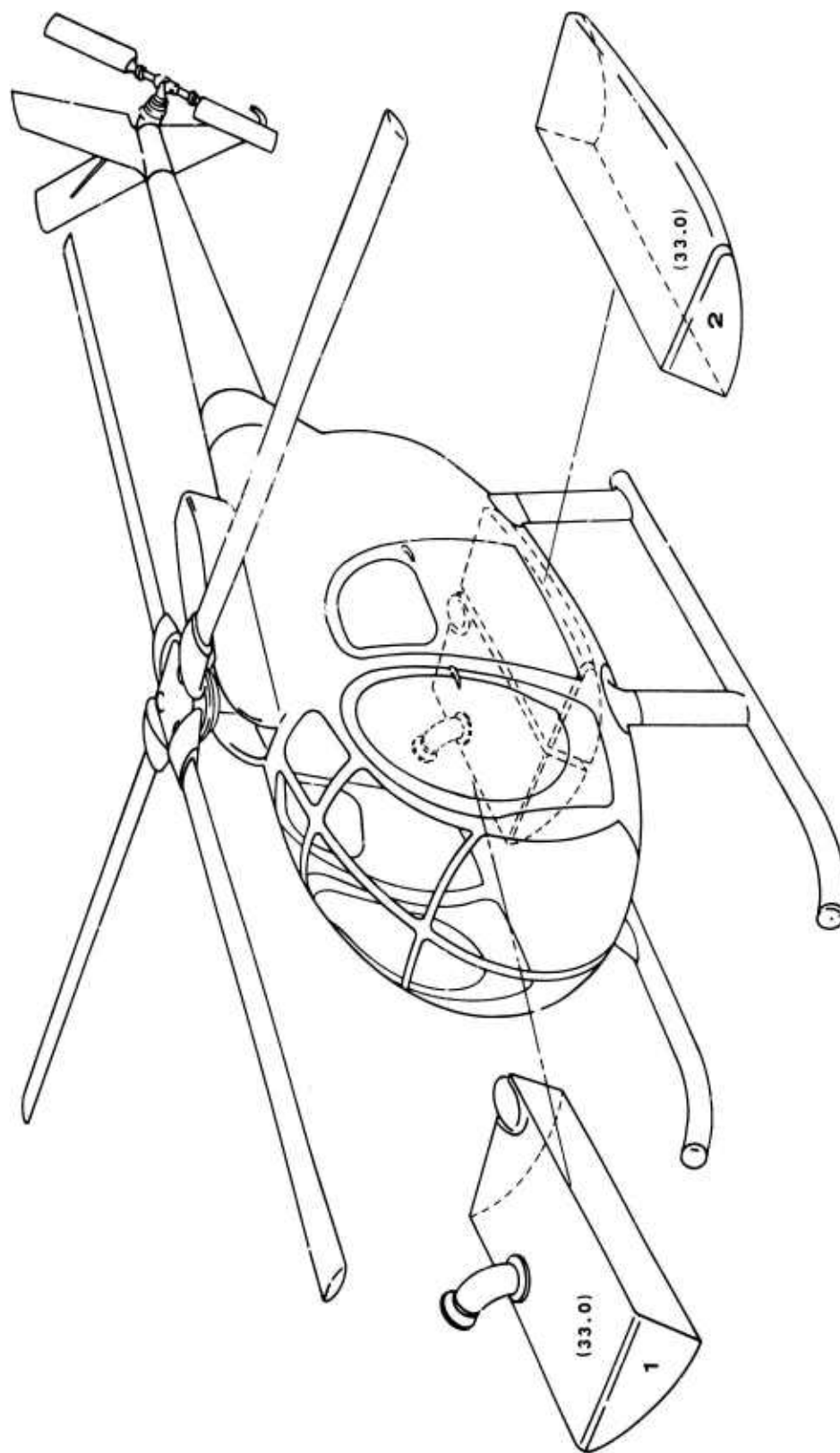


Figure 35. Fuel Tank Configuration and Location for the OH-6 Aircraft.

Fuel capacity (gallons) of each cell given in parentheses.

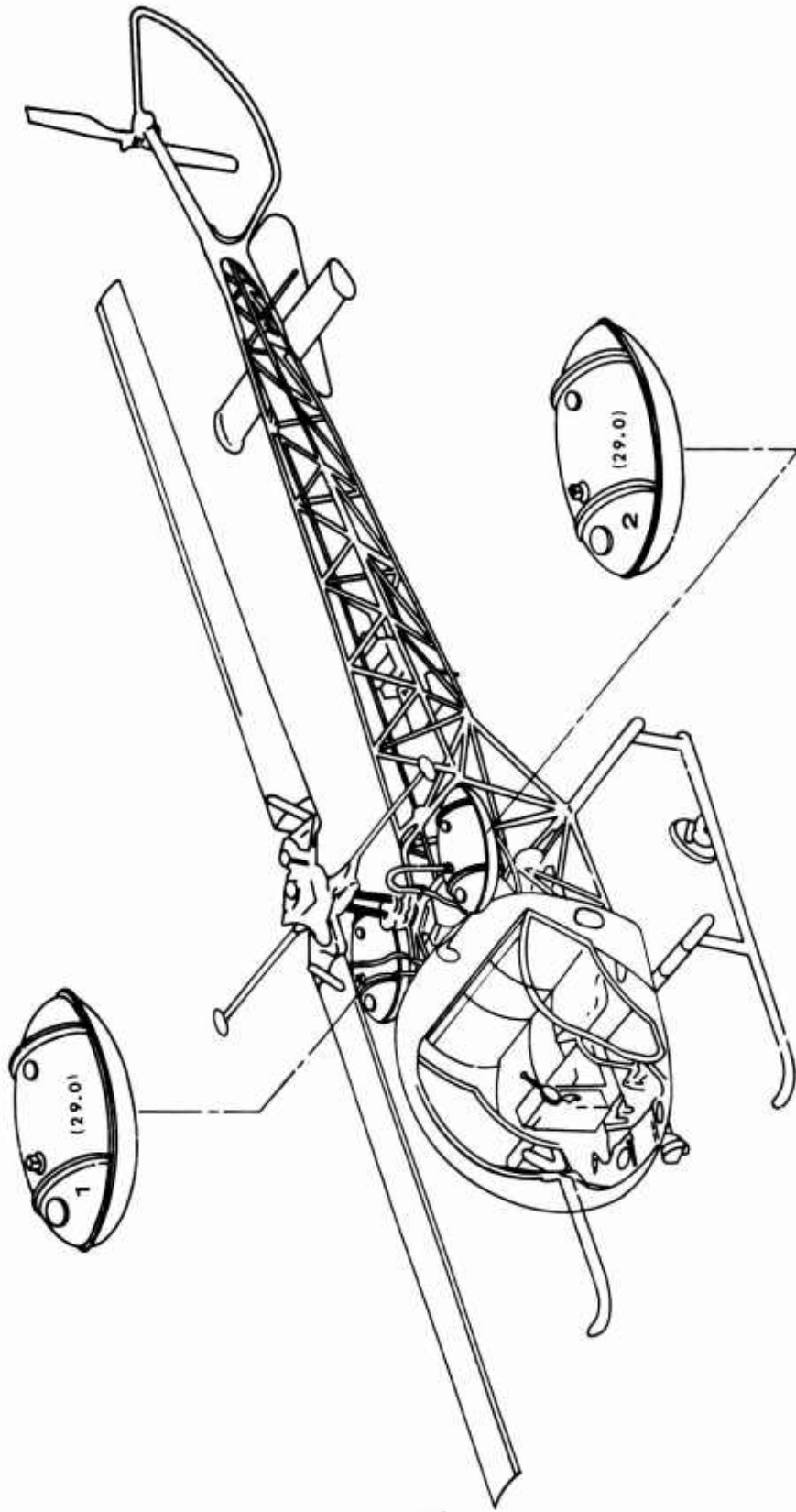


Figure 36. Fuel Tank Configuration and Location for the OH-13 Aircraft.

Fuel capacity (gallons)
of each cell given in
parentheses.

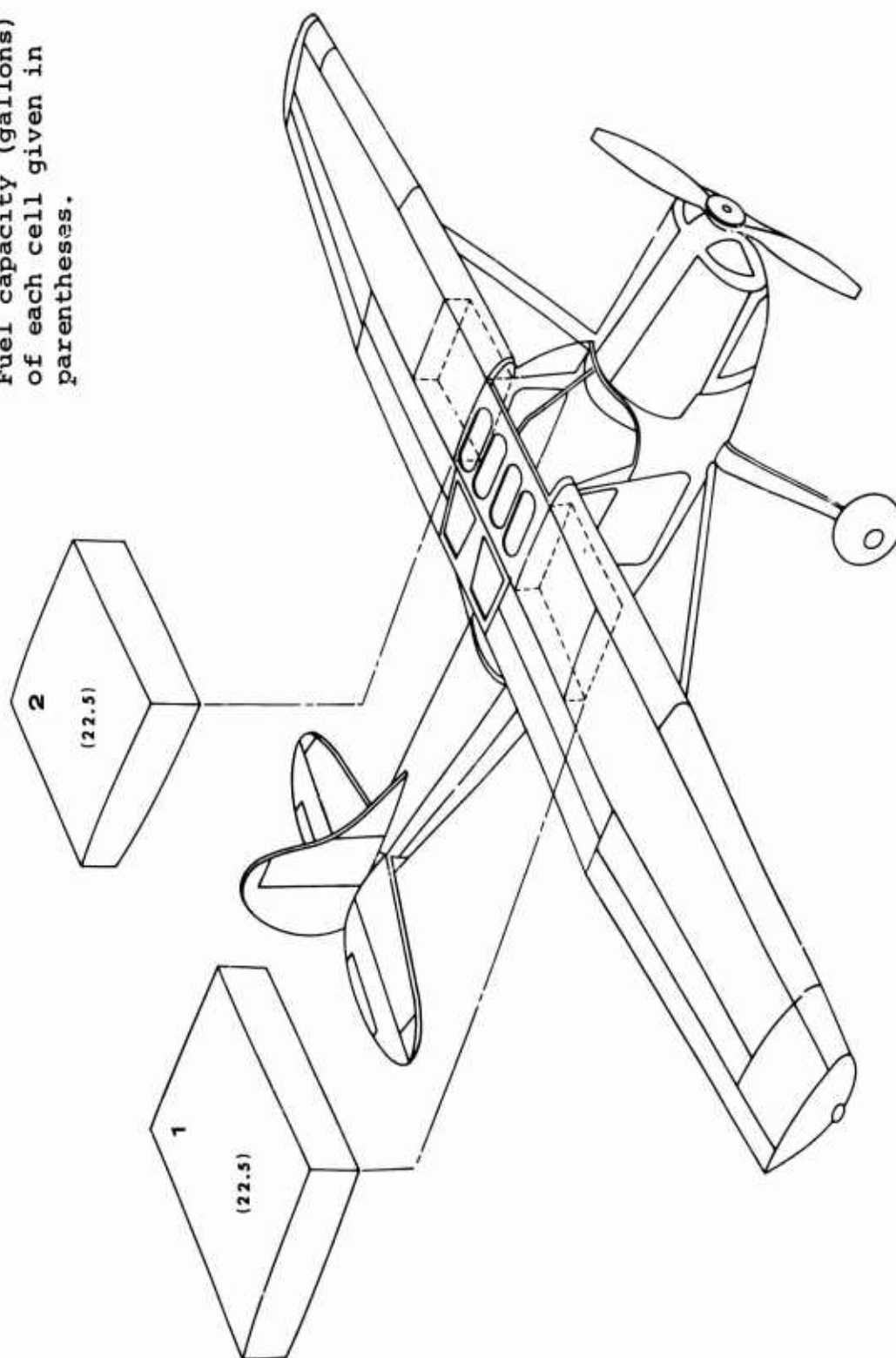


Figure 37. Fuel Tank Configuration and Location for the O-1F Aircraft.

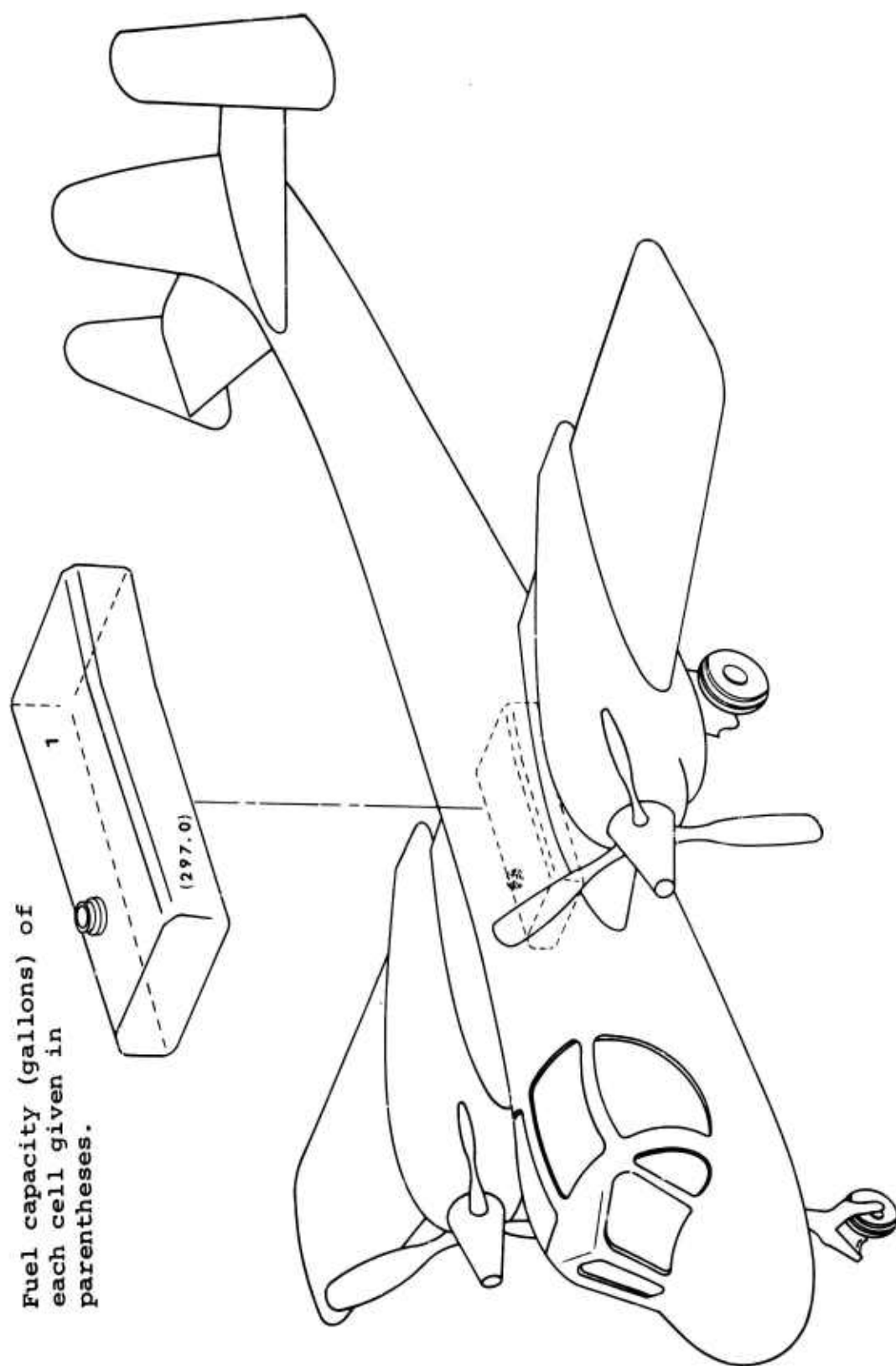


Figure 38. Fuel Tank Configuration and Location for the OV-1A, B, and C Aircraft.

Fuel capacity (gallons) of each cell given in parentheses.

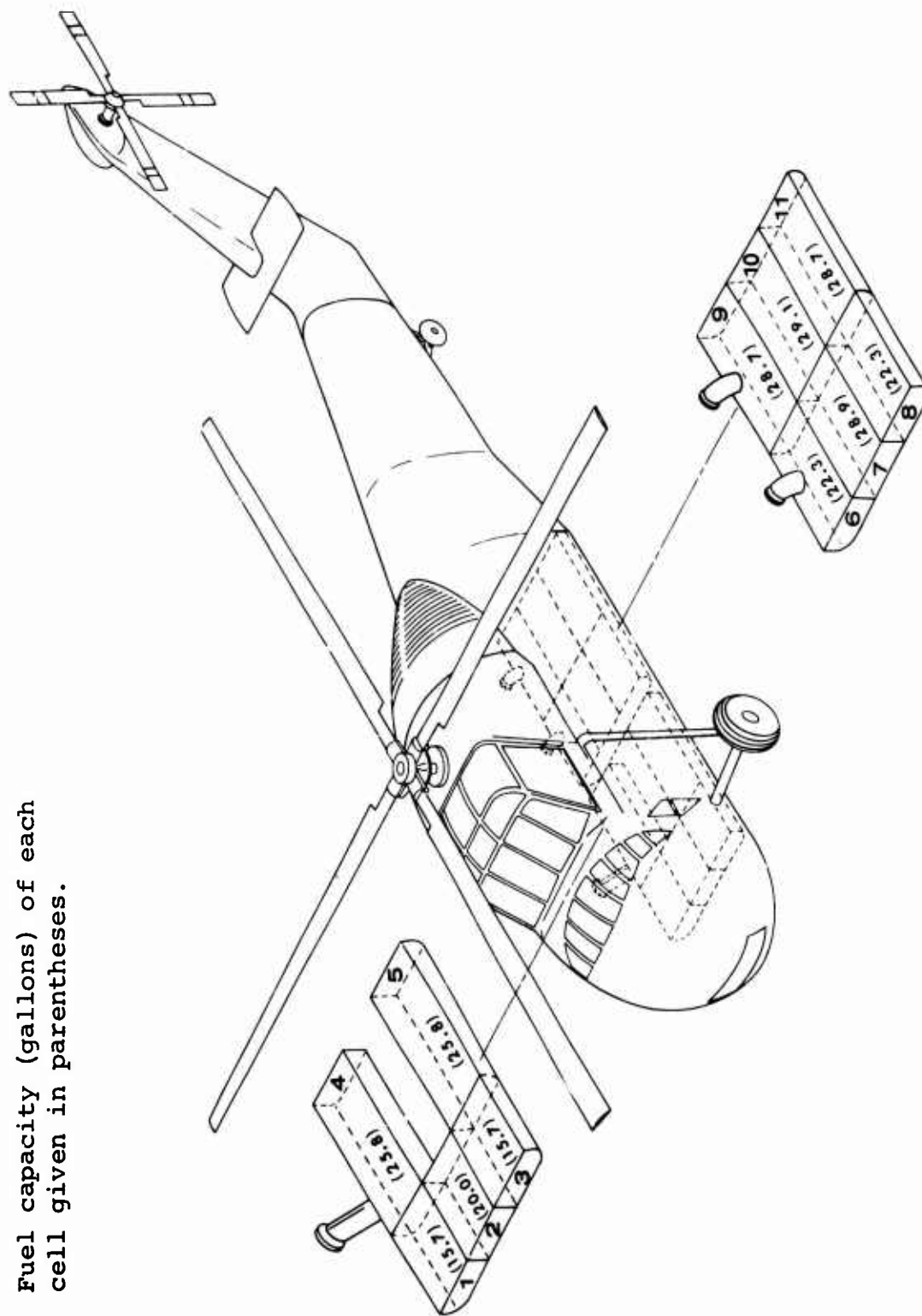
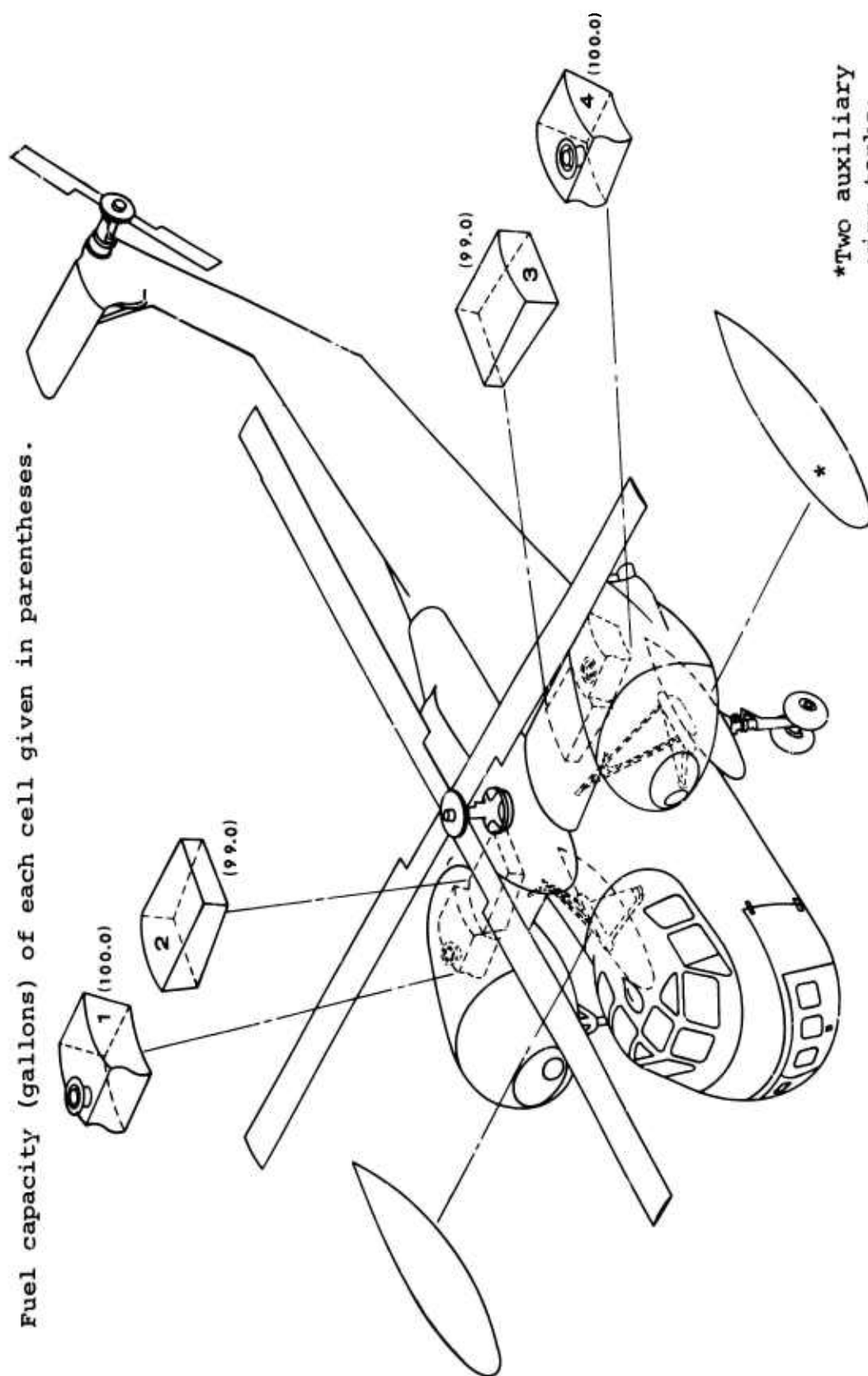


Figure 39. Fuel Tank Configuration and Location for the CH-34 Aircraft.

Fuel capacity (gallons) of each cell given in parentheses.



*Two auxiliary wing tanks; 150 gal. ea.

Figure 40. Fuel Tank Configuration and Location for the CH-37 Aircraft.

Fuel capacity (gallons) of each cell given in parentheses.

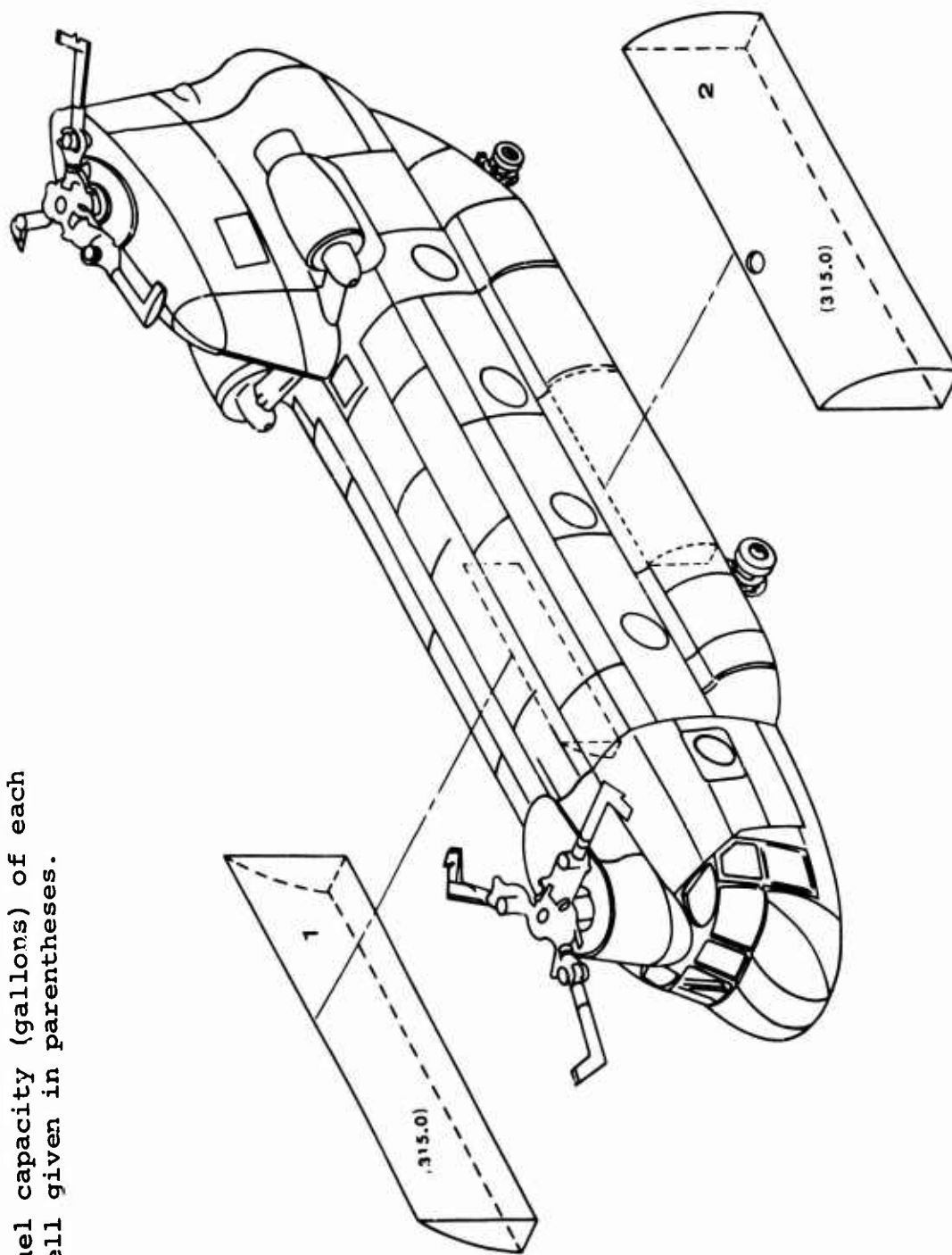
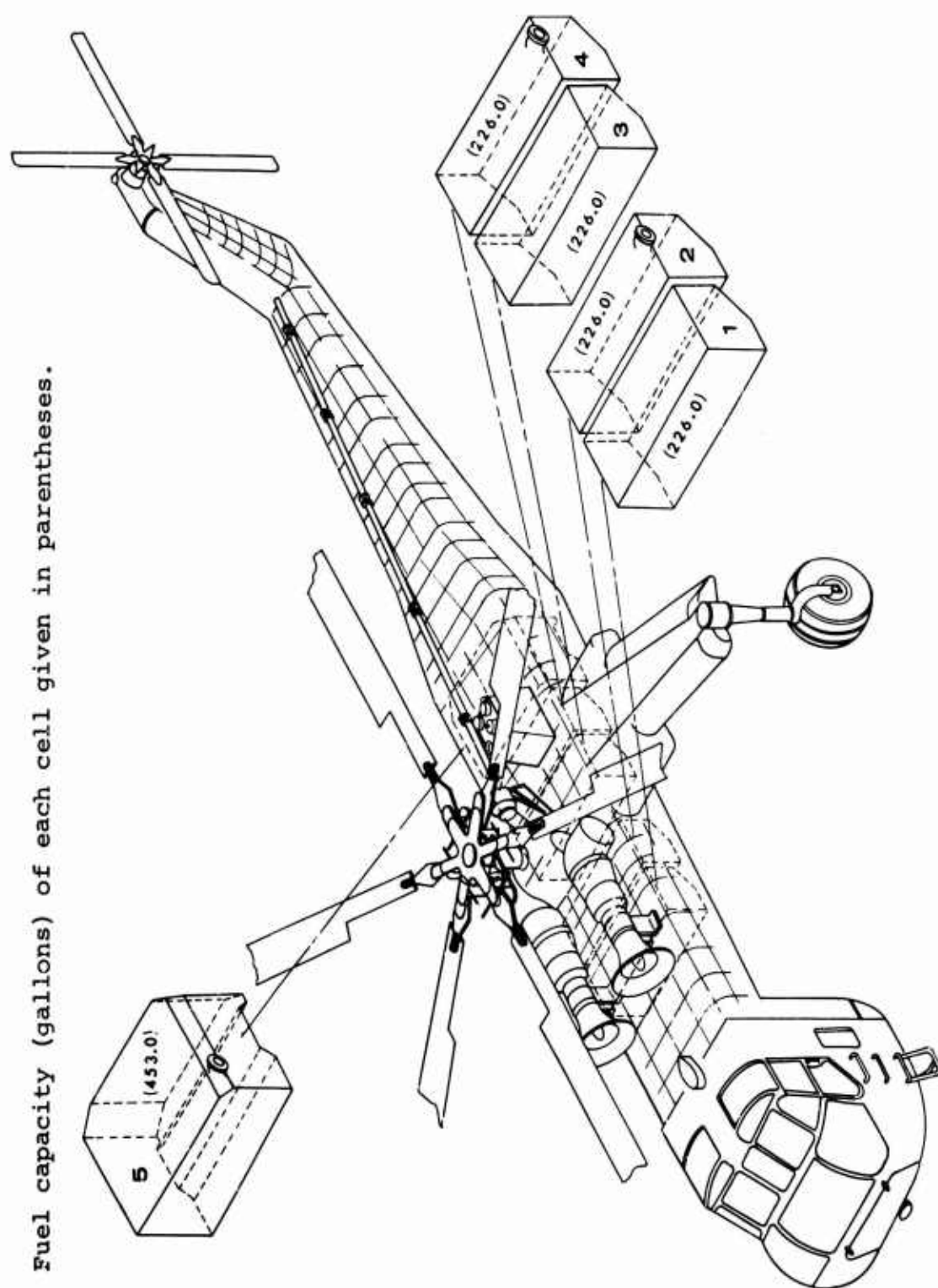


Figure 41. Fuel Tank Configuration and Location for the CH-47 Aircraft.



Fuel capacity (gallons) of each cell given in parentheses.

Figure 42. Fuel Tank Configuration and Location for the CH-54 Aircraft.

Comparisons of S. I. values for fuel tanks of considerably different fuel capacities are rather subjective. In most cases, however, a valid conclusion will be reached by such comparisons. For example, the fuel cells Nos. 1 and 2 of the U-8D (Figure 33) have a fuel capacity of 44.0 gallons and an S. I. of 2.20. These tanks are shallow tanks of roughly equal width and length. Fuel cells Nos. 2 and 3 of the CH-37 (Figure 40) also have a nearly equal S. I. of 2.50, but they have a fuel capacity of 99.0 gallons. On the basis of nearly equal S. I. values, it is concluded that these cells are of the same general configuration. A review of Figures 33 and 40 demonstrates the validity of this conclusion.

The S. I. may also be used in analyses of fuel cell surface-area-related measure of explosion suppression systems. The quantity of materials, such as foam liners and tank bladders, required to fit against the interior tank surface is determined, of course, by the total surface area of the cell. Those types of fuel cells, within a given fuel capacity class, which are characterized by lower S. I. values represent those cells requiring the largest amounts of protective materials. In terms of materials costs, they then represent the "more expensive" cells for protection by surface-area-related suppression systems. Lower S. I. valued fuel cells also represent the more expensive fuel cells to protect by visual detection measures, since in many cases additional viewing devices would be required to survey the volume of the more irregularly shaped fuel cells.

The W. I. values of the aircraft fuel cells in Table XV range from 0.82 to 7.62 gallons per pound. The smaller W. I. values generally indicate heavier, self-sealing types of fuel cells. The single cell of the OV-1 series of aircraft (W. I. = 2.95) and the forward cells of the CH-34 (W. I. = 0.82) are examples of 100-percent self-sealing fuel tanks. Several other types of fuel cells are only partially self-sealing, with the upper portions of the cells being constructed of some type of lighter material. These types include the cells of the CH-47 (W. I. = 5.7) and the CH-54 (W. I. = 4.0). The W. I. values of the types of partially self-sealing cells are, in general, somewhat higher than those of 100-percent self-sealing cells. The W. I. values of lightweight non-self-sealing fuel cells observed in Table XV are at the higher end of the W. I. scale and generally range from 6.0 to 7.5 gallons per pound.

TABLE XV
FUEL SYSTEM CHARACTERISTICS FOR SPECIFIC U. S. ARMY AIRCRAFT

Aircraft Type Manufacturer	No. of Fuel Cells	Fuel Cell Total Capacity		Fuel Cell Size		Shape Index S.I. gal/ft ² of Surface Area	Weight Index W.I. gal/lb of Empty Cell wt.	Fuel Cell Type	Type of Fuel
		(gals)	(lbs)	Surface Area (ft ²)	Empty Cell Weight (lbs)				
(1) UH-1B (BELL)	2	242.0	1551.0						
	(1)* (2)	(122.0) (120.0)	(781.9) (769.1)	39.0 39.0	40.0 33.0	3.13 3.07	3.05 3.64	Cells 1&2 rubber self-seal- ing cell; flexible	JP-4 (6.409 lbs/ gal)
Earlier Models of the UH-1B	2	165.0	1057.0						
	(1) (2)	(82.0) (83.0)	(525.5) (531.5)	30.0 30.0	34.0 33.5	2.73 2.77	2.41 2.48	cell construction nonpressurized system; 60% of fuel tank self- sealing against cal .50 and 20 mm, remaining portion nonself- sealing bladder type. Cells 3,4, & 5 nonself-seal- ing. MIL-T-5578	
(2) UH-1D (BELL)	5	220.0	1410.0						
	(1)	(44.2)	(283.3)	22.1	27.5	2.00	1.61		
	(2)	(44.2)	(283.3)	22.1	28.0	2.00	1.58		
	(3)	(34.3)	(219.8)	18.5	4.5	1.85	7.62		
	(4)	(63.0)	(403.8)	26.6	9.0	2.37	7.00		
	(5)	(34.3)	(219.8)	18.5	5.5	1.85	6.24		
(3) U-1A (DEHAVILLAND)	4	213.5	1229.5						
	(1)	(61.2)	(352.4)	26.1	9.5	2.35	6.44	Nonself- sealing rubber cell with	Gasoline 115/ 145
	(2) (3)	(51.0) (51.0)	(293.7) (293.7)	25.8 25.8	8.5 8.5	1.98 1.98	6.00 6.00		

*Fuel cells numbered in Figures 29 through 42

TABLE XV (Continued)

Aircraft Type Manufacturer	No. of Fuel Cells	Fuel Cell Total Capacity		Fuel Cell Size		Shape Index S.I. gal/ft ² of Surface Area	Weight Index W.I. gal/lb of Empty Cell wt.	Fuel Cell Type	Type of Fuel
		(gals)	(lbs)	Surface Area (ft ²)	Empty Cell Weight (lbs)				
(3) U-1A (Continued)	(4)	(50.3)	(289.7)	25.8	8.5	1.95	5.92	plastic coated lining; nonpres- surized system	(5.759 lb per gal)
(4) U-6A (DEHAVILLAND)	5 (1) (2) (3) (4) (5)	139.8 (35.7) (35.6) (25.5) (21.5) (21.5)	855.0 208.8 208.3 186.3 125.8 125.8	21.0 21.0 16.0 9.4 9.4	14.0 14.0 11.0 11.0 11.0	1.70 1.70 1.59 2.29 2.29	2.55 2.55 2.32 1.95 1.95	nonself- sealing; nonpres- surized system; aluminum 0.040 g. and 0.032 g. con- struction	Gasoline 80/87 (5.85 lb per gal)
(5) U-8D (BEECH)	8 (1) (2)	230.0 (44.0) (44.0)	1324.0 (253.0) (253.0)	20.0 20.0	6.1 6.1	2.20 2.20	7.21 7.21	nonmetallic pressur- ized sys- tem;	Gasoline 115/ 145

TABLE XV (Continued)

Aircraft Type Manufacturer	No. of Fuel Cells	Fuel Cell Total Capacity		Fuel Cell Size		Shape Index S.I. gal/ft ² of Surface Area	Weight Index W.I. gal/lb of Empty Cell wt.	Fuel Cell Type	Type of Fuel
		(gals)	(lbs)	Surface Area (ft ²)	Empty Cell Weight (lbs)				
(5) U-8D (Continued)	(3) -	(23.0)	(132.5)	(21.0; (2)	(6.2; (2)	(1.10; (2)	(3.71; (2)	rubber- bladder type cells	
	(6)	each	each	(15.0; (2)	(6.0; (2)	(1.53; (2)	(3.83; (2)		
	(7)	(25.0)	(144.0)	13.0	7.6	1.39	3.29		
	(8)	(25.0)	(144.0)	18.0	7.6	1.39	3.29		
(6) U-8F (BEECH)	8	230.0	1324.0					Same as U-8D	Gaso- line 115/ 145
	(1)	(44.0)	(253.0)	20.0	6.1	2.20	7.21		
	(2)	(44.0)	(253.0)	20.0	6.1	2.20	7.21		
	(3) -	(23.0)	(132.5)	(21.0; (2)	(6.2; (2)	(1.10; (2)	(3.71; (2)		
(7) OH-6 (HUGHES)	(6)	each	each	(15.0; (2)	(6.0; (2)	(1.53; (2)	(3.83; (2)	nonmetallic flexible cell construction nonpressurized; 60% of tank self- sealing against cal .50 and 20 mm	JP-4
	(7)	(25.0)	(144.0)	18.0	7.6	1.39	3.29		
	(8)	(25.0)	(144.0)	18.0	7.6	1.39	3.29		
	2	66.0	423.0						
(7) OH-6 (HUGHES)	(1)	(33.0)	(211.5)	19.0	10.8	1.74	3.06	nonmetallic flexible cell construction nonpressurized; 60% of tank self- sealing against cal .50 and 20 mm	JP-4
	(2)	(33.0)	(211.5)	19.0	10.5	1.74	3.14		

TABLE XV (Continued)

Aircraft Type Manufacturer	No. of Fuel Cells	Fuel Cell Total Capacity			Fuel Cell Size		Shape Index S.I. gal/ft ² of Surface Area	Weight Index W.I. gal/lb of Empty Cell wt.	Fuel Cell Type	Type of Fuel
		(gals)	(lbs)	Fuel Cell Total Capacity	Surface Area (ft ²)	Empty Cell Weight (lbs)				
(8) OH-13 (BELL)	2	58.0	348.6		12.9	5.2	2.25	5.58	nonpres- surized system; aluminum 0.040 g. construc- tion	Gaso- line 100/ 130 (6.010 lb per gal)
	(1) (2)	(29.0) (29.0)	(174.3) (174.3)		12.9	5.2	2.25	5.58		
(9) O1-F (CESSNA)	2	45.0	259.0		20.1	10.95	1.12	2.05	nonpres- surized self-seal- ing system aluminum 0.040 g. con- struction MIL-T-5578C	Gaso- line 115/ 145
	(1) (2)	(22.5) (22.5)	(129.5) (129.5)		20.1	10.95	1.12	2.05		
(10) OV-1A (GRUMMAN)	1	297.0	1903.5		84.0	100.8 based on FTL-11- 24 tank construc- tion	3.54	2.95	nonmetallic self-sealing; flexible cell; pressurized fuel system MIL-T-5578 (A-2)	JP-4

TABLE XV (Continued)

Aircraft Type Manufacturer	No. of Fuel Cells	Fuel Cell Total Capacity		Fuel Cell Size		Shape Index S.I. gal/ft ² of Surface Area	Weight Index gal/lb of Empty Cell wt.	Fuel Cell Type	Type of Fuel
		(gals)	(lbs)	Surface Area (ft ²)	Empty Cell Weight (lbs)				
OV-1B (GRUMMAN) Figure 16	1	297.0	1903.5	84.0	100.8	3.54	2.95	See OV-1A	JP-4
OV-1C (GRUMMAN) Figure 16	1	297.0	1903.5	84.0	100.8	3.54	2.95	See OV-1A	JP-4
(11) CH-34 (SIKORSKY)	11 Fwd Cells: (1) (2) (3) (4) (5) Aft Cells: (6) (7) (8) (9)	263.0 (15.7) (20.0) (15.7) (25.8) (25.8) (22.3) (28.9) (22.3) (28.7)	1525.4 (91.1) (116.0) (91.1) (149.6) (149.6) (129.3) (167.6) (129.3) (166.5)	13.2 (13.2) (15.8) (13.2) (20.5) (20.5) (14.9) (16.8) (14.9) (18.9)	19.1 23.0 19.1 29.8 29.8 15.8 17.7 15.8 19.9	1.19 1.27 1.19 1.26 1.26 1.50 1.72 1.50 1.52	0.82 0.87 0.82 0.87 0.87 1.41 1.63 1.41 1.44	nonmetallic self-seal- ing; flexible cell con- struction MIL-T-5578 PLIOCELLS non-self- sealing; nonmetallic cells MIL-T-6396	Gasoline (5.80 lbs per gal)

TABLE XV (Continued)

Aircraft Type Manufacturer	No. of Fuel Cells	Fuel Cell Total Capacity			Fuel Cell Size		Shape Index S.I. gal/ft ² of Surface Area	Weight Index W.I. gal/lb of Empty Cell wt.	Fuel Cell Type	Type of Fuel
		(gals)	(lbs)	Fuel Cell Total Capacity	Surface Area (ft ²)	Empty Cell Weight (lbs)				
(11) CH-34 (Continued)	(10)	(29.1)	(168.8)		22.5	23.7	1.29	1.23		
	(11)	(28.7)	(166.5)		18.9	19.9	1.52	1.44		
(12) CH-37 (SIKORSKY)	4	398.0	2308.0							
	(1)	(100.0)	(580.0)		45.4	66.0	2.20	1.52	nylon- cloth	Gasoline
	(2)	(99.0)	(574.0)		39.5	43.0	2.50	2.30	imp. with rubber;	(5.8 lbs
	(3)	(99.0)	(574.0)		39.5	43.0	2.50	2.30	encased in Fiberglas liner	per gal)
	(4)	(100.0)	(580.0)		45.4	66.0	2.20	1.52	MIL-T- 6396A	
(13) CH-47 (BOEING)	2	630.0	4038.0							
	(1)	(315.0)	(2019.0)		98.0	55.0	3.21	5.73	lower 50% self-seal-	JF-4
	(2)	(315.0)	(2019.0)		98.0	55.0	3.21	5.73	ing MIL-T-5578 upper 50% non- self-sealing MIL-T-6396	

TABLE XV (Continued)

Aircraft Type Manufacturer	No. of Fuel Cells	Fuel Cell Total Capacity		Fuel Cell Size		Shape Index S.I. gal/ft ² of Surface Area	Weight Index gal/lb of Empty Cell wt.	Fuel Cell Type	Type of Fuel
		(gals)	(lbs)	Surface Area (ft ²)	Empty Cell Weight (lbs)				
(14) CH-54 (SIKORSKY)	5	1359.0	8832.0						
	(1)	(226.0)	(1472.0)	71.4	56.2	3.17	4.02	nonmetallic	JP-4
	(2)	(226.0)	(1472.0)	73.5	60.5	3.07	3.74	self-seal- ing;	
	(3)	(226.0)	(1472.0)	73.5	60.5	3.07	3.74	flexible	
	(4)	(226.0)	(1472.0)	71.4	57.0	3.17	4.02	construc- tion; non-	
	(5) aux. tank	(453.0)	(2944.0)	113.3	109.9	4.00	4.12	pressur- ized sys- tem; self- sealing against cal .30 MIL-T-5578	

The many different types of materials used in fuel cell construction are of widely differing weights per unit area. Thus, the W. I. of a fuel cell of a given geometric shape can vary greatly depending upon the type of construction materials used. It is clear that there is a considerable overlap of W. I. values among non-self-sealing and types of self-sealing fuel tanks. Thus, the magnitude of the W. I., in many cases, will not readily identify the type of cell involved. On the other hand, the W. I. does facilitate the computation of weight penalties involved in using different types of fuel cells in a given aircraft. For example, the weight penalty (or weight reduction) involved in replacing a non-self-sealing tank with some type of self-sealing cell may be computed through the use of the W. I. values. To illustrate, assume that a lightweight, 25-gallon-capacity fuel tank is to be replaced with a heavier type of self-sealing tank. The original tank is of a certain geometric shape and has a W. I. of, say, 5.0. The original tank must be replaced in most cases with a tank of the same geometric configuration. The self-sealing tank can obviously be constructed from many types of materials. All materials, however, can be identified by a W. I. index value. In general, the W. I. value of a self-sealing cell is lower than that of the lighter tank, say, in this case, in the range of 1.0 to 3.0. The weight penalty involved with replacing the original cell is calculated by multiplying the fuel capacity of the tank by the difference in the W. I. values of the original and replacement tanks.

B. CONDITIONAL PROBABILITY OF FUEL CELL PENETRATION

The conditional probability of incurring a fuel cell explosion is conditioned by the event that the cell is first struck by an incendiary round. This event is also described by a conditional probability of a fuel cell hit, given an incendiary round hit on the aircraft. Studies by the Ballistic Research Laboratories of Vietnam combat data (Ref. 11) have shown that bullet hits on low-flying aircraft tend to be uniformly distributed over the surface of the aircraft. Relying on this observation, the conditional probability of a fuel cell hit by an incendiary round may be reasonably approximated by the ratio of fuel cells to total aircraft presented areas.

The two presented areas are defined as the planar areas resulting from the parallel projection of the fuel cells and the aircraft surfaces into a plane normal to the flight path of the striking projectile. The presented area of an aircraft fuel system is largest when the aircraft is viewed from directly above or directly below. These two views may represent highly improbable directions of attack, however, and may not reflect the "average" fuel system presented area exposed to gunfire.

In an effort to approximate the average fuel cell presented area, each aircraft has been drawn in Figures 29 through 42 from a view corresponding to a probable attack aspect. These presented areas correspond to those exposed to a ground view, 180° from the present line-of-sight. It is the ground view rather than the aerial view often illustrated which is assumed to represent the probable attack aspect. Each figure portrays the proportional dimensions of fuel cells and aircraft presented areas as exposed to a typical attack. Most aircraft have been drawn from a topside view in order to illustrate more aircraft design detail. The conditional probability of a fuel cell hit has been estimated from each figure by computing the proportional fuel cells to total aircraft presented area. These conditional estimates, denoted as $P\{FC|H\}$, are presented in the following table.

TABLE XVI
CONDITIONAL PROBABILITIES OF HITS ON AIRCRAFT FUEL CELLS
GIVEN A HIT ON THE AIRCRAFT

Aircraft	$P\{FC H\}$
UH-1B	0.069
UH-1D	0.129
U-1A	0.057
U-6A	0.077
U-8D	0.109
U-8F	0.128
OH-6	0.129
OH-13	0.066
Ol-F	0.083
OV-1A,B,C	0.037
CH-34	0.201
CH-37	0.057
CH-47	0.078
CH-54	0.201

The conditional probabilities of Table XVI range from 4% to 20%. There is no indication in these estimates that the fuel cells of any one class of aircraft would be any more vulnerable than those of other classes of aircraft. For example, the fuel cell hit probabilities associated with the group of fixed-wing aircraft (U-1A, U-6A, U-8D, U-8F, O1-F, and the OV-1A, B, and C) are relatively low, but those of the U-8D and U-8F are definite exceptions. The fuel cell arrangement in the U-8D and U-8F consists of eight shallow small-capacity fuel cells arrayed side by side in the internal wing areas. With this arrangement, a significant amount of fuel cell surface area is exposed to gunfire, as is reflected by the high $P\{FC|H\}$ estimates.

The vulnerability of combat helicopter fuel cells in the UH-1B and UH-1D differs considerably. The $P\{FC|H\}$ estimate for the two-cell UH-1B is only 0.069, while the probability of a fuel cell hit in the UH-1D is estimated as 0.129. The fuel system capacities and the physical design of the UH-1B and the 5-cell UH-1D are roughly equivalent; thus, the degradation effect usually accompanying an increase in the number of fuel cells in a fuel system of a given capacity may be observed from the contrasting $P\{FC|H\}$ values.

The cargo helicopters (CH-34, CH-37, CH-47, and CH-54) are also characterized by widely varying fuel system vulnerabilities. The CH-34 and CH-54 are multifuel-cell aircraft where again the fuel cells are arranged side by side and cover a large portion of the total floor surface in each aircraft. These aircraft expose a considerable amount of fuel cell surface area to almost all directions of attack and thus are among the most vulnerable aircraft considered.

V. SUMMARY OF INTERNAL TANK PROTECTION SYSTEM WEIGHT
AND COST ESTIMATES

A. THE APPROACH TO COMPARISON

The widely diversified requirements of the fuel cell passive defense systems considered and the variety of aircraft fuel systems included in this study complicate direct comparisons between weight penalties and cost estimates for the alternative approaches. For instance, care must be exercised in making comparisons of Army aircraft of a near-equal fuel system capacity because of the large variance in the number of separate fuel cells employed by such aircraft. To illustrate, all Army aircraft included in this study with a fuel capacity of between 200 and 300 gallons might be considered as a single class. These aircraft and their respective number of fuel cells are: the UH-1B, 2 cells; the UH-1D, 5 cells; the U-1A, 4 cells; the U-8D and 8F, 8 cells; the OV-1A, B, and C, 1 cell; and the CH-34, 11 cells. The actual weights of the empty fuel cells in these aircraft vary from 35 pounds for the U-1A to 234 pounds for the CH-34. Some of the passive defense systems require weight penalties which are a function of the number of individual cells in the fuel system, while others are independent of cell characteristics and are a function of capacity only. The detection and chemical extinguishant system is a representative example of the former, since a complete extinguishant system is required for each fuel cell. The weight penalties and system costs of the detection and chemical extinguishant system for aircraft in this class thus vary greatly, and a weight estimate associated with a particular aircraft in this class cannot be properly used as a representative of all aircraft types.

The weight requirements of the reticulated foam, the fuel additives, and the gas purge systems are controlled directly by the fuel capacity of the aircraft and are quite independent of the number of individual fuel cells involved. The variance between weight or cost estimates for these protection systems in aircraft of similar fuel capacities is very small. Thus, the estimate associated with any one particular aircraft may well serve as a representative estimate for all aircraft of a similar fuel capacity.

The fact that some protection systems require replenishment adds an additional constraint to cost comparisons. The reticulated foam, chemical extinguishant, and collapsible bladder approaches all represent "permanent" systems, in that no additional materials are required after the initial installation in the aircraft. Operational use of the aircraft does not influence permanent systems unless the tanks are actually hit by bullets or fragments. No strictly operational costs are incurred with permanent systems other than the periodic maintenance expense.

The nitrogen gas purge system requires frequent replacement of the compressed gas. The hardware for this system is permanently installed in the aircraft and requires only periodic maintenance. The resupply requirements and schedule are dependent upon the type of operational use to which the aircraft is subjected. The operational costs of the gas purge system will thus vary considerably among aircraft of the same type which are used in different ways.

The fuel additive approach to fuel cell protection, in effect, requires a "new system" with each refill. The operational costs depend upon the number of missions flown where protection is required and the type of fuel additive used. These costs are cumulative, and cost comparisons with other explosion suppression systems are meaningful only when the number and range of missions are known.

In order to facilitate useful comparison of protection systems, the 16 Army aircraft included in this study have been classified by fuel system capacities, as shown in Table XVII.

The Class I and Class III aircraft have been represented by the "average" aircraft of 56- and 244-gallon fuel capacities. Weight and cost estimates for each explosion suppression system have been obtained for Classes I and III aircraft by averaging the respective estimates for these aircraft. These two average estimates are associated with the hypothetical 56- and 244-gallon fuel capacity aircraft. These estimates, together with the four-point estimates derived directly for the U-6A, CH-37, CH-47, and CH-54 aircraft, have been used to provide estimating functions (weight and cost) for the passive defense systems.

TABLE XVII
CLASSIFICATION OF U.S. ARMY AIRCRAFT BY FUEL SYSTEM CAPACITY

Class	Aircraft	Number of Fuel Cells	Fuel Capacity (gal)	Average Fuel Capacity (gal)
I	OH-6	2	66	56
	OH-13	2	58	
	Ol-F	2	45	
II	U-6A	5	140	140
III	OV-1A,B,C	1	297	244
	UH-1B	2	242	
	UH-1D	5	220	
	U-1A	4	214	
	U-8D & 8F	8	230	
	CH-34	11	263	
IV	CH-37	4	398	398
V	CH-47	2	630	630
VI	CH-54	5	1357	1357

B. WEIGHT PENALTY GUIDES

Weight estimating functions for all protection systems, derived by the previously described procedures, are presented as functions of fuel system capacity in Figure 43. These weight estimates are based on the specific considerations outlined in the discussion of the particular protection systems as well as the function generating techniques discussed in this section. The fuel additive used is bromotrifluoromethane, and the nitrogen gas requirement in the purge gas system has been established as twice the volume of the fuel tank.

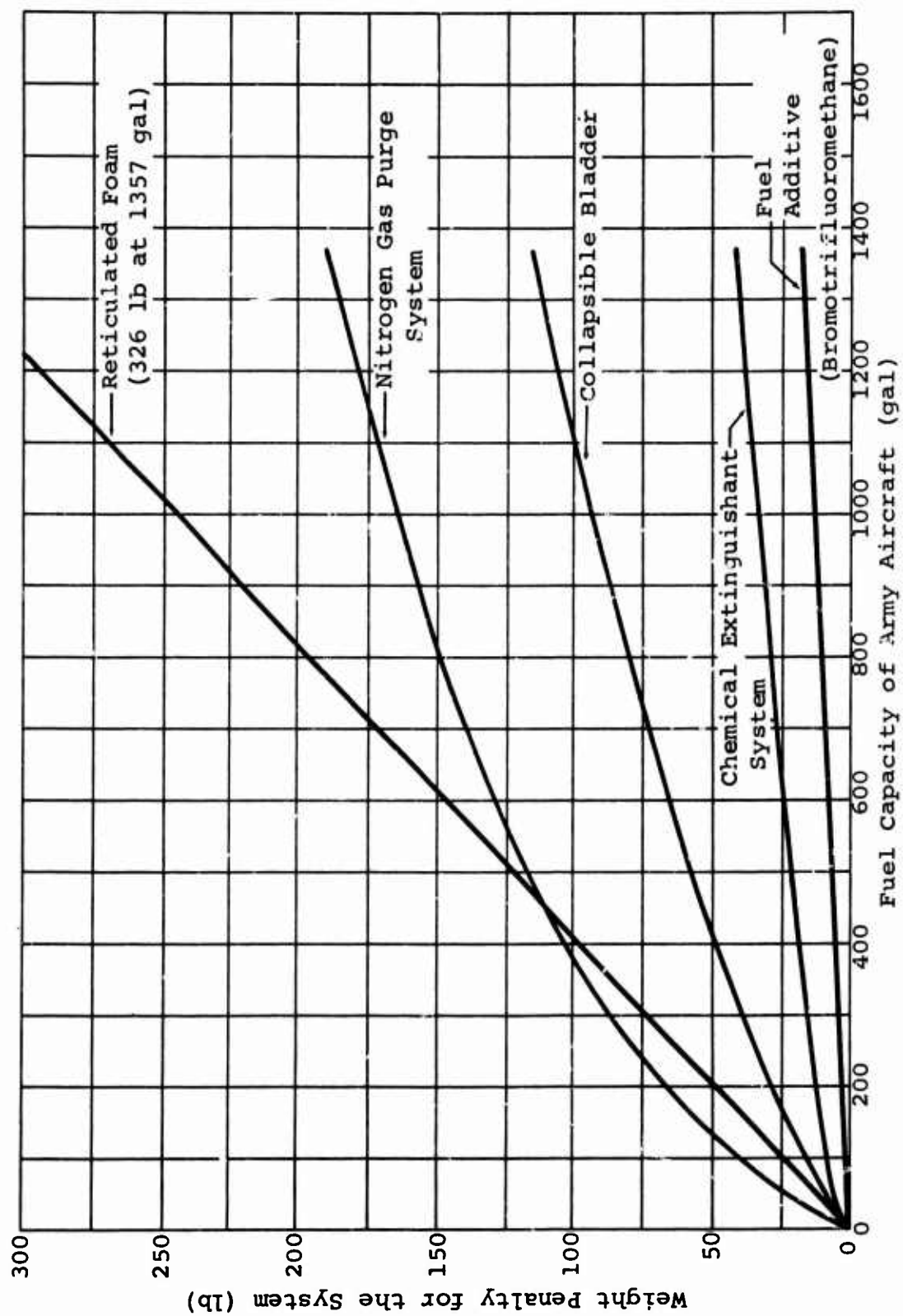


Figure 43. Weight Penalties for Internal Tank Protection Systems.

As illustrated in Figure 43, the fuel additive and chemical extinguishant system approaches to fuel cell protection impose significantly smaller weight penalties on Army aircraft than the remaining three protection measures. The weight penalties associated with the lighter weight systems for the largest (1357-gallon) fuel capacity CH-54 aircraft are 20 and 41 pounds. The use of reticulated foam in this aircraft results in an estimated 326-pound weight penalty. The differences in the weight penalties of the lighter systems and of reticulated foam are, of course, significant; but, considering that the 326 pounds represent only approximately 2% of the 14,864-pound cargo capacity of the CH-54, this weight penalty may be considered justified.

The cargo weights of all aircraft considered in this study were listed in Table V. The heaviest internal tank protection technique considered, as indicated in Figure 13, is the nitrogen gas purge system for fuel systems of less than about 400 gallons and reticulated foam for all larger systems.

A comparison of all aircraft cargo weights with the estimated weight of each proposed protection system indicates that even the heaviest approaches impose weight penalties of less than 3.5% of the aircraft cargo weight, with one exception: the OV-1 series of reconnaissance aircraft.

The takeoff weight of the OV-1A, B, and C is 12,672 pounds; the weight when fully equipped with 297 gallons of fuel and the several hundred pounds of normally carried radar, photographic, and electronic surveillance equipment is approximately 11,904 pounds. The 768-pound difference is much smaller than the normal margin found in aircraft of this weight category. The weight differential is classified as cargo weight, although no additional cargo is intended for the OV-1 aircraft. The use of a nitrogen gas purge system or reticulated foam in the fuel tank of this plane will result in a weight penalty greater than 10% of the cargo weight defined in this way.

These data indicate that, while there are significant weight differences between proposed systems, the weight penalty imposed on an aircraft by any of the five proposed systems is quite low when it is related to the total cargo capacity of the aircraft. Factors such as installation and operational costs of protection; ease of installation; compatibility with

the aircraft engine and fuel system; the system reliability; and the corollary benefits derived from the system's use should be considered along with weight penalties in the final selection of an appropriate passive defense approach for internal fuel tank protection.

C. DOLLAR COST EVALUATION

The estimated costs of three proposed internal fuel cell protection systems are presented as a function of aircraft fuel capacity in Figure 44. The collapsible bladder approach and the explosion detection and suppression technique have not been included in this figure because of particular problems in relating these costs to fuel capacity.

It has been shown that the collapsible bladder approach is effective as a passive defense measure and is considered to be feasible for relatively simple aircraft fuel tanks. A substantial development and design cycle will be required to produce a bladder system which can be used in a specific aircraft.

There are several current programs which are developing collapsible bladder fuel systems for zero-gravity environments and for the controlled handling of hazardous fuels and oxidizers. The conditions which these bladders must withstand are much more severe than Army aircraft requirements, and thus the cost of bladders produced through these approaches is potentially very high. It is believed that the present state of the art in elastomeric fabrication would permit fuel bladders to be produced at a moderate cost to meet Army aircraft needs. A substantial effort in design and testing would be required to bring this feasible approach to the point of practical application. The availability of other passive defense measures may offer more immediate solutions to the problem and preclude the need for an immediate program to develop collapsible fuel bladders.

The dollar costs of bladders for the Army aircraft included in this study have not been estimated because these costs would depend upon the approach and findings of a development program which has not yet been undertaken and is not recommended as an immediate need.

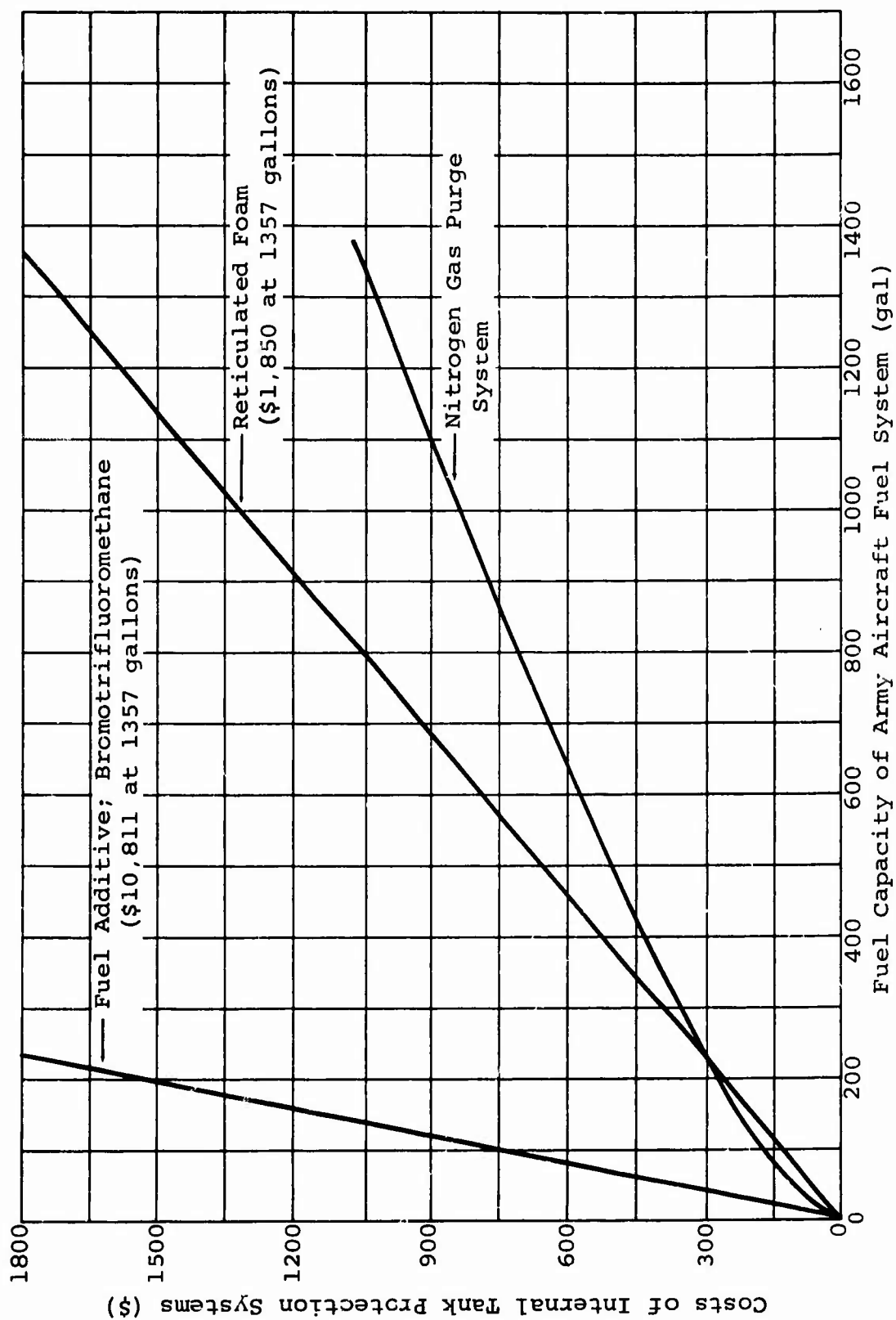


Figure 44. Costs of Internal Tank Protection System (based on 100 missions).

The costs of applying the fire detection and chemical explosion suppression systems to the fuel systems of this study have not been shown in Figure 44 because of the difficulties in relating these costs to fuel system capacity. Two factors complicate the cost estimating process for these systems. First, a complete system including the detector and extinguishing cartridge must be placed in each fuel cell; thus the CH-34 with 11 cells would require 11 times the equipment of the OV-1 aircraft, which has a single cell of slightly greater capacity. Second, there are strong patent rights (Ref. 33) established for the equipment required to detect and extinguish the fire. Some of the cost of detection and extinguishing systems must be attributed to these rights, and thus the basis upon which estimates can be made is complicated by the rights and judgement of the owners of the proprietary factors.

Perhaps the most technologically advanced chemical extinguishant system to be installed in an operational aircraft is the Fenwal Corp. system which has been installed in some models of Boeing commercial aircraft. This system is installed in a 15-gallon fuel surge tank in the venting system, which is primarily designed to protect against the lightning hazard. The estimated price of this Fenwal system is \$1000 per tank. The quoted price of this system reflects not only the costs of system component equipment and system installation but a considerable amount of development costs.

Two of the most apparent methods of deriving cost estimates for a chemical extinguishant system are simple to extrapolate the \$1000 per 15 gallons of fuel capacity figure to all Army aircraft fuel systems or to use the estimated dollar cost for all fuel cells regardless of fuel capacity. Neither of these methods seems appropriate, since it is believed that the present price can and will be revised to become more competitive with prices of other types of fuel cell protection systems.

For comparative purposes, it is seen that if a \$1000 figure is used for each fuel cell, the chemical extinguishant system would be economically competitive with the gas purge system and reticulated foam only if used in large-capacity one-cell fuel systems. Figure 44 indicates that the chemical extinguishant system is cheaper than reticulated foam if used in

single-cell fuel systems of greater than 700 gallons capacity. No Army aircraft included in this study have such fuel systems.

The cost estimates for the systems which require replenishment (gas purge system and fuel additives) have been based on 100 maximum-range missions for each aircraft. Average cost estimates for each suppression system have been calculated for aircraft classified in Classes I and III of Table XVII.

Figure 44 indicates that the fuel additive approach, with its cumulating costs, would be prohibitively expensive over even as few as 100 missions and that it is not economically competitive with the other approaches. However, if any of several other halocarbons, such as bromochloromethane or carbon tetrachloride, prove to be safe, effective fuel additives and could replace bromotrifluoromethane, the costs associated with the fuel additive approach can be reduced by as much as 80%. Then these costs would compare favorably with those associated with the use of reticulated foam.

For small aircraft with fuel systems of less than 200- to 300-gallon capacity, the reticulated foam protection system is clearly the most economical. Thirteen of the 16 aircraft considered in this study have fuel systems of less than 300-gallon capacity. Larger aircraft give the nitrogen gas purge system an opportunity to become competitive. The cost of frequent service and gas replenishment on such systems will eventually increase their cost; thus, this factor must be considered in selecting passive defense for the larger aircraft.

While the cost of the fuel additive approach becomes quite high over many missions, it may represent an economical "quick fix" for some existing aircraft. If the additive can be shown to be compatible with engines and fuel system components, the additive will require no aircraft modification and will be instantly available to the forces in the field by supplying the chemical additive and instructions for its use. The cost of this approach could be reduced to some extent by using the additive only on missions where enemy fire is anticipated.

The cost of any of the passive defense measures considered becomes very economical if their use can reduce aircraft losses to a significant extent.

VI. CONCLUSIONS

The understanding of Army aircraft fuel systems and passive defense measures, which has been achieved by this study, has provided a basis for several important conclusions. The data presented in this report are believed to be adequate to support the specific conclusions which follow.

In considering these conclusions, it is important to understand that in this study attention has been concentrated upon passive defense measures applicable to internal fuel tank protection, specifically to the problem of preventing flame and explosions within fuel tank vapor spaces. This focusing of attention is not intended to minimize the importance of other aspects of fuel vulnerability such as fuel loss and the hazards associated with fires outside of fuel cells. The contributors to this study fully understand that the elimination of vapor space explosions is but one aspect of the total fuel vulnerability problem.

1. The extent of the dynamic vapor space hazard existing in operating aircraft is generally unknown. No reports relative to the measurement of actual fuel vapor concentrations in the vented space of operating aircraft fuel tanks have been found in the documents available to this study, and it seems improbable that such data exist.
2. Important work which has a direct bearing on internal tank protection is in progress at the time of this writing. Examples of these programs include the Army's programs with modified fuels; the Army's project to produce improved tank materials; the Air Force's work with reticulated foam tank fillers; the Navy's program to investigate fuel additives; and the Army's project to improve incendiary ammunition functioning.
3. The 10-pore reticulated foam material has performed impressively in preventing vapor space explosions both in the tests conducted during this contract and in the tests conducted at other facilities.

4. The mechanism of reticulated foam action in preventing flame propagation is not fully understood and thus may not have been optimized.
5. Reticulated foam offers two important side benefits in addition to excellent explosion suppression. These are excellent slosh control and probable improved self-sealing action.
6. Reticulated foam is compatible with aircraft fuel system components and engines.
7. Reticulated foam will provide a high degree of internal fuel tank protection to Army aircraft for generally acceptable weight and dollar costs.
8. Reticulated foam should not be considered for fuel tanks that operate at pressures above 1 psig until more data concerning the behavior of flames passing through foam under elevated pressures become available.
9. Direct halocarbon additions to fuel offer promise as a "quick fix" means of internal tank protection for existing aircraft where the cost or time to modify fuel systems to apply other approaches is considered prohibitive.
10. Halocarbon fuel additives do not appear to be promising as long-term or ultimate solutions to fuel tank passive defense requirements because of their high dollar cost.
11. Explosion detection and flame suppression within the fuel cells of Army aircraft are feasible and impose a low weight penalty. The systems are expensive, complex, and require more service than some of the preferred alternatives.
12. Nitrogen or other inert gas purge systems are feasible and practical means of preventing explosions within fuel cells. They impose substantial weight penalties for small fuel systems; require frequent service and replenishment; and are thus potentially more costly and less reliable than alternative protection measures over long periods of use.

13. The use of collapsible fuel bladders within self-sealing fuel cells is a feasible approach which has the advantage of a low weight penalty. The development of suitable bladders would require a substantial design and development program which is not justified at the present time.
14. The fuel systems of present Army aircraft vary greatly in tank type, shape, and container efficiency and must surely reflect widely divergent or changing viewpoints regarding the Army's requirements for passive defense of combat aircraft.
15. The technological advances of the past 2 years have made it possible to accept fuel tank perforations by effective incendiary projectiles while still assuring a high probability of aircraft and mission survival.

VII. RECOMMENDATIONS

The following recommendations are offered in accordance with the conclusions drawn from this study of Army aircraft fuel systems and the approaches to the protection of internal fuel cell vapor spaces from flame and explosion.

1. Reticulated polyurethane foam tank filler materials should be considered for application to all present or future aircraft which may be exposed to the threat of small-arms fire.
2. Since the mechanism of the fire suppressive action of reticulated foam is not fully understood, present continuing studies should be closely followed and new work should be undertaken, if needed, to insure the optimum selection of foam characteristics at the earliest practical date.
3. Alternative ways of filling fuel cells with foam should be investigated to evaluate their economies, effectiveness, and acceptability.
4. The synergistic aspects of self-sealing fuel cells filled with reticulated foam should be evaluated, and the results should be quantified to the maximum extent possible.
5. The use of halocarbon fuel additives should be considered as a "quick fix" solution to current internal tank protection requirements where retrofitting with foam fillers is not feasible or expedient. The high dollar costs of this approach may be very economical where the probability of aircraft hits by incendiary or tracer rounds is high.
6. Immediate, short-term testing of the compatibility of halocarbon additives with Army aircraft engines and fuel system components should be undertaken to facilitate the implementation of recommendation number 5.

7. A short-term screening of the effectiveness of cheaper and more readily available halocarbons should be undertaken in an effort to cut the cost of fuel protection by this approach.
8. If Army aircraft fuel systems require continuing internal protection which cannot be achieved through the installation of reticulated foam (because of tank pressure, lack of access panels, etc.), a nitrogen gas purge system should be considered as the most practical alternative.
9. The use of explosion detection and chemical suppression systems within aircraft fuel cells is not recommended because of the availability of more economical and dependable alternatives.
10. The development and application of collapsible internal tank bladders are not recommended at this time because of the costs associated with such a program and the availability of effective alternatives which are already well along in the development cycle.
11. A study of the compatibility and effectiveness of halocarbon fuel additives with emulsified or solidified fuels now under development should be initiated.
12. A study of the fuel target characteristics of at least one Army aircraft and its fuel system should be initiated. This study should define the aircraft skin thickness, obliquity angles, interior components, and shot line distances encountered by small-arms hits on fuel system presented areas for realistic attack angles.
13. The feasibility of a program to experimentally evaluate the dynamic composition of fuel/air mixtures which are formed and continually change within operating aircraft should be considered.
14. Work toward total fuel system passive defense should be continued through programs to reduce fuel loss and external fire hazards, since internal tank protection is not full protection even if it is completely effective.

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13. ABSTRACT (U) The study covered by this report has focused attention upon the potential means of protecting the vapor spaces of Army aircraft fuel systems from the threat of fire and explosions caused by incendiary ammunition hits. As a means of implementing and quantifying passive defense data, the fuel containment of 16 models of Army aircraft has been studied and their capacity, location, shape, surface area, empty weight, and tank material determined. These data have been used in conjunction with the parameters of the potential vapor space protection techniques to provide estimates of the weight penalties and dollar costs associated with the passive defense measures applied to the aircraft of interest. Data relative to the fuel systems of the following aircraft are presented: UH-1B, UH-1D, U-1A, U-6A, U-8D, U-8F, OH-6, OH-13, O1-F, OV-1A, OV-1B, OV-1C, CH-34, CH-37, CH-47, and CH-54. The passive defense measures which have been reviewed and considered by the study include: inert gas purging, fire detection and suppression by chemical means, collapsible internal tank bladders, reticulated foam tank fillers, and the direct addition of halocarbons to fuel. The conclusions and recommendations which have resulted from the study are qualified to the extent that work is still in progress at several facilities on two of the most attractive passive defense measures. Thus, findings, subsequent to this report, may possibly indicate modifications to the conclusions presented herein.		

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Incendiary ammunition threat						
Fuel fire						
Fuel explosions						
Fuel tank vapor space protection						
Passive defense measures						
Inert gas purging						
Chemical fire suppression						
Collapsible tank bladders						
Foam tank fillers						
Halocarbon addition to fuel						
Fuel vulnerability						