A. HOLTEN

AFAPL-TR-73-74

FIRE AND EXPLOSION MANUAL
FOR
AIRCRAFT ACCIDENT INVESTIGATORS

Joseph M. Kuchta

Pittsburgh Mining and Safety Research Center
Bureau of Mines
Report No. 4193

TECHNICAL REPORT AFAPL-TR-73-74

August 1973

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

Air Force Aero Propulsion Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

804

NOTICES

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* AFAPL/SFH W-PAFB, Ohio 45433	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

FIRE AND EXPLOSION MANUAL FOR AIRCRAFT ACCIDENT INVESTIGATORS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report - July 1, 1972 - July 31, 1973.

5. AUTHOR(S) *(First name, middle initial, last name)*

Joseph M. Kuchta

6. REPORT DATE August 1973	7a. TOTAL NO. OF PAGES 131	7b. NO. OF REFS 69

8a. CONTRACT OR GRANT NO. F33615-72-M-5008	9a. ORIGINATOR'S REPORT NUMBER(S) Bureau of Mines PMSRC Report No. 4193
b. PROJECT NO. 3048	
c. Task. 304807	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* AFAPL-TR-73-74
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY AFAPL/SFH WPAFB, Ohio 45433

13. ABSTRACT

This manual was prepared at the request of the Air Force to provide aircraft accident investigators with compilations of various safety data and with suitable guidelines for investigating aircraft fires or explosions. Sections are included on investigative procedures, physical properties of materials, ignitability and flammability characteristics of flammable fluids or solids, damage analysis of fires or explosions, and the evaluation of protective measures. Compilations of selected data for fuels, lubricants, hydraulic fluids, explosives, and other materials of interest are given in the appendix for quick reference. Definitions and theory necessary to the application of these data are included in the appropriate sections of the manual. Most of the tabular and graphical data were derived from research programs sponsored by the Air Force and other federal agencies interested in fuel safety.

DD FORM 1 NOV 65 1473

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fire and Explosions						
Fuels						
Combustible Materials						
Aircraft Accident Investigation						

AFAPL-TR-73-74

FIRE AND EXPLOSION MANUAL
FOR
AIRCRAFT ACCIDENT INVESTIGATORS

by

Joseph M. Kuchta

ERRATA

Page 8, line 22: Correct spelling - aboard not abroad

Page 10, line 20: Correct spelling - total not toal

Page 16, line 1: Correct spelling - rich not ruch

Page 28, line 1: Change (10 in Hg) to read (7.73 in Hg)

Page 74, Figure 38: The units on the X-axis should be $ft/lb^{1/3}$ not ft/lb^3

Page 77, line 15: $(P_1V_1\gamma_1 = P_2V_2\gamma_2)$ should read $(P_1V_1^\gamma = P_2V_2^\gamma)$

Page 78, equation 50: Correct $\sin \alpha$ to read $\sin 2\alpha$

Page 88, line 3: Correct spelling - where not there

Page 105, Table 3A: Last line, 6th column (under Heat Capacity) should be corrected to read 0.52 (g) instead of 1.10.

Page 112, Table 10A: Last line, 1st column (under Material) should be corrected to read Aircraft paints instead of Aircraft points.

Page 102; Add following reference,

70. ASTM Metric Practice Guide, American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa., Dec. 1966, 46 pp.

Page 113, Table 11-A, 6th column: Multiply values by 1000.

AQM02-10-2384

Corrected page 78 to be inserted in

AFAPL-TR-73-74 "Fire and Explosion Manual for Aircraft
Accident Investigators" August 1973.

FIRE AND EXPLOSION MANUAL
FOR
AIRCRAFT ACCIDENT INVESTIGATORS

Joseph M. Kuchta

Approved for public release; distribution unlimited.

FOREWORD

This report was prepared by the Pittsburgh Mining and Safety Research Center of the U. S. Bureau of Mines under USAF Contract No F33615-72-M-5008. The contract was initiated under Project 3048, "Fuels, Lubrication, and Fire Protection," Task 304807, "Aerospace Vehicle Fire Protection." It was administered under the direction of the Air Force Aero Propulsion Laboratory, with Mr. Robert G. Clodfelter (AFAPL/SFH) acting as project engineer.

This report summarizes the work recently completed under this contract during the period 1 July 1972 to 31 July 1973.

Dr. Robert W. Van Dolah was the adminstrator for the U. S. Bureau of Mines; Mr. Joseph M. Kuchta prepared this report at the U. S. Bureau of Mines, Pittsburgh Mining and Safety Research Center, Bruceton, Pennsylvania.

This report was submitted by the author July 1973.

This technical report has been reviewed and is approved.

ROBERT G. CLODFELTER
Chief, Fire Protection Branch
Fuels and Lubrication Division

ABSTRACT

This manual was prepared at the request of the Air Force to provide aircraft accident investigators with compilations of various safety data and with suitable guidelines for investigating aircraft fires or explosions. Sections are included on investigative procedures, physical properties of materials, ignitability and flammability characteristics of flammable materials, damage analysis of fires and explosions, and the evaluation of protective measures. Compilations of selected data for fuels, lubricants, hydraulic fluids, explosives, and other materials of interest are given in the appendix for quick reference. Definitions and theory necessary for the application of these data are included in the appropriate sections of the manual. Most of the tabular and graphical data were derived from research programs sponsored by the Air Force and other federal agencies interested in fuel safety.

TABLE OF CONTENTS

PAGE

TABLE OF CONTENTS (cont'd)

TABLE OF CONTENTS (cont'd)

PAGE

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

ILLUSTRATIONS (Cont'd)

ILLUSTRATIONS (Cont'd)

ILLUSTRATIONS (Cont'd)

TABLES

APPENDIX A

TABLES (cont'd)

APPENDIX B

INTRODUCTION

The investigation of aircraft accidents requires consideration of fire and explosion as a causative or contributing factor to the damage produced in a crash-fire disaster. General guidelines for investigating these accidents are given in handbooks prepared by the U.S. Air Force (Ref. 1), Federal Aviation Administration (FAA) (Ref. 2), U.S. Naval Aviation Center (Ref. 3), and the International Civil Aviation Organization (ICAO) (Ref. 4). Of these publications, only the latter two provide any factual information useful for a fire or explosion analysis, although the information is largely limited to system malfunctions and material failures. Somewhat similar information is given in a recent handbook by the National Fire Protection Association (NFPA)(Ref. 5), which emphasizes the fire aspects of an aircraft accident. Nevertheless, these publications generally do not contain extensive compilations of fire and explosion safety data. Also, they lack many of the theoretical or empirical guidelines that can be useful in defining the hazard properties of aircraft combustibles and in analyzing the damage from an accident. Accordingly, the present manual was prepared at the request of the Air Force, to include such information in a single comprehensive report and, thereby, facilitate the task of the investigator.

As a convenience, this manual is organized to permit easy access to the particular data or information of interest. The first section outlines general procedures that can be used to investigate fires and explosions and briefly discusses the various types of evidence that have been found to be valuable in an aircraft accident investigation. Subsequent sections describe the ignitability, flammability, and physical properties of aircraft combustibles (or noncombustibles) and elaborate upon the application of these data to various temperature and pressure environments; both static and flowing combustible vapor-air systems are considered. The combustibles range from jet fuels to lubricants and hydraulic fluids and to various metals, fabrics, and other materials that may be encountered on an aircraft. Because of the great importance of damage analysis in an accident, the effects of fires and explosions on material surroundings are treated in a separate section. Here, damage criteria are correlated with energy equivalences and other combustion parameters. Since explosives or detonable propellants may be involved in a military aircraft accident, similar data are included for several typical explosive compositions. The final section of the text is devoted to the adequacy of safety measures which an investigator must evaluate.

The appendix contains compilations of various fire safety data that are available for aircraft combustibles and other materials of interest. Data are included for various classes of chemicals or "neat" fuels to indicate possible trends with changes in combustible composition; useful properties of noncombustible materials are also listed. Pertinent theory necessary to understanding these data is presented in the appropriate sections of the text.

Most of the fire and explosion data for aircraft combustible fluids were obtained by the Bureau of Mines under Air Force-sponsored programs, as cited in the list of references. Particularly noteworthy as a reference is the review by Van Dolah, Zabetakis, Burgess, and Scott (Ref. 6) describing many of the basic concepts pertinent to the application of such data. Other references that are widely used in this connection include the flammability bulletin by Zabetakis (Ref. 7) and the comprehensive fire protection handbook by the NFPA (Ref. 8). Although this manual contains many of the essential data and guidelines for investigating aircraft fires and explosions, the investigator must rely upon operational manuals for information on performance specifications and possible malfunctioning conditions for a particular aircraft system.

It is most important that all phases of the investigation are properly documented in a formal report and suitable measures are recommended to prevent recurrences of similar accidents. The fire expert should report on the fire and explosion aspects of the accident in terms of immediate causes and/or physical consequences. Factors pertaining to the survivability of occupants and the crashworthiness of the aircraft should be among the paramount considerations in the case of post-crash fire accidents.

PROCEDURES FOR ACCIDENT INVESTIGATIONS

The investigation of an aircraft accident is generally conducted by a team of specialists, including at least one fire and explosion expert. The investigating team should meet as soon as possible to obtain a briefing on the accident, to organize a plan of action, and to establish task groups with clearly defined areas of responsibility. Prior to or during the formal investigation, arrangements should be made with the proper authorities to take the following actions:

A. Initial Actions of Investigating Team

(1) Isolation of accident site.

(2) Protection of evidence.

(3) Photographic coverage.

(4) Recovery of wreckage.

(5) Documentation of witness accounts.

These actions are necessary to insure that any available evidence is not inadvertently lost or destroyed. The photographer should be instructed to obtain both color and black and white photographs of the wreckage, including detailed exposures of suspect items, and to tag each item in place.

As is frequently the case, the cause of an aircraft accident may be difficult to establish because of the destruction of valuable evidence by fire alone. Furthermore, if an explosion or crash landing is involved, aircraft fragments can be scattered over an extensive area and may not be recovered. Accordingly, to properly investigate such accidents, it is necessary to use a methodical approach and to rely upon both direct and indirect evidence to reconstruct the events leading to the mishap. A general guide for investigating aircraft accidents is given herein with the emphasis on the fire and explosion aspects.

B. Plan for Investigating Aircraft Fires or Explosions

(1) Briefing for background information.

(2) Inspection of accident site.

(3) Interviewing of witnesses and flight personnel.

(4) Analysis of fire or explosion evidence.

    (a) Source of combustible
    (b) Source of ignition
    (c) Development of fire
    (d) Correlation of damage patterns

(5) Final review and conclusions.

    (a) Sequence of events
    (b) Probable cause of accident

(6) Adequacy of safety measures.

(7) Report and recommendations.

(1) Background Information. At the outset, the investigator must obtain background information pertaining to the accident and the aircraft involved. This information is normally obtained at the initial briefing and should include a description of the aircraft and operating conditions, the performance characteristics of the aircraft or aircraft systems, the sequence of events that led to the accident, and all the evidence accumulated at the time. It is essential that the investigator recognizes what facts are known and what evidence must be substantiated or uncovered.

A close examination should be made of maintenance records, flight logs, weather reports, radio transmissions, witness accounts, and other records that may be helpful in establishing the evidence. Previous records should be included to note equipment or procedural changes, troublesome areas, and any accident histories for the particular model of aircraft. A study of maintenance and operational manuals is also necessary, especially in understanding the normal or abnormal functioning of a particular aircraft system. In reviewing the available evidence, the investigator must be open-minded and reserve judgment until the roles of all human and material factors have been carefully considered.

(2) Inspection of Accident Site. Inspection of the accident site is one of the most important steps in obtaining physical evidence in the investigation. This includes examination of the wreckage and surroundings, as well as any materials that may have been removed from the scene. Initially, the surroundings and general nature of the wreckage are examined to determine the probable direction, attitude, deceleration, and speed of the aircraft at the instant of the crash or fire. Subsequently, a detailed examination of the wreckage is made to obtain evidence on the origin of fire, the damage patterns due to fire, explosion, or impact, and the material failures or system malfunctions that could have contributed to the accident. At the same time, the investigator must search for clues which may reveal pilot error, sabotage, or weather disturbances as direct causes. The following items are typical of the evidence which the fire expert must look for:

(a) Fuels or combustibles consumed and soot formation.
(b) Fuel tank damage and amount of fuel spill.
(c) Ruptured lines or loose fittings in fuel, hydraulic fluid, and lubricating systems.
(d) Ruptured lines or loose fittings in oxygen supply systems.
(e) Intensity and spread of fire as indicated by discoloration, fusion, or consumption (combustion) of aircraft structural materials.
(f) Intensity and spread of fire in aircraft cabin and cockpit.
(g) Electrical overloads or faults in wiring, relays, starters, generators, accessory motors, navigational equipment, and other electrical equipment where failure can provide a source of ignition; these faults may be revealed by a study of any localized breakdown of insulation, "weld-like" fusions and erosions of metals produced by arcings, and other signs of shorted or overloaded circuits.
(h) Failures of engine power plants, pumps, and powered accessories as indicated by broken turbine blades, damaged bearings, eroded gaskets or seals, or any evidence of seizure.
(i) Abnormal functioning of after-burner as evidenced by burn-through of fuselage or other severe fire damage in this area.
(j) Fuel explosion occurrence as indicated by some fragmentation and wide dispersal of aircraft components.
(k) Ordnance fires and explosions as indicated by intense heating, fragmentation, and damage to surroundings, e.g. ground craters.
(l) Positions of flight control systems.
(m) Location and physical condition of victims.

The area with the greatest fire damage should be examined carefully because this area is frequently the source of the fuel or oxidizer. Since the fire may originate inflight, it is important to know that the fire intensity will be more severe in the areas exposed to an air stream;

also, the fire pattern will tend to follow the slipstream. The damage from inflight fires, as well as those involving the rupture of a high pressure hydraulic fluid line or an oxygen line, will tend to be similar to that produced by a torch. To assist the investigator in evaluating the fire damage, a section on the properties of aircraft materials is included in this manual. Reference to Air Force technical manuals should be made in determining the significance of any evidence pertaining to flight controls, aircraft performance, or the normal and abnormal functioning of an aircraft system.

(3) Witness Accounts. Accident accounts by witnesses and surviving flight crew members are usually obtained at the start of the investigation. However, after inspection of the accident site, the investigator will want to interview the witnesses, crew members, or maintenance personnel to account for any inconsistent "facts" and to possibly confirm new evidence. It is important to remember that the accuracy of a witnesses' statement will depend upon his sight and hearing limitations and ability to resolve the temporal sequence of a series of rapid events. Particularly in the case of an explosion, it is not unusual for a witness to claim that two or more explosions were heard when only one actually occurred. If at all possible, the witness should be required to relate his observations to specific landmarks or objects and to events which have been established temporally and spatially.

(4) Analysis of Evidence. After accumulation of the available evidence, analyses are made of the information to develop a plausible explanation for the accident. The fire or explosion analysis may be conducted concurrently with the analyses pertaining to aircraft flight performance but should be completed before a final description of the accident is formulated. In the fire or explosion analysis, it is necessary to account for the source of the combustible, the probable source of ignition, the history of the fire, and the observed fire damage. Any assumptions that are made must be reasonably consistent with the evidence on system malfunctions, material failures, and the sequence of events.

(a) Source of Combustible. Aircraft jet fuels frequently account for the major amount of fire damage in an aircraft fire but they may not necessarily be involved in the initiation stage. In a ground or inflight fire, the leakage of jet fuels as well as other volatile flammable fluids should be suspected as a combustible source, depending upon the evidence on ruptured lines, loose fittings, etc. Aircraft jet fuels, particularly JP-4 or Jet B type, are usually prime suspects in an explosion or sudden widespread fire because of their high volatility and great ease of forming flammable vapor-air mixtures; the lower volatility fuels, such as JP-5 or Jet A type, can be equally hazardous at slightly elevated temperatures or reduced pressures, or when agitated to form flammable mists. The hydraulic fluids and lubricating oils or greases have rather low volatilities but can be the prime suspects in the case of an engine compartment fire, particularly if no jet fuel leaks are detected. The pattern of soot formation may be useful in determining the combustible source; however, chemical analyses of the soot or other deposits are normally required when the evidence is inconclusive. In assessing the possible role of any combustible fluid, the following items should be considered:

(1) Quantity and distribution of combustible.

(2) Vapor pressure and flash point of combustible.

(3) Concentration limits of flammability.

(4) Temperature requirements for ignition.

(5) Flame temperatures and propagation rates.

(6) Effects of ambient temperature, pressure, ventilation rate, and other flight environmental variables.

Other combustibles which may be involved in an aircraft fire are metals, fabrics, insulation, tires, packaging materials, and other flammable solids. Although their involvement is usually an aftermath of the fire, their possible role as a cause factor cannot be ignored. Particular attention should be given to those materials which readily ignite and spread flame at high rates; also, the quantity and distribution of the combustibles are important in assessing the heat release and damage. Ordnance items, if present, are also involved as an aftermath of fire and can be expected to produce damage characteristic of detonating materials, i.e., explosives.

(b) Sources of Ignition. As is known from experience, the chance of ignition after a fuel leak occurs in aircraft engine compartments or adjacent areas is relatively great. The possible sources of ignition in these areas include the combustion chamber surfaces, overheated engine accessories, and sparks or arcs from electrical circuits and equipment; other sources are electrostatic sparks, flames, hot gases, lightning, aerodynamic heating, and frictional heat or sparks. The entrainment of afterburner gases into a fuel tank vent is an example of the hot gas ignition hazard. Generally, most ignitions are caused by hot surfaces or electrical energy sources, although in a crash situation multiple sources can be encountered. For sustained ignition to occur, flammable vapor-air mixtures must be present or the combustible liquid or solid must be heated to produce at least a flammable layer of gas at the surface. Thus, the physical state of the combustible is important in determining whether a particular heat or energy source could produce ignition. Furthermore, the investigator must be aware of the fact that ignition temperature requirements can be much higher in a flowing system than in a static system. The following ignition properties can be useful in this analysis:

(1) Minimum autoignition temperatures and ignition delays

(2) Minimum spark ignition energies

(3) Electrostatic spark ignition energies

(4) Wire ignition and hot plate ignition temperatures

(5) Hot gas ignition temperatures

(6) Radiant ignition energies

(c) Development of Fire. The origin of the fire is deduced from a combination of the evidence developed in determining the sources of ignition and combustible and the material failures or system malfunctions. The spread of the fire is determined from a study of the distribution of combustibles, the flammability properties of the combustibles, the intensity and distribution of the fire damage, and the known airflow or ventilating conditions throughout the aircraft. Witness accounts should be used to help corroborate the fire sequence indicated by the physical evidence.

The presence of soot can be used to indicate whether a jet fuel or organic combustible fire occurred in a given location. Extensive deposits of soot or char usually indicate that the combustion occurred under non-optimum conditions, e.g. insufficient air, and that the average fire temperature was probably of the order of only 1000° F. However, some soot deposits are expected in the aft compartments of the aircraft fuselage from normal operations, such as in taxiing, when exhaust gases are entrained by intake of coolant air. Evidence of soot formation and heat damage to aircraft structural materials should be used in determining the progress of the fire.

Generally, the fire spread rate will be greatest where flammable vapor-air mixtures can form readily and where the fire is fanned by wind or flowing air, as in the engine bay of an aircraft. Thus, inflight fires exposed to an airstream will spread rapidly from the point of origin to the aft part of the aircraft, depending upon the available quantity of combustible. In comparison, the pattern of a ground fire will be more irregular, with more vertical and lateral flame spread. The amount of fuel leakage or spillage will greatly determine how widespread the fire will be. Other factors to be considered are combustible volatility, amount of atomization, mass burning rates, and the flame speeds of fuel vapor-air mixtures.

(d) Damage Patterns. The intensity of an aircraft fire can be determined by comparing the temperature limitations of the aircraft materials that were consumed and those that were highly resistant to heat. Most aircraft materials, including metals and fire resistant materials, cannot withstand the temperatures reached in a hydrocarbon fuel type fire; titanium and stainless steels are among the exceptions and tend to show damage only in inflight fires or in torchlike fires. The fire temperature, exposure time, and the airflow or available oxygen must be considered in evaluating any fire damage. Where a massive fuel spillage has occurred in a fire, the entire aircraft and part of the adjacent surroundings will show widespread fire damage. In the event that incendiaries, magnesium, or other high energy combustibles are involved, the fire damage will be severe and localized in the areas where these materials are present. Damage from electrical arcing is even more localized and can be identified from the erosion, splatter, and fusion of metals that is characteristic of arc welding. In the absence of current, e.g. after a crash fire, fire damage to a wire bundle will normally not show bead-like fusions or other such intense heating unless strands of fine wire or unusually high fire temperatures are present.

Damage from explosions is usually indicated by the rupture of an aircraft compartment and the dispersal of fragments. Fuel tanks and other aircraft compartments cannot sustain most combustible vapor-air explosions, although they may sustain partial propagations under certain conditions. Explosion pressures can be more severe in an "empty" fuel tank than in a filled one, depending upon the fuel volatility and the flight altitude pressure. In assessing the explosion damage, it is necessary to consider both the structural limitations of the confinement material and the degree of venting that existed; e.g., an explosion not sustained in a fuel tank can conceivably be sustained in a vented compartment, such as the engine bay. Also, the investigator must consider the damage contribution from any physical explosions or implosions, e.g. sudden decompression of compartments or rupture of fuel tanks from overpressurization, and from the detonation of ordnance items or high energy fuels that may be abroad.

An analysis of the fragmentation and air blast effects can provide an estimate of the chemical or pressure energy of the explosion; crater evidence can also be useful in this connection. Examination of metal fractures will indicate whether tension, compression, or torsion failures occurred, providing the fractured part has not been greatly damaged by fire; metallographic analyses are usually required to determine the exact nature of any fatigue failures. Combustible vapor-air explosions (deflagrations) will be evidenced by tension failures, whereas gas detonations will ordinarily produce less stretching and cleaner breaks since a detonation wave propagates faster than the material can react or stretch to its stress limit. A map or diagram showing the size and spatial distribution of fragments should be prepared to facilitate the correlation of damage with the potential explosion energy.

Finally, an analysis must be made of the accident casualties and the fire fighting and rescue operations. Again, a diagram is recommended in order to relate the fire development with the position of each occupant. The immediate effects of fire or explosion on the flight crew and passengers can be deduced from the analysis of the fire development and any records of radio transmissions with the crew; subsequent effects can be determined from medical records and a consideration of toxicity limits, asphyxiation limits, and physiological thresholds of heat and dynamic pressures. An evaluation of the fire fighting phase is important in developing the fire evidence as well as in determining the adequacy of the extinguishants and procedures for fighting aircraft fires.

(5) Review and Conclusions. When the fire and explosion analysis is completed, both direct and indirect evidence are reviewed to reconstruct the accident. The fire expert should make certain that his analysis does not conflict with established evidence developed by other members of the investigating team. The sequence of events should then be described on the basis of the known or established evidence. This should include a description of the aircraft operations prior to the accident, initial signs of malfunction or trouble, apparent origin and development of fire, nature of any fire fighting or rescue measures, and extent of the resultant damage. Finally, the most probable cause of the accident should be ascertained and substantiated insofar as is possible. Frequently, more than one fault is required to cause a fire or explosion since a fuel must be heated or exposed to an energy source for ignition to occur.

(6) Adequacy of Safety Measures. As a part of an accident investigation, equipment and operational procedures must be examined to determine possible unsafe conditions and the necessary precautionary measures to prevent an accident. In an aircraft, the protective measures can include the use of permissible electrical junction boxes, fuel tank flame arrestors, and explosion inerting or suppression systems. These require a knowledge of gap quenching and flame extinguishant requirements to determine their adequacy. Flame detectors and alarms are also an important part of fire protection systems in engine bays, fuel tanks, and other hazardous areas of the aircraft. Since fire extinguishants and fire resistant materials yield toxic products in a fire, their use must be carefully regulated.

(7) Report and Recommendations. The complete findings of the investigator should be documented in a final accident report. The report should summarize all aspects of the investigation and give recommendations which can be useful in preventing similar occurrences. Research programs may also be recommended to investigate unresolved problems.

PHYSICAL PROPERTIES OF AIRCRAFT COMBUSTIBLES AND NONCOMBUSTIBLES

Selected properties of various classes of combustibles or noncombustibles are given in Appendix A, Tables 1-A through 12-A. These tables list most of the common physical properties, as well as fire safety properties, which the investigator will need for a given material, at least at normal ambient temperature and pressure. Although temperature and pressure effects are discussed in this and other sections, it is necessary to refer to the cited literature for any additional information on properties that may be required.

A. Air Atmosphere

The ambient temperature, pressure, and density of air at various altitudes is defined in Table 1-A for the standard atmosphere (Ref. 9). This atmosphere closely corresponds to that defined by NACA or ICAO up to 35,000 ft; over this range, the temperature varies approximately 3.6° (Fahrenheit) per 1000 ft. The composition of the atmosphere is generally computed on a dry basis and is assumed to be uniform at the lower altitudes (troposphere). Table 2-A gives the composition of dry air and some physical properties of air and its components. For most applications, it will be sufficiently accurate to take air as containing 20.95 percent oxygen, 78.1 percent nitrogen, and 0.95 percent argon and carbon dioxide, on a volume basis.

The densities (ρ) of the gases in Table 2-A are given in lbs/ft^3 and are for 32° F and 1 atmosphere pressure. They may be calculated for other temperatures (T) or pressures (P) by use of the following expression, P and T being in absolute units:

$$\rho_2 = \overset{\checkmark}{\rho_1} \left(\overset{\checkmark}{T_1}/T_2\right)\left(\overset{\checkmark}{P_2}/P_1\right) \tag{1}$$

The relative weight of each gas compared to that of air, which has a density of 0.0765 lb/ft^3 at 60° F (1 atm), is indicated by the specific gravity of the gas. If the density is unknown, it can be calculated by use of the ideal gas law:

$$\rho(\text{lbs/ft}^3) = MP/RT \tag{2}$$

where M is molecular weight (lbs), P is total pressure (lbs/ft^2), T is absolute temperature (°R), and R is the universal gas constant (1545 ft-lbs/°R-lb mole); T(°R) = T (°F) + 460. At high pressures, a modified equation of state is necessary to correct for non-ideal gas behavior.

For mixtures of ideal gases, the toal pressure (P) is proportional to the total moles (N) and is equal to the sum of the partial pressures of the gases. Thus, the mole percent or volume percent (X_i) of a component in the mixture is

$$X_i\% = 100\ p_i/P = 100\ n_i/N \tag{3}$$

where p_i is partial pressure and n_i is number of moles of the ith component of gas. The partial pressure of the gas component in a given volume (V) is defined by the following forms of the ideal gas law:

$$p_i = n_i \frac{RT}{V} = \frac{W_i}{M_i} \frac{RT}{V} \tag{4}$$

If equation (2) units are used, p_i must be in lbs/ft^2, n_i in lb moles, W_i in lbs, and V in ft^3. These relations are important in defining the volume or weight concentrations involved in the combustion of gases and liquid vapors.

B. Hydrocarbons and Miscellaneous Combustible Liquids or Gases

The various properties of selected hydrocarbons, alcohols, ethers, and other gaseous or liquid combustibles are summarized in Table 3-A. Data for these materials are well documented and are therefore included to help the investigator to define the physical and flammability properties of similar classes of combustibles that may be encountered in an aircraft fire.

As noted, the specific gravities of the vapors of the combustibles are a function of the molecular weight and are generally greater than that of air (Sp.Gr. = 1) for most of the organic type fuels. Their densities at 60° F can be readily calculated by multiplying the specific gravities by 0.0765 lb/ft^3. Although liquid specific gravities are not listed, most are less than that of water (Sp.Gr. = 1).

Vapor pressures are particularly useful in determining the vapor concentrations that may be formed above the surface of a combustible liquid. They are strongly dependent upon the temperature. For a single component ideal liquid, its vapor pressure at a given temperature can be taken as the fuel partial pressure (p_i) in the vapor space and the volume concentration (X_i) calculated using equation (3). As an example, a fuel tank partially filled with n-hexane at 70° F and 1 atmosphere (vapor pressure = 2.5 psia) will have a fuel vapor concentration equal to 100 x 2.5/14.7 or 17 volume percent, assuming uniform mixing of the fuel vapor and air. Note in Table 3-A that this hexane concentration is greater than the upper limit of flammability (7.4%) for this fuel in air.

For mixtures of ideal liquids, the vapor partial pressure of each component can be calculated by applying Raoult's law:

$$p_i = X_i \; p_o \qquad (5)$$

where p_i is the vapor pressure of the i^{th} component in solution, p_o is the vapor pressure of the component in the pure state, and X_i is its mole fraction in the solution. Thus, if the n-hexane liquid in the above example was mixed with n-octane in a molar ratio of 9 to 1, the partial pressure of the n-hexane vapor would have been 2.25 psia.

The specific heat or heat capacity of a substance permits one to determine the quantity of heat (Q) that must be supplied or removed to realize a particular level of temperature. In the simplest form, this may be expressed as follows:

$$Q(Btu) = Wc\ (T_2-T_1) \qquad (6)$$

where W is the material mass (lbs) having a constant specific heat c in Btu/lb-°F and T_2-T_1 is the temperature change in °F. Gases as well as most liquids have specific heats less than that of water (1.0). To apply equation (6) to various temperature regions, the variation of specific heat with temperature should be known, although the variation is not great for most gases. The values in Table 3-A are for temperatures of 60-70° F and refer primarily to constant pressure conditions; specific heats are lower under constant volume conditions in the case of gases or vapors.

The amount of heat release that is possible when a pound of fuel is burned in air to completion is defined by its heat of combustion. For most common saturated or unsaturated hydrocarbons, the net heats of combustion (Q_c) are between 17,000 and 20,000 Btu per pound of fuel, with carbon dioxide (CO_2) and water vapor (H_2O) as the products. The total heat release (Q) from the combustion of various vapor concentrations of a fuel (X_f) in a given chamber can be obtained from the following expression:

$$Q(\text{Btu}) = X_f V \rho_f Q_c \qquad (7)$$

where the units are consistent with those in the earlier discussion. It is significant that the heat releases for the organic compounds in Table 3-A are of the order of 18,000 Btu/lb mole for vapor-air mixtures that will just sustain flame. Further discussion on this and other related topics is given in the sections on flammability and damage analysis.

C. Aircraft Fuels, Lubricants, and Hydraulic Fluids

Tables 4-A and 5-A summarize the important properties of the aircraft fuels and fluids. Jet fuels have liquid specific gravities of approximately 0.8, whereas hydraulic fluids and engine oils have values that are at least about 0.9 and, in some instances, noticeably greater than 1; these specific gravities are relative to water which has a density of 62.3 lbs/ft^3 at 70° F. Unfortunately, data on their vapor densities appear to be scarce. Also, the physical properties of interest are more complete for the fuels than for the hydraulic and lubricating fluids.

Jet aircraft fuels can be classed as low or high volatility petroleum mixtures. The low volatility grades are typically kerosenes, such as Jet A, JP-5, JP-6, JP-8, or JP-1, which have a 10 percent boiling point of at least 350° F. The high volatility grades are blends of kerosene and aviation gasoline (Avgas), such as Jet B, JP-4, or JP-3, which have a 10 percent boiling point of about 230° F or lower. Their vapor pressures are also indicative of their volatility and are normally defined as Reid vapor pressures at 100° F; the latter tend to be lower than true vapor pressures because the vapor-liquid volume ratio is not ideal (~ 0) in Reid determinations. Nevertheless the Reid vapor pressures are sufficiently precise for most practical applications considering the variation (>1 psi) permitted by aircraft fuel specifications (Ref. 10).

Figure 1 shows the Reid vapor pressures of various aircraft fuels as a function of temperature (Ref. 11, 12). It is seen that at 70° F the vapor pressures of the high volatility fuels are at least 1.0 psia and those of the low volatility fuels are below 0.06 psia. Assuming ideal behavior (equation 3), the corresponding fuel vapor concentrations at 1 atmosphere pressure would be greater than 1.0/14.7 or 6.8 percent and less than 0.06/14.7 or 0.41 percent. Note in Table 4-A that the 6.8 percent concentration would fall within the limits of flammability listed for the high volatility fuels; correspondingly, the 0.41 percent falls outside the limits of flammability for the low volatility fuels. The minimum temperature at which the fuels can form flammable vapor-air mixtures at atmospheric pressure is approximately equal to their flash points (closed cup). The following expression can be used to estimate the lower limit (LL) of flammability of a fuel from its flash point and vapor pressure:

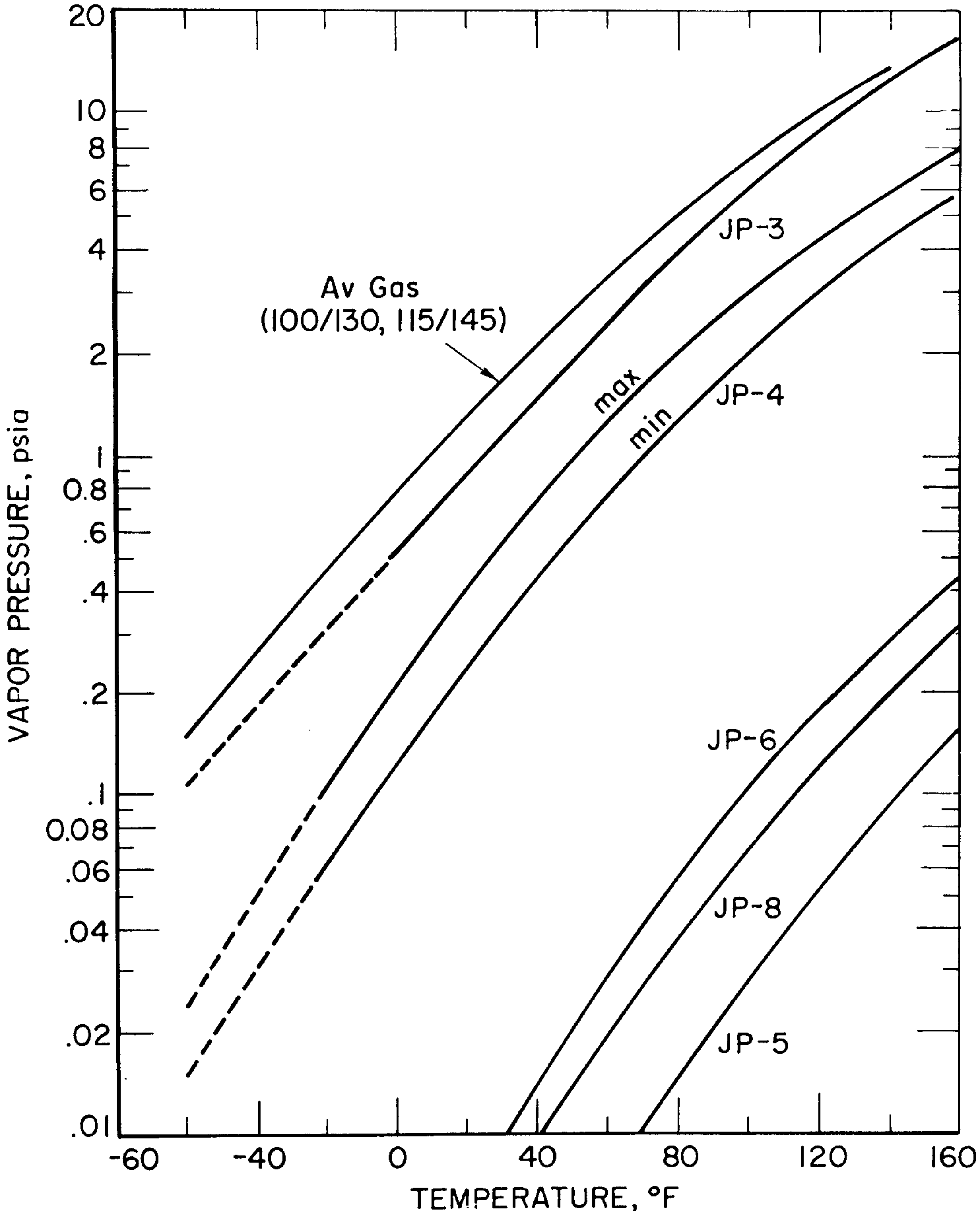


FIGURE 1. Reid vapor pressure vs temperature for various aircraft fuels.

$$LL\ (\text{vol\%}) \simeq 100\ (p_i/P)_{F.Pt.} \qquad (8)$$

where p_i is the fuel vapor pressure (psia) and P is the total pressure at the flash point conditions.

If a liquid fuel mixture is vaporized, the vapor volume can be calculated from the liquid specific gravity and the vapor specific gravity (vapor density ratio). The vapor volume for the vaporization of 1 gal of liquid at 70° F is given by

$$\text{Vapor volume } (\text{ft}^3/\text{gal}) = 111\ \frac{\text{Liquid specific gravity } (H_2O = 1)}{\text{Vapor specific gravity (Air = 1)}} \qquad (9)$$

where the constant 111 is the ratio of the weight of 1 gallon of water (8.33 lbs) to the density of air ($0.075\ \text{lb/ft}^3$). Where the vapor specific gravity is not known, it may be estimated from the ratio of the molecular weight of the liquid to that of air (28.95). In the case of aircraft fuels and fluids, the composition and molecular weight of their vapors will vary with the liquid temperature or the amount that is vaporized because of the nonuniform fractionation of components. Therefore, equation (9) should be used only when near-total vaporization occurs to insure the vapor composition is representative of all the liquid components present.

The heats of combustion of the aircraft fuels are between 18,000 and 19,000 Btu/lb., comparable to those of most hydrocarbon fuels. For other liquid hydrocarbon fuels or fluids, their heating value per pound of fuel can be estimated by

$$Q\ (\text{Btu}) = 13{,}500\ C + 60{,}890\ H \qquad (10)$$

where C is the carbon content and H is the hydrogen content in weight percent.

D. Combustible and Noncombustible Solids

Some physical properties of combustible metals, including those not ordinarily combustible, are given in Table 6-A. Melting points are of particular interest since they can be used to determine if fire occurred in a section of the aircraft and its intensity. The common aircraft materials of construction like aluminum and magnesium melt when heated to over 1200° F, whereas steel and titanium components require temperatures in excess of 2600° and 3100° F, respectively. In comparison, copper wiring should melt at about 2000° F and lead solder at only about 600° F. Note also that aluminum and magnesium have the highest heats of combustion for the metals listed and, therefore, are capable of producing the greatest heat release when involved in a fire, depending upon the combustion products.

The mechanical properties of metals are important in the structural analysis in an aircraft accident. One of the most useful mechanical properties in this connection is the maximum stress (longitudinal) beyond which failure of metal occurs, i.e., tensile strength; another is the stress required to produce deformation, i.e., yield point. Table 7-A lists the tensile strengths and yield points of various metals and alloys. These values are for tension and are comparable to or less than those for compression or bending, depending upon the modulus of elasticity of the material. If stress ($S, lb/in^2$) is applied uniformly to a given area (A, in^2), the total force (F) is

$$F\ (lbs) = SA \tag{11}$$

The pressure (P) at which a tank of diameter, d (in) and thickness, t (in) will fail is

$$P\ (lb/in^2) = \frac{2\ E\ St}{d} \tag{12}$$

where E is the efficiency of the weld or joint (usually equal to 1) and S is the tensile strength of the tank material in lbs/in^2.

Tables 8-A and 9-A are limited to the ignition or flammability properties of various combustible fabrics and other solids. The self-ignition temperatures given in Table 9-A can be taken as minimum temperature limits for reaction of these materials. Other temperature limits for selected materials of interest are listed in Table 10-A.

E. Explosives

Properties of representative explosives are given in Table 11-A. The primary high explosives are generally used as initiators or detonators and are extremely sensitive to ignition by heat, shock, and electrical discharge. The secondary high explosives are used as the main charge of a blasting material or ballistic weapon. They differ from primary explosives in that they are much less sensitive to heat, shock, and electrostatic discharges, and generally require a booster charge to initiate a high order detonation. Their detonation properties, such as velocity and pressure, are strongly dependent upon their densities. The heats of detonation are for conversion to the most stable reaction products and represent the upper limit of chemical energy obtainable from each explosive.

FLAMMABILITY CHARACTERISTICS

A. Flammable Fluids

(1) Temperature and Concentration Limits of Flammability. The ability of a liquid fuel to form flammable vapor-air mixtures is defined by its temperature and concentration limits of flammability. The lower temperature limit (T_ℓ) is realized when the liquid fuel temperature is high enough to produce a minimum fuel vapor concentration (equilibrium) which when uniformily mixed with air will sustain flame, if ignited by an external heat source. This temperature limit is usually slightly lower than the flash point of the liquid because the latter is determined under less favorable conditions of propagation (downward). The upper temperature limit (T_u) corresponds to the liquid fuel temperature above which the equilibrium fuel

concentration of the saturated vapor-air mixture is too ruch to sustain flame. These temperature limits are not as wide as those for fuel sprays or mists which can form under dynamic or non-equilibrium conditions.

Closed cup flash points should be preferred to open cup flash points since the former generally yield more conservative values. Useful expressions relating the flash point directly to the boiling point, vapor pressure, and lower concentration limit of flammability have been derived by Mullins (Ref. 14) and Affens (Ref. 15) for simple hydrocarbon fuels. For example, the following expression is given as the relationship between flash point (T_f) and lower concentration limit of flammability (LL) for the n-alkanes at atmospheric pressure:

$$T_f = \left[77{,}290/_{LL} - 3365\right]^{1/2} - 277.3 \qquad (13)$$

where LL is in volume percent and T_f is in °C [T_f(°F) = 1.8 T_f(°C) +32]. However, similar correlations for the complex aircraft fuels or lubricants are much more difficult to derive because of vapor composition uncertainties. The flash points of Jet A type fuels are between 100° and 150° F and those of Jet B type fuels between -20 and 20° F (see Table 4-A). Avgas has a value close to about -50° F. In comparison, hydraulic fluids, lubricants, and engine oils have noticeably higher flash points. Their values range from 195° F for the MIL-H-5606 mineral oil fluid, to over 400° F for MIL-L-7808 and MIL-L-9236 phosphate ester fluids, and to over 500° F for some of the other fire resistant fluids included in table 5-A.

(2) Flammability Diagrams. The relationship of the vapor pressure and the temperature and concentration limits of flammability is illustrated by the flammability diagrams for JP-4 (Figure 2) and JP-5 (Figure 3) jet fuels at atmospheric pressure. The possible range of flammable vapor-air mixtures (upward propagation) is indicated by the lower or lean limit (LL) and the upper or rich limit (UL), both of which are widened by increasing temperature. These mixtures can be readily ignited by an electric spark or other heat source and are capable of autoignition if they are heated to the ambient temperatures shown in each figure. The intersection of the LL and UL curves with the vapor pressure curve occurs at the T_ℓ and T_u temperature limits, respectively, which define the range of flammability of the equilibrium saturated vapor-air compositions. Note that "cool" flames may form above the upper limits (UL's) of these fuels. Although such flames are normally associated with a small temperature rise, e.g. 100-200° (°F), they may promote normal "hot" flame reactions or produce pressure rises which an aircraft compartment cannot withstand. Note also that flammable mists are possible and that they may form even below the lower temperature limit (T_ℓ) or the flash point of the fuel. Ordinarily, fuel mists or sprays will require more energy for ignition than vapor-air mixtures.

With decreasing pressure, the concentration limits vary only slightly but the temperature limits decrease markedly. Figure 4 is derived from reference 16 and shows the variation of the temperature limits of

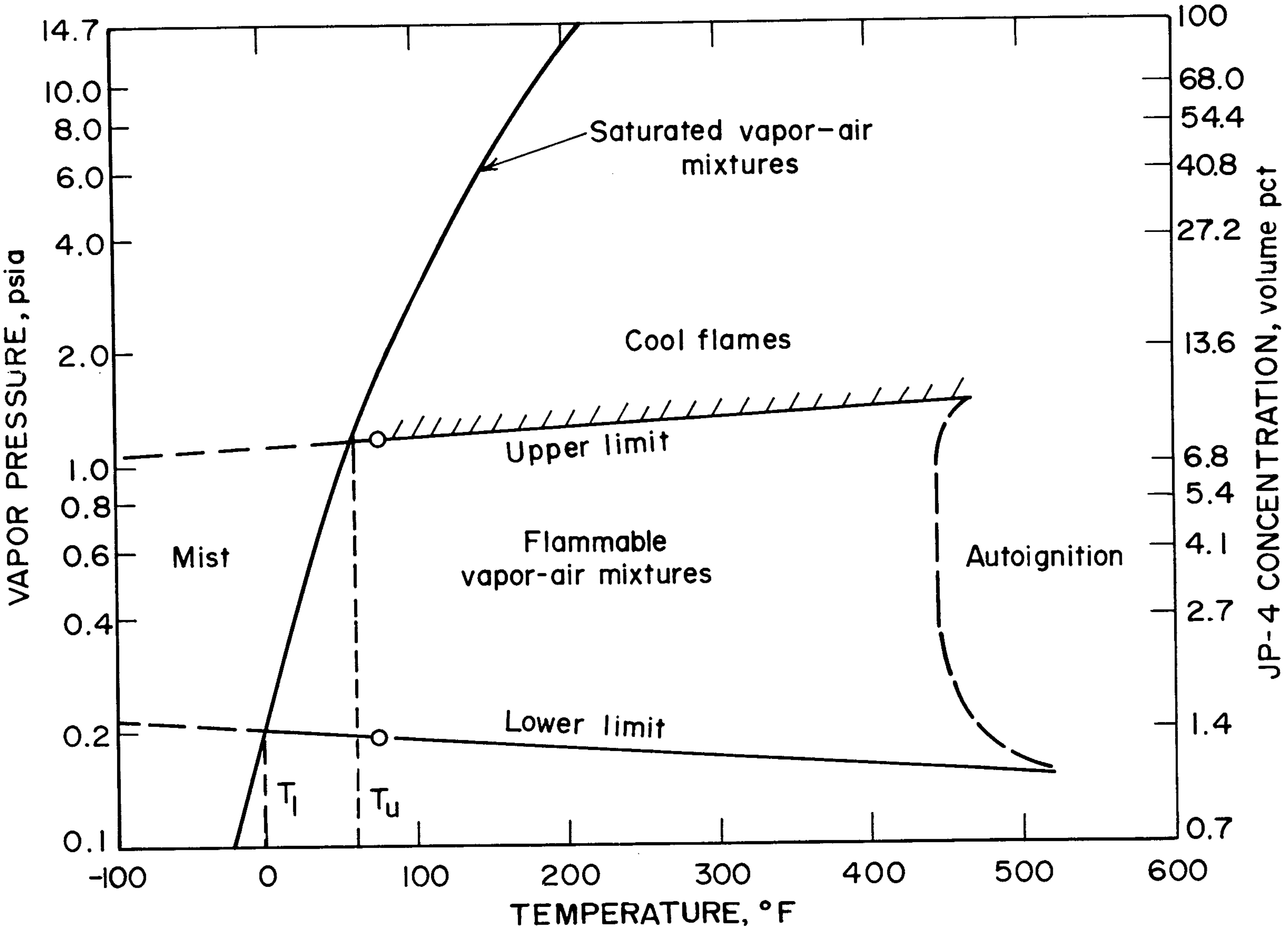


FIGURE 2. Flammability diagram of JP-4 in air at atmospheric pressure.

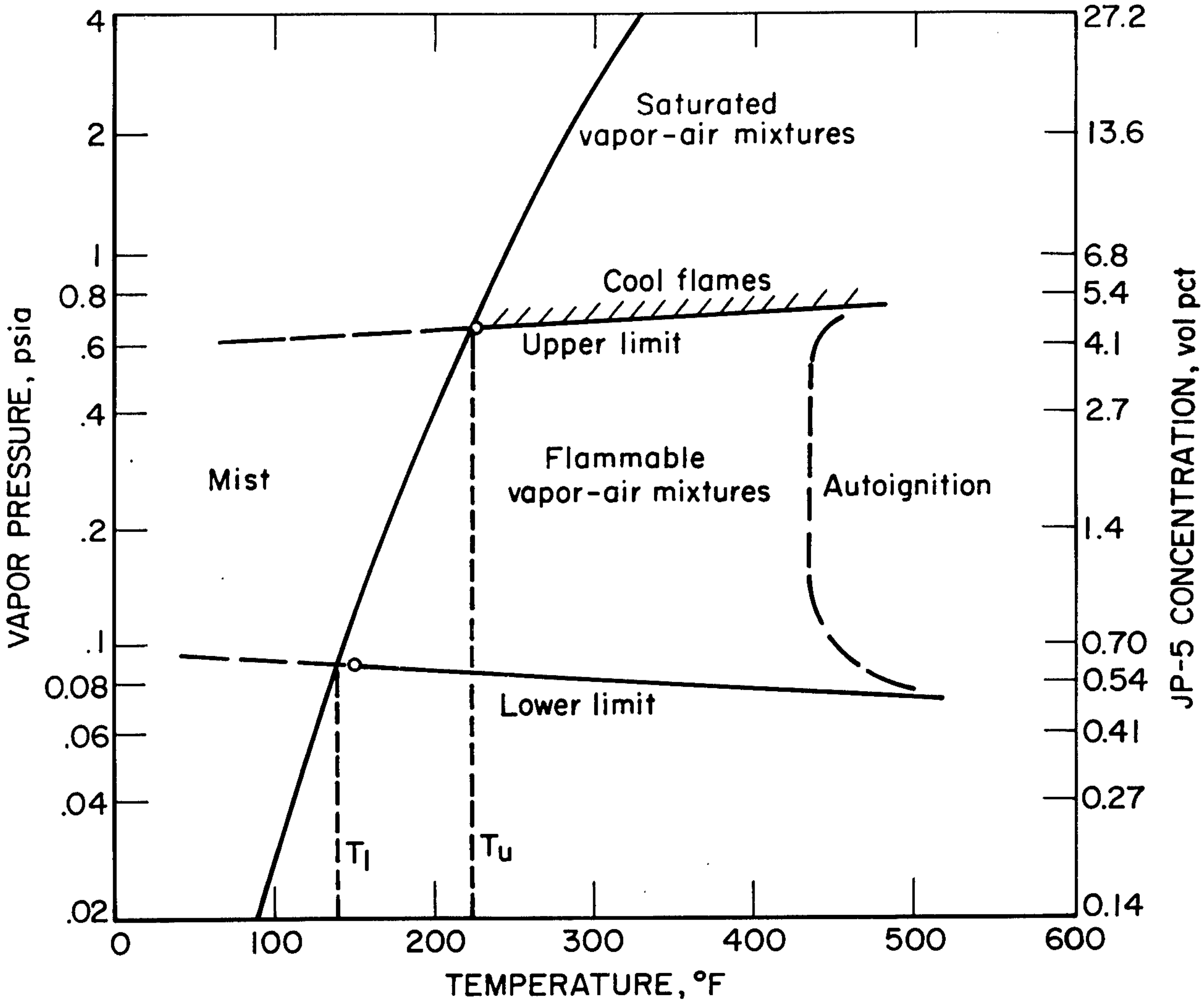


FIGURE 3. Flammability diagram of JP-5 in air at atmospheric pressure.

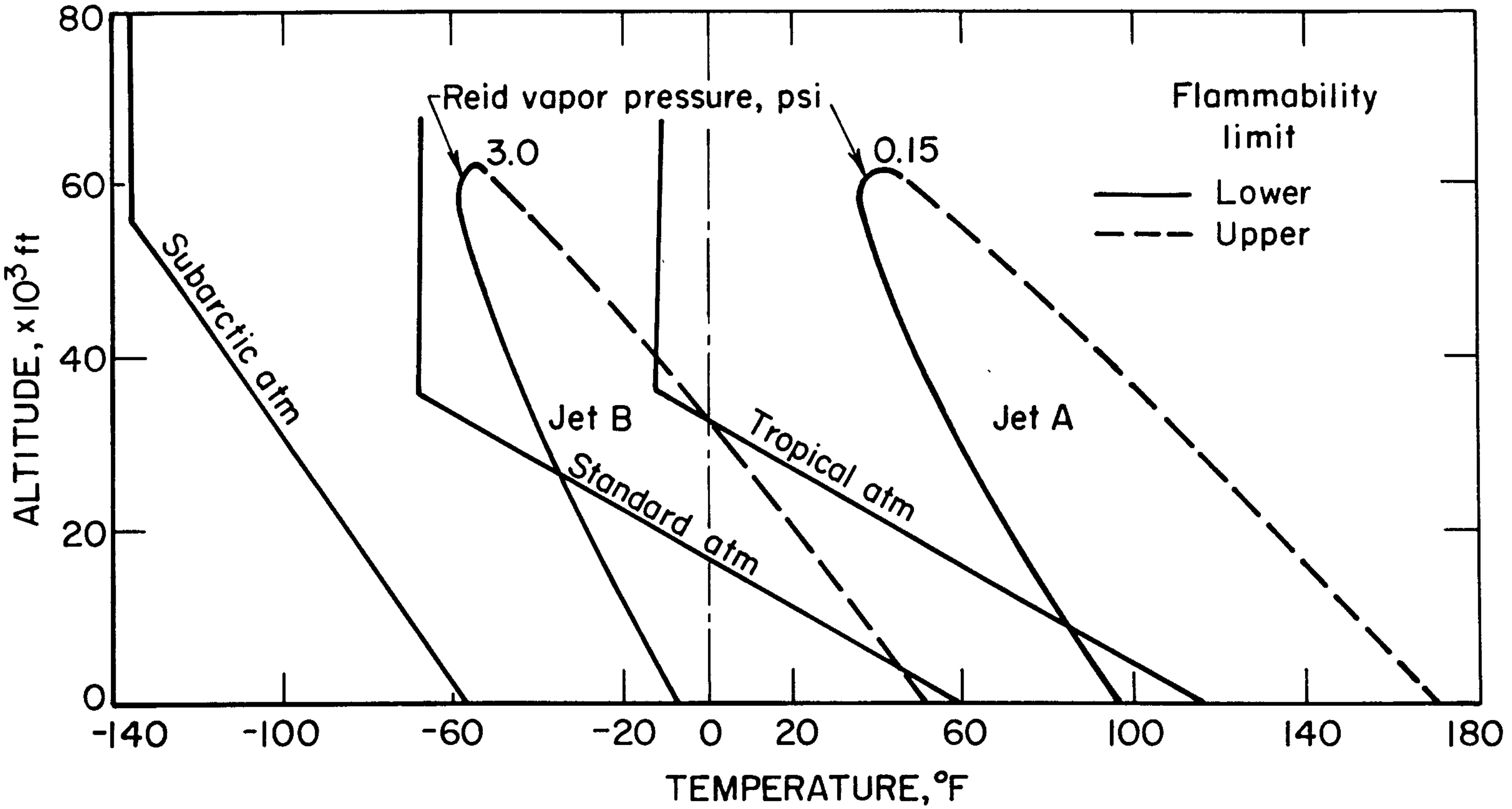


FIGURE 4. Altitude-temperature limits of flammability for Jet A and Jet B type fuels in air. (Large quenching effects at high pressure altitudes.)

flammability as a function of simulated pressure altitude for typical Jet A and Jet B type fuels. This figure has superimposed on it the altitude temperatures that could be expected for standard, tropical, and subarctic atmospheres. The lack of flame propagation observed with these fuels at pressure altitudes slightly greater than 60,000 feet can be attributed to apparatus or ignition source limitations. Nevertheless, it is important to note that the possibility of the Jet A type fuel to form flammable vapor-air mixtures is largely limited to a tropical environment and to low pressure altitudes, i.e., during the climbing stage of a flight. Also, in subarctic environments, only high Reid vapor pressure (>3.0 psi) fuels will form flammable equilibrium vapor-air mixtures. Figure 5 (Ref. 12) is representative of the small effect of reduced pressure (<1 atm) on the concentration limits of flammability for such hydrocarbon fuels, until a low pressure limit is reached. This limit is an ignitability limit and is greatly influenced by wall quenching, as discussed under the ignition section; it will vary with the ignition source energy, size and geometry of the confining chamber, and the combustible-oxidant composition. Obviously, a weak ignition source, such as an electrostatic discharge, would not be a hazard with gasoline vapor-air mixtures at the low pressures indicated by curves a and b in figure 5.

It is evident from table 4-A that only small vapor concentrations (≥ 0.6 vol %) of the aviation fuels are required to form flammable mixtures in atmospheric air. For these and other similar hydrocarbon fuels, their lower limits in air are equal to approximately 0.048 oz per cubic foot (48 mg/l) of air at 32° F and 1 atmosphere (Ref. 7). The following expressions may be used to estimate their lower (LL) and upper (UL) limits, from the stoichiometric fuel concentrations (C_{st}) for complete combustion:

$$LL_{75^\circ} = 0.55\ C_{st} \tag{14}$$

$$UL_{75^\circ} = 4.8\ C_{st} \tag{15}$$

where all concentrations are in volume percent. If such limits are known at ambient temperature, their approximate values at other temperatures can be calculated by the relations suggested by Zabetakis (Ref. 7). Here, the expressions are converted to the Fahrenheit degree scale:

$$LL_T = LL_{77^\circ}\,[1-0.000401\ (T-77^\circ)] \tag{16}$$

$$UL_T = UL_{77^\circ}\,[1+0.000401\ (T-77^\circ)] \tag{17}$$

In all cases, these expressions are limited to normal flame propagation. The upper limits of the high molecular weight paraffinic hydrocarbons and the jet aircraft fuels tend to deviate significantly from those of expression (17) at relatively low temperatures because of their great ease of autoignition. These fuels form "cool" or blue flames at lower temperatures than do the lower molecular weight paraffins. The following table illustrates the varied effect temperature can have on the upper flammability

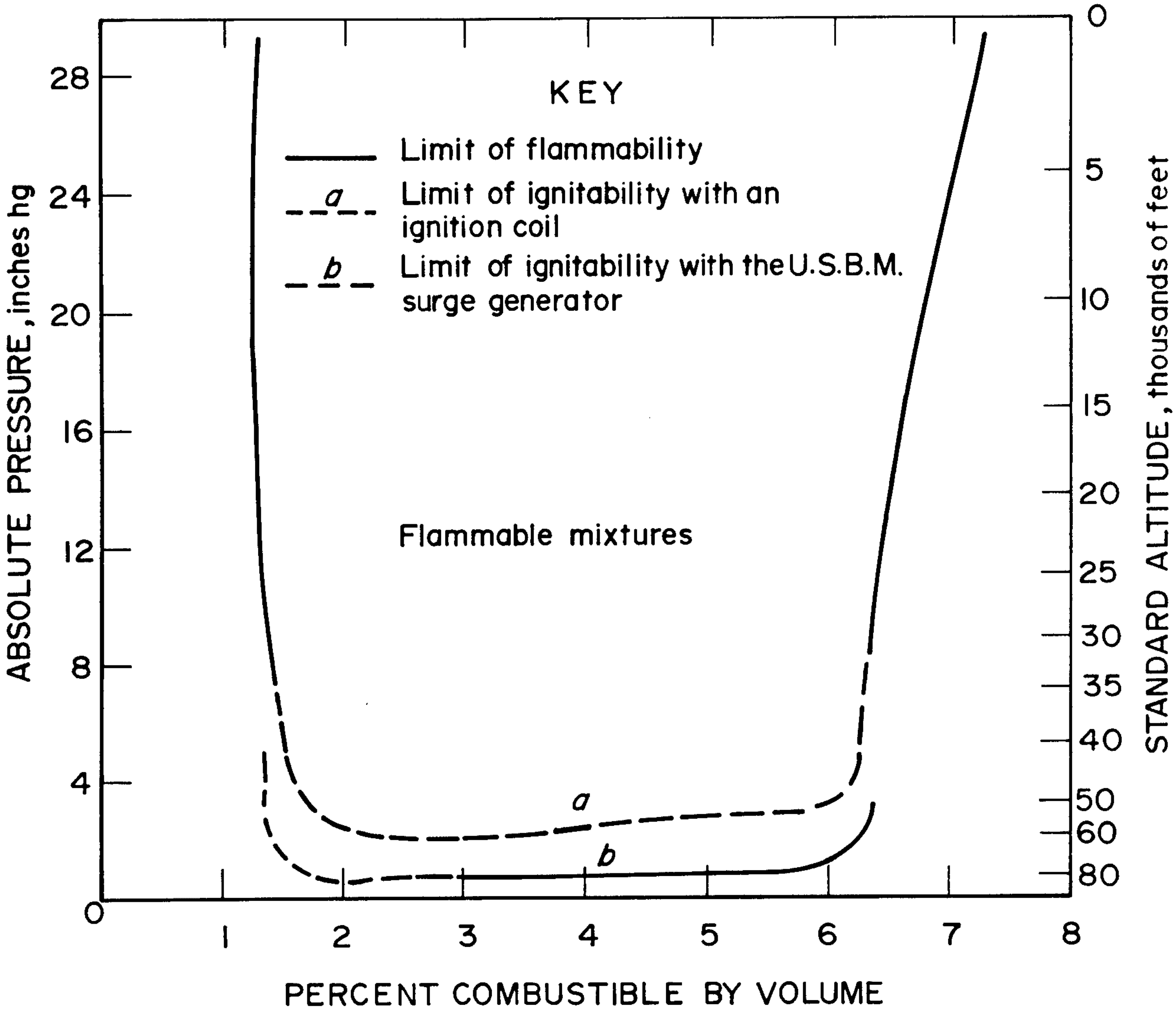


FIGURE 5. Concentrations limits of flammability for aviation gasoline (100/130) vapor-air mixtures at 80°F and various altitude pressures.

limits of several fuels.

Table 1. Effect of Initial Mixture Temperature on Upper Limits of Flammability of Various Hydrocarbon Fuel Vapor-Air Mixtures (1 Atm).[a]

Fuel	Temp. °F	Vol.%	Temp. °F	Vol.%	Temp. °F	Vol.%
Propane	75	9.5	---	---	355	12.9
n-Butane	75	8.4	250	9.9	355	10.6
n-Pentane	75	7.8	210	8.8	390	13.8
n-Hexane	75	7.4	250	9.3	390	26.6
n-Octane	140	6.1	250	20.5	355	30.5
n-Decane	185	5.6	250	15.7	355	18.4
JP-6	210	5.4	250	5.5	410	10.3

a/ Reference 17.

Similar flammability data for the aircraft lubricants and hydraulic fluids are meager. The lower limit of the MIL-L-7808 fluid (500° F) in air is approximately 0.048 oz/ft^3, but the corresponding values for the Oronite 8515 (550° F) and MIL-H-6083B (400° F) hydraulic fluids appear to be closer to 0.06 oz/ft^3 (Ref. 18). The effect of temperature on the limits of such materials can vary greatly because of the wide variation in thermal stability that is observed with these fluids.

Flammability limits of fuel blends or mixtures that behave like the paraffinic hydrocarbons can be estimated by use of Le Chatelier's additive law. For example, the lower limit of flammability of a mixture containing 25% JP-4 and 75% JP-5 at 75° F (1 atm) is

$$LL = \frac{100}{\frac{25}{LL\ (JP\text{-}4)} + \frac{75}{LL\ (JP\text{-}5)}} \qquad (18)$$

Using the data from table 4-A, the calculated lower limit of the mixture is 0.69 volume percent. This "law" has proved to be accurate for predicting the limits of many classes of organic combustible mixtures.

(3) Minimum Oxygen Values. The effect of inert gas diluents on flammability limits is important in determining inerting requirements for fuel-oxidant systems. Figures 6 and 7 (Ref. 7) describe the complete range of flammability that is possible for the aviation gasoline (115/145 grade) and JP-4 fuels, respectively, in atmospheric air (80° F) with nitrogen and carbon dioxide as the diluents. As noted, the upper limits are affected more than the lower limits, and carbon dioxide is more effective than nitrogen as an inert because of its higher heat capacity. The minimum

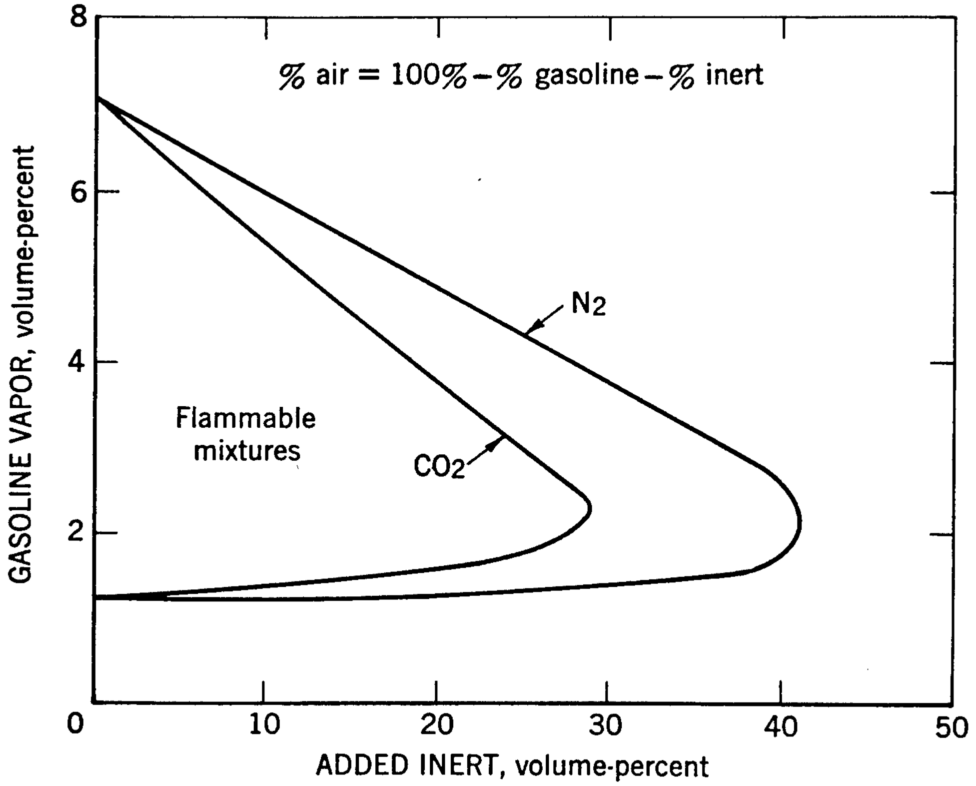


FIGURE 6. Limits of flammability of aviation gasoline (115/145) vapor-air mixtures with nitrogen and carbon dioxide inerts at 80°F and atmospheric pressure.

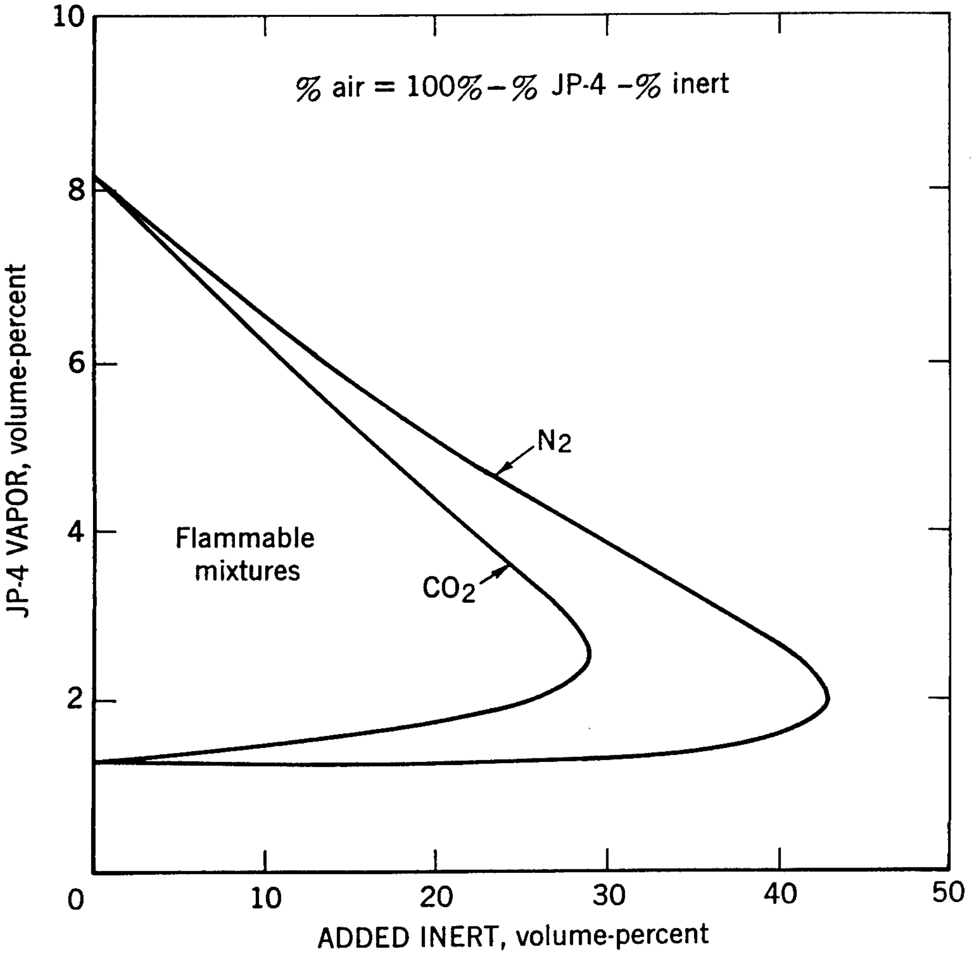


FIGURE 7. Limits of flammability of JP-4 vapor-air mixtures with nitrogen and carbon dioxide inerts at 80°F and atmospheric pressure.

oxygen (O_2) concentrations necessary for inerting these fuel systems are determined by drawing a tangent of constant oxygen content to the nose of each curve. Generally, the minimum O_2 values for such fuels are between 11 and 12 volume percent with the N_2 diluent and between 14 and 15 percent with the CO_2 diluent. A comparison of minimum O_2 values for various hydrocarbon type fuels is illustrated in the bargraph shown in Figure 8 (Ref. 12, 19). The effect of temperature should be similar to that predicted for the lower limits of flammability.

$$(\text{Min } O_2)_T = (\text{Min } O_2)_{77^\circ} [1-0.000401 (T-77^\circ)] \qquad (19)$$

Like the fuel concentration limits, the minimum O_2 values for homogeneous fuel vapor-air-diluent mixtures vary slightly with decreasing pressure. Table 2 compares the minimum O_2 values for JP-4 vapor-air-N_2 and JP-4 vapor-air CO_2 mixtures at various reduced pressures and with single or multiple spark ignition sources. The values found by Stewart and Starkman with the latter ignition source are lower because of excessive heat input into the mixture by the more severe energy source and also because their flammability criterion (any appearance of flame) was less stringent than that used by the Bureau of Mines (complete propagation).

Table 2. Minimum Oxygen Requirements for Flame Propagation of JP-4 Vapor in Air-N_2 and Air-CO_2 Mixtures (~75° F) at Various Pressures

Pressure in Hg	Pressure Altitude, ft	Min. O_2, Vol. % N_2 Inert	Min. O_2, Vol. % CO_2 Inert
		Single Spark Source[a]	
29.3	0	11.5	14.3
15.0	18,000	11.4	14.5
8.0	32,000	11.7	14.6
4.0	47,000	12.4	14.9
		Multiple Spark Source[b]	
29.3	0	9.8	12.5
13.75	20,000	10.4	13.2
5.54	40,000	11.3	14.1
2.13	60,000	13.3	15.7

a/ Reference 19.
b/ Reference 20.

When the fuel is in the form of a spray or mist, the minimum O_2 values are greater than with homogeneous fuel vapor-air mixtures. Data for the JP-4 and aviation gasoline (115/145) sprays in air-N_2 and air-CO_2 atmospheres are compared in figure 9, which also shows the effect of reduced pressure. The pronounced effect of pressure below a pressure altitude of

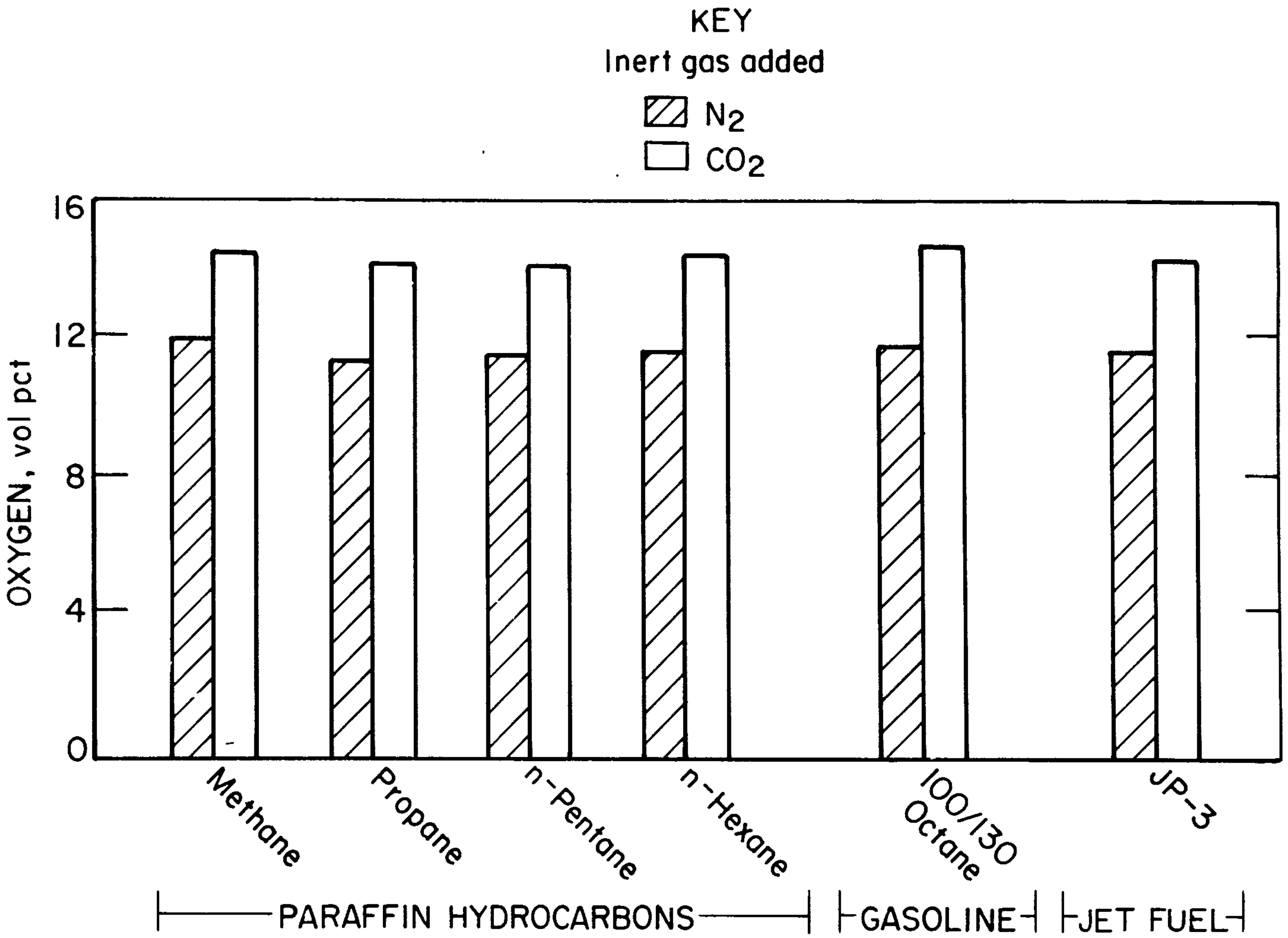


FIGURE 8. Comparison of minimum oxygen concentrations required for flame propagation of various fuel vapor-air-inert gas mixtures at 80°F and atmospheric pressure.

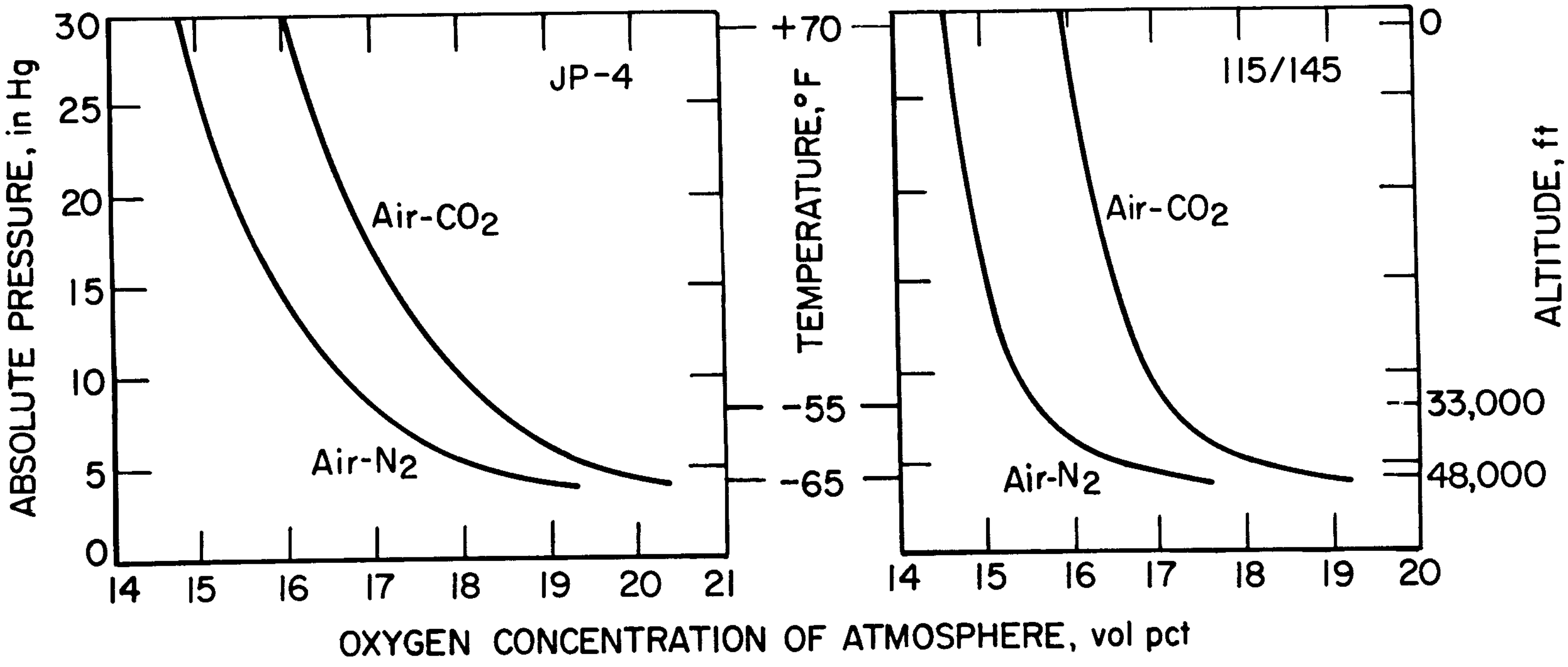


FIGURE 9. Minimum oxygen concentrations required for flame propagation of JP-4 and aviation gasoline (115/145) sprays in air-CO_2 and air-N_2 atmospheres at various pressure altitude conditions.

33,000 ft (10 in Hg) is largely attributed to wall quenching and ignition source energy effects.

Most organic combustibles in table 3-A have minimum O_2 values similar to those cited above for the hydrocarbon type fuels, although many have a wider range of flammability. Acetylene is a special case since it is capable of propagating a decomposition flame in the absence of air. Other acetylenic hydrocarbons, as well as ethylene, are capable of similar behavior if the pressure and/or temperature are sufficiently elevated. Hydrogen and carbon monoxide also merit special mention as they have a very wide flammability range and a minimum O_2 value as low as approximately 5 percent at 1 atmosphere with N_2 as the diluent. The flammability limits of all the combustibles will tend to widen with a large increase of pressure or oxygen concentration, particularly the upper concentration limits; reference 7 should be consulted for data in such environments.

(4) Flame Propagation and Burning Rates. The flame spread rate of a liquid fuel provides a measure of the flash propagation hazard that may exist when a fuel spillage occurs. This rate is maximum when the ambient temperature is higher than the flash point or when the fuel is finely dispersed to form a mist, as in an aircraft crash situation. Thus, the low volatility Jet A fuels display a low flame spread rate at 75° F with the fuel at rest. When both Jet A and Jet B fuels are heated sufficiently above their flash points, their flame spread rates attain a constant value, which can be over 10 ft/sec in quiescent air (Figure 10)(Ref. 21); the original figure from reference 21 has been modified to include rate data for Jet A fuels of two different flash points, 100° and 140° F. This maximum rate is roughly in agreement with the maximum flame speed that would be expected in spherical flame propagation with quiescent homogeneous mixtures of the vapors of these fuels and air at atmospheric pressure. In adiabatic constant volume combustion, the flame speed of a stoichiometric composition of a hydrocarbon fuel and air should be slightly greater than 7 (expansion ratio) times the burning velocity; the maximum burning velocity of the paraffinic hydrocarbons in air is about 1.5 ft/sec, indicating the flame speed should be approximately 10.5 ft/sec. Figure 11 was obtained by Andrews and Bradley (Ref. 22) and shows the relationship expected between the flame speed (S_s), burning velocity (S_u), and gas velocity (S_g) for spherical methane-air explosions (1 atm) as a function of equivalence ratio (ratio of actual fuel/air ratio to theoretical fuel/air ratio for complete combustion); this relationship is simply

$$S_s = S_u + S_g \qquad (20)$$

Under turbulent conditions or in high velocity air streams, both S_u and S_g are increased and the flame speeds are much greater than 10 ft/sec. Also, flames tend to accelerate in propagations through ducts (particularly in the vertical mode) and may develop into detonations, depending upon the length/diameter ratio, the ignition energy, and the initial pressure. Detonations of the hydrocarbon type fuels are more likely to occur in an oxygen atmosphere, where the propagation rates will ordinarily exceed 5000 ft/sec.

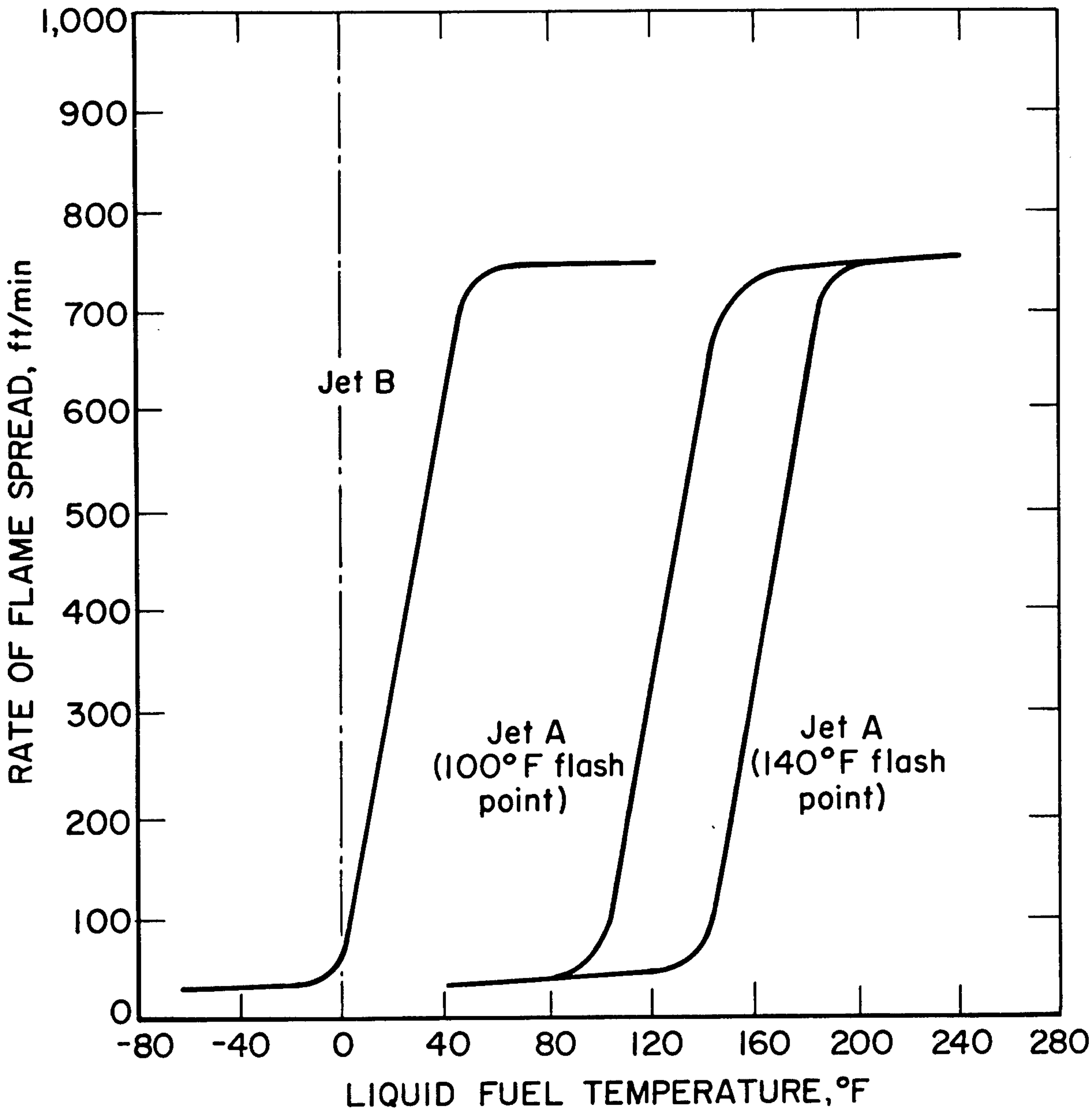


FIGURE 10. Rate of flame spread vs liquid fuel temperature for Jet A and Jet B type fuels in air at atmospheric pressure.

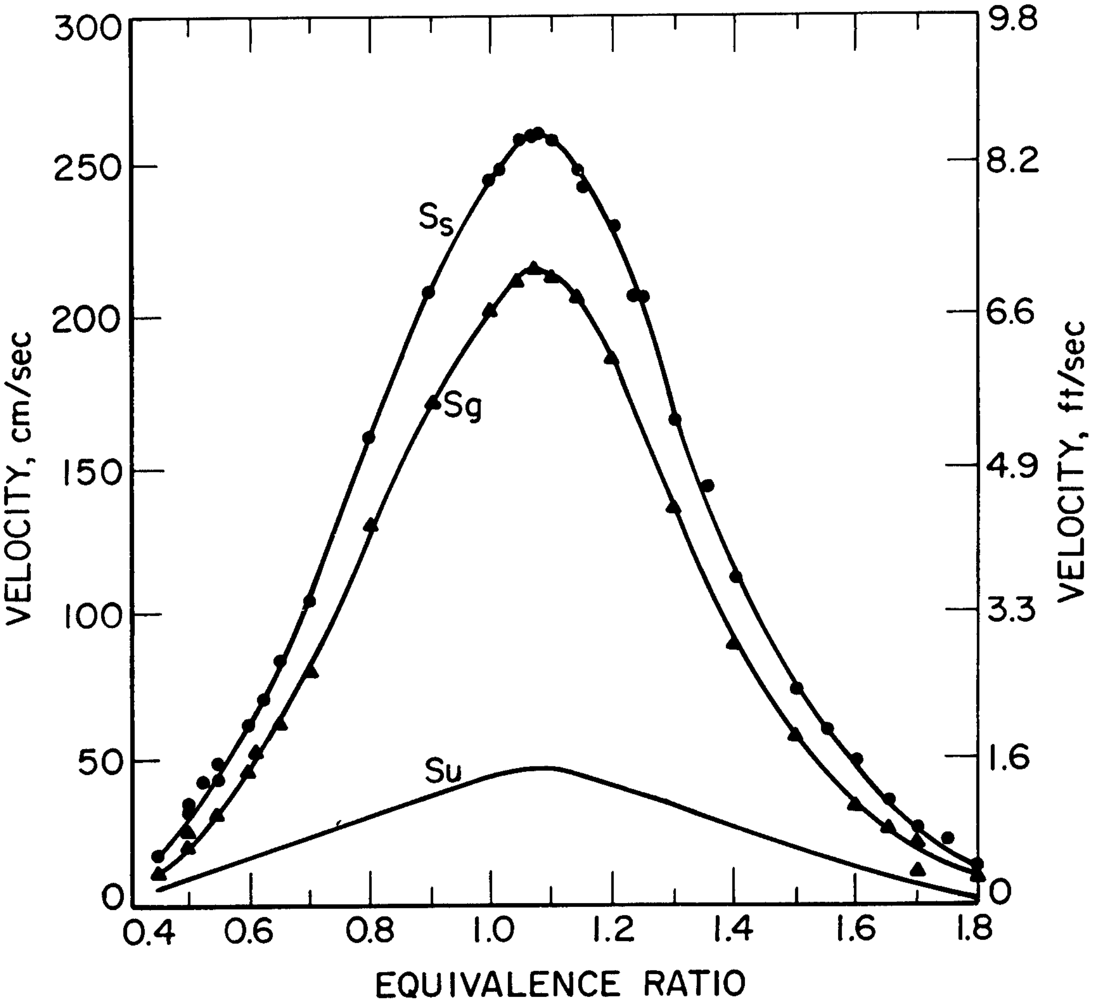


FIGURE 11. Flame speed (S_s), gas velocity (S_g), and burning velocity (S_u) for different equivalence ratios of methane-air at atmospheric pressure and 298°K (77°F).

The heat release from a pool fire is governed largely by the heat of combustion and the burning rate of the bulk fuel, which depends upon the pool diameter, wind currents, and the thermal radiation fed back to the pool. The linear burning rates (regression rates) of various classes of combustibles are shown in figure 12 (Ref. 23) as a function of pool diameter. For an infinite pool diameter, the approximate burning rate of most of these combustibles can be predicted by the following expression suggested by Burgess and Zabetakis (Ref. 23).

$$V_{\infty}\ (\text{in/min}) = 0.003 \left(\frac{\text{Net heat of combustion}}{\text{Sensible heat of vaporization}}\right) \qquad (21)$$

For aircraft jet fuels, the calculated value is about 0.35 in/min, as compared to reported values of 0.28 to 0.35 in/min for gasoline pool fires 10 ft in diameter. The linear rate can be used to calculate the corresponding mass burning rate by considering the liquid fuel density. Generally, more consistent results are obtained in the above correlation if the empirical expression is based upon mass burning rates instead of linear rates.

B. Flammable Solids

(1) Flame Spread Rate. The flame spread rates of combustible solids are markedly lower than those of combustible liquids, excluding fire resistant fluids. Such factors as the loading density, orientation of burning, and the size of fire can have a great influence on these rates. For example, the flame spread rate of cotton sheeting in air (1 atm) was observed to be about 40 times greater with upward burning than with downward burning for specimens in a vertical position (Ref. 24). Thus, the values listed in table 8-A for downward burning should only be used to indicate the relative flammability of the materials.

Generally, the flame spread rates of combustible solids increase with the total pressure and the oxygen concentration of the atmosphere. Figure 13 (Ref. 24) shows that the rates for such materials as paper drapes, natural rubber sheeting, cotton sheeting, and a fire retardant treated cotton sheeting correlate well with the oxygen partial pressure; these data were obtained with 45° angle burning (upward) in various O_2-N_2 ($\geq 21\%\ O_2$) atmospheres. Other materials such as Plexiglas sheet and white pine wood strips have flame spread rates that are about 1/10 of those observed for paper in atmospheric air. Also, such materials as Nomex, blanket wool, and polyvinyl chloride sheet do not appear to sustain flame in ambient air under the same burning conditions. On the other hand, it must be remembered that in a full-scale fire, all combustibles - including fire resistant materials - will usually be consumed if they are exposed for a sufficient time to the flame temperatures (e.g. >2000° F) that can be encountered.

As a guideline, the burning rate or mass consumption rate is about an order of magnitude greater with upward burning than with downward burning of a material such as cotton sheeting. Also, the flame spread rates and burning rates are normally higher for finely divided materials and for

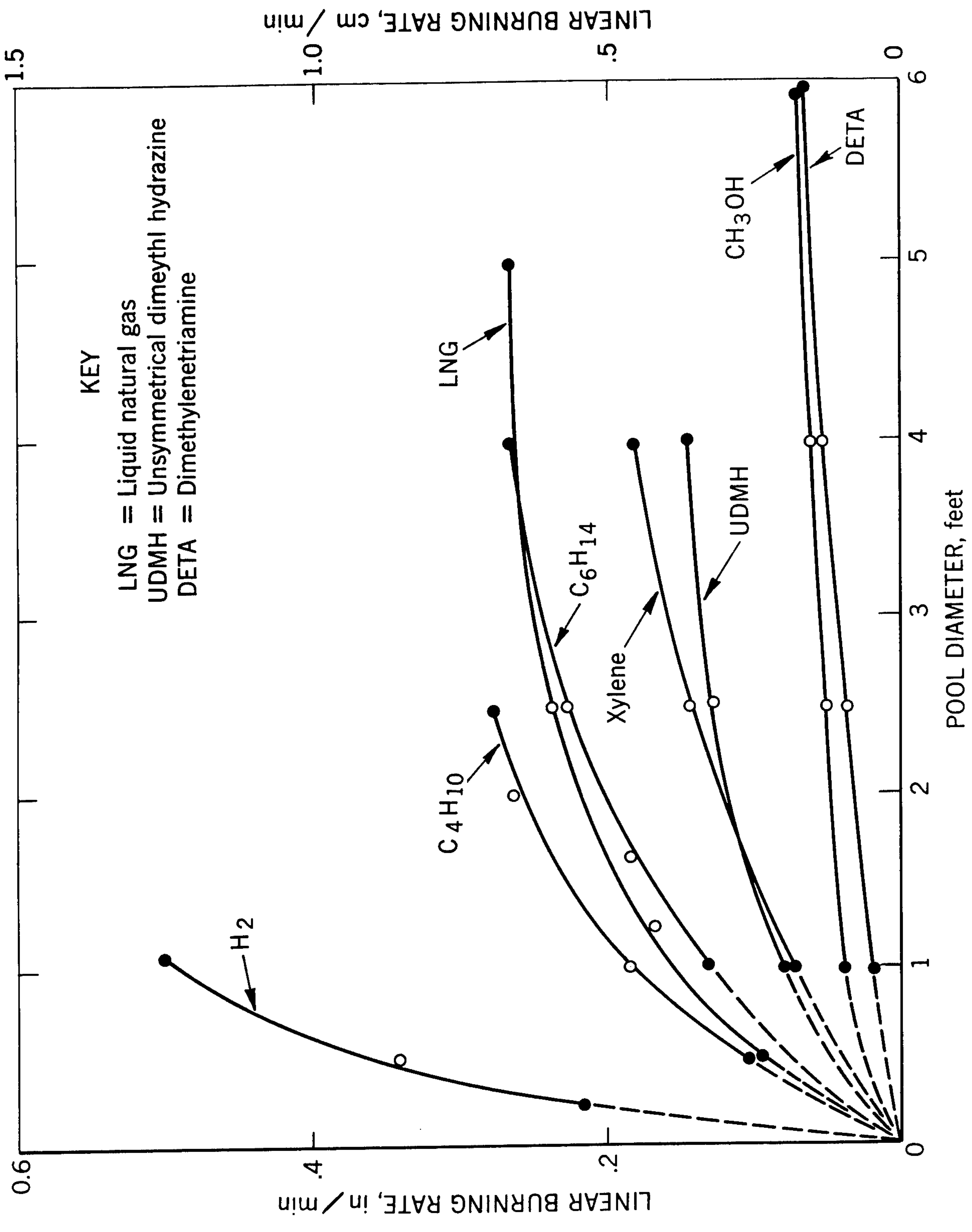


FIGURE 12. Linear burning rate of combustible liquids as a function of pool diameter.

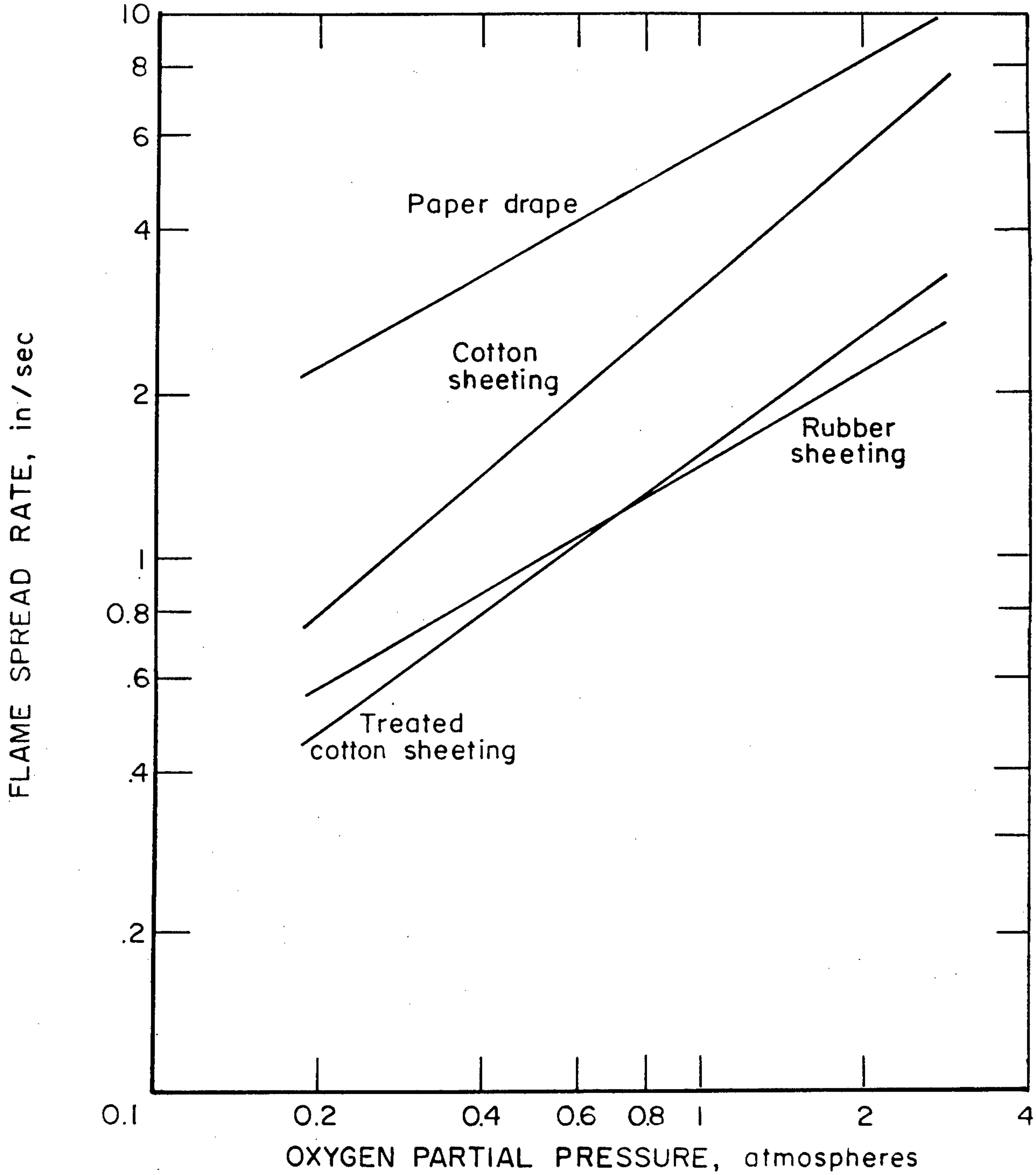


FIGURE 13. Flame spread rates of paper, cotton, and rubber combustibles in oxygen-nitrogen mixtures (≥21% O_2) at 0.2 to 6 atmospheres total pressure (45° angle burning).

conditions of increased air velocity or turbulence.

IGNITABILITY CHARACTERISTICS

A. Flammable Fluids

If a flammable vapor-air mixture is formed, ignition can occur only if some critical volume of the mixture is sufficiently heated to produce an exothermic reaction that propagates flame. Such reactions can be initiated by electrical sparks or arcs, heated surfaces, hot gases (including flames), self-heating, and by other less common modes. In the case of a highly concentrated energy source, such as an electrical spark, the time scale of heating is extremely short (e.g. microseconds) and ignition is determined by the amount of energy supplied. In comparison, temperature is the critical factor where the source of heating is more spatially distributed, as in autoignition, and the time scale is much greater (e.g. minutes). Both temperature and rate of heating are important for the intermediate cases. An excellent discussion on the subject of ignition is given in the review of aircraft combustible hazards by Van Dolah and co-workers (Ref. 6).

(1) Electrical Sparks and Arcs. Electrical ignitions are generally classified as high voltage or electrostatic spark type and low voltage or break spark type. The generation of electrostatic charges occurs by a process of triboelectrification and is encountered when two unlike materials or surfaces are rubbed together. Some examples of this phenomenon are found during the pumping of liquid fuels, conveying of fine solids through air ducts, and the use of plastic materials as covers, liners, or containers. The energy of electrostatic discharge is given by

$$E = 1/2\ C\ V^2 \qquad (22)$$

where E is the energy in joules, C is the material capacitance in farads, and V is the potential difference in volts. The capacitance of an object depends upon its physical dimensions and its proximity to nearby objects. Typical capacitances are

Man	-	100 to 300 x 10^{-12} farads
Automobile	-	500 x 10^{-12} farads
Tank truck	-	1000 x 10^{-12} farads

Accordingly, man with a capacitance of 300 x 10^{-12} farads may produce a static discharge of 1.5 x 10^{-2} joules (15 mj) if he is charged to 10,000 volts. Although the charge accumulated by highly conductive materials can be dissipated by bonding and grounding, other measures are necessary for the low conductive materials; these include increased air humidification, use of anti-static additives, and the control of flow conditions. Liquids having resistivities higher than 10^{10} ohm-centimeter, which includes most petroleum products, are generally considered capable of accumulating a charge (Ref. 8).

The electrostatic spark energy required for ignition of a flammable atmosphere is determined at an optimum length of spark gap. The requisite ignition energy is much greater with a break spark energy source, such as that produced by opening an electrical switch or by the separation of current carrying conductors. Since the energy associated with break sparks or arcs depends upon the inductance and current, it is more meaningful to define the maximum safe current for ignitions with this type of energy source. Nevertheless, for very fine wires and rapid separations, the ignition energy requirements with break sparks can be nearly of the order of those associated with electrostatic sparks at short gap lengths. Data using the latter energy source with flanged electrodes are presented herein.

(2) Minimum Spark Ignition Energy. Figure 14 (Ref. 6) shows that the spark ignition energy varies with the fuel-air ratio of the mixture and tends to be minimum near the stoichiometric mixture ratio for complete combustion. Also, the spark ignition energies tend to increase sharply at mixture ratios approximating the limits of flammability of the system. For the paraffinic hydrocarbons, their minimum ignition energy (MIE) is approximately 0.25 mj at atmospheric pressure and normal ambient temperature (Figure 15) (Ref. 6): aircraft fuels would be expected to have a comparable MIE value. As noted in figure 15, the MIE tends to occur at fuel concentrations increasingly greater than stoichiometric with increasing molecular weight, largely because of differences in fuel diffusivities. The MIE values are noticeably lower for such fuels as ethylene (0.07 mj), acetylene (0.017 mj) and hydrogen (0.017 mj). On the other hand, they can be of the order of several millijoules or more for the halogenated hydrocarbons, depending upon their fire resistance properties.

In a flight environment, the minimum ignition energies of the aircraft fuel vapor-air mixtures will be greater than in normal ambient air at sea level. The MIE values will vary approximately as an inverse square function of pressure. They also will increase with decreasing temperature, roughly a factor of 2 for a 150° (°F) temperature change (Ref. 25). Figure 16 (Ref. 19) illustrates the effect of mixture pressure as well as oxygen concentration on the MIE of propane-oxygen-nitrogen mixtures at normal ambient temperature. In an O_2 atmosphere, the MIE's of hydrocarbon fuels are reduced by more than an order of magnitude, compared to the values in air. The corresponding values at the minimum O_2 concentrations required for flame propagation would tend to be maximum, although such data are meager.

In assessing the ignitability hazard, the minimum ignition energy and the quenching distance can be useful. The latter quantity is also important in the design of explosion proof equipment. Excluding the higher energy fuels such as hydrogen and the acetylenic hydrocarbons, the minimum ignition quenching distance for most conventional hydrocarbon fuel vapor-air mixtures at atmospheric pressure is between 0.05 and 0.1 inch. A composite of ignition energy and quenching distance data (flat plates) for various fuels that were investigated by the Bureau in various O_2-N_2 atmospheres is

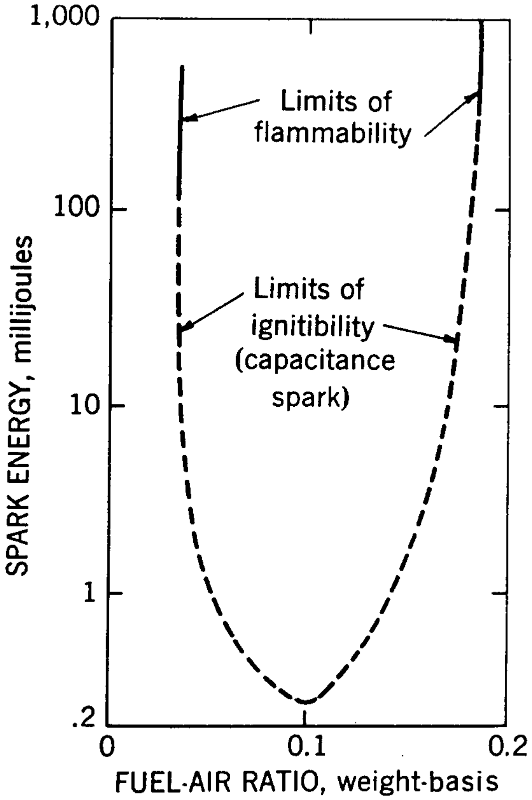


FIGURE 14. Spark ignition energy vs fuel-air ratio for n-butane-air mixtures at 1 atmosphere and 78°F.

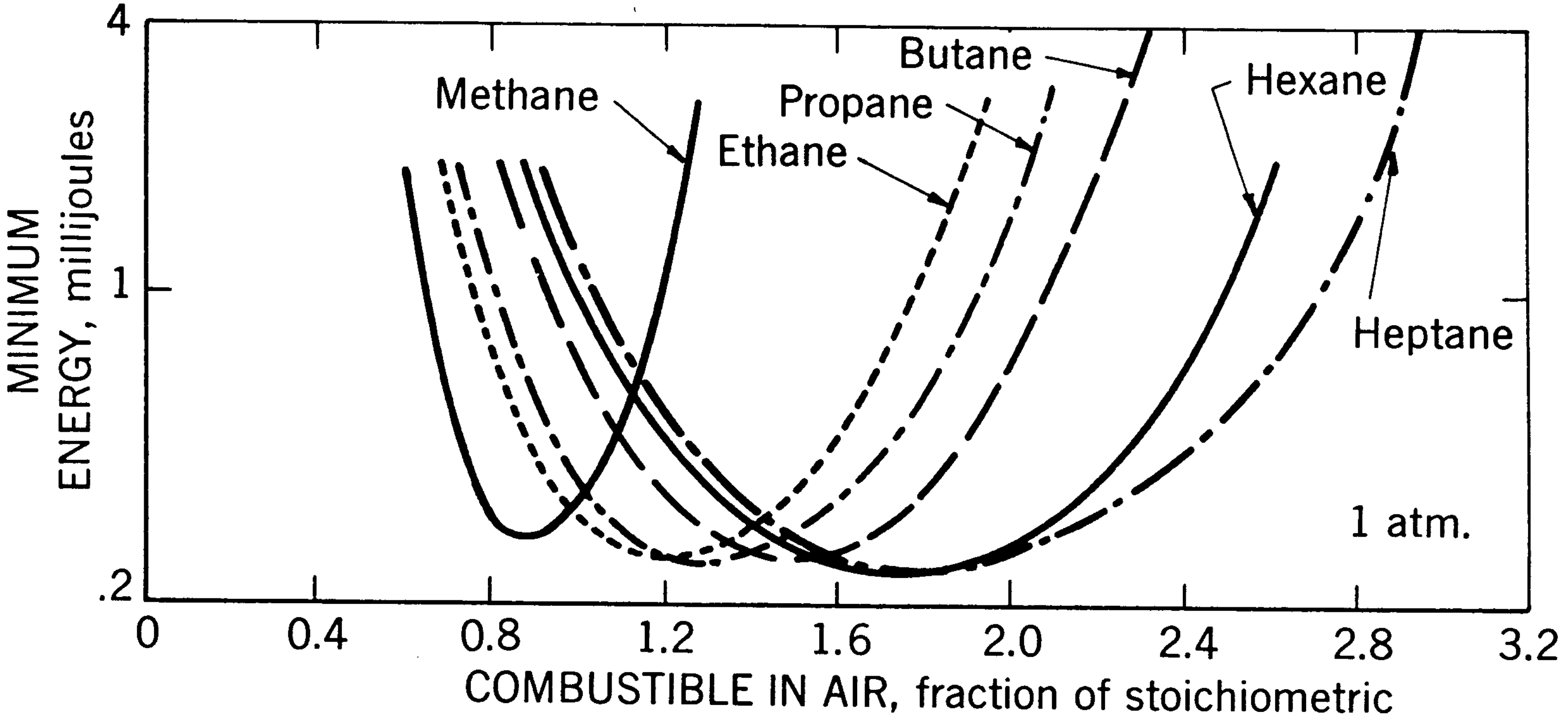


FIGURE 15. Spark ignition energy vs mixture composition for mixtures of various straight chain saturated hydrocarbons with air at 1 atmosphere.

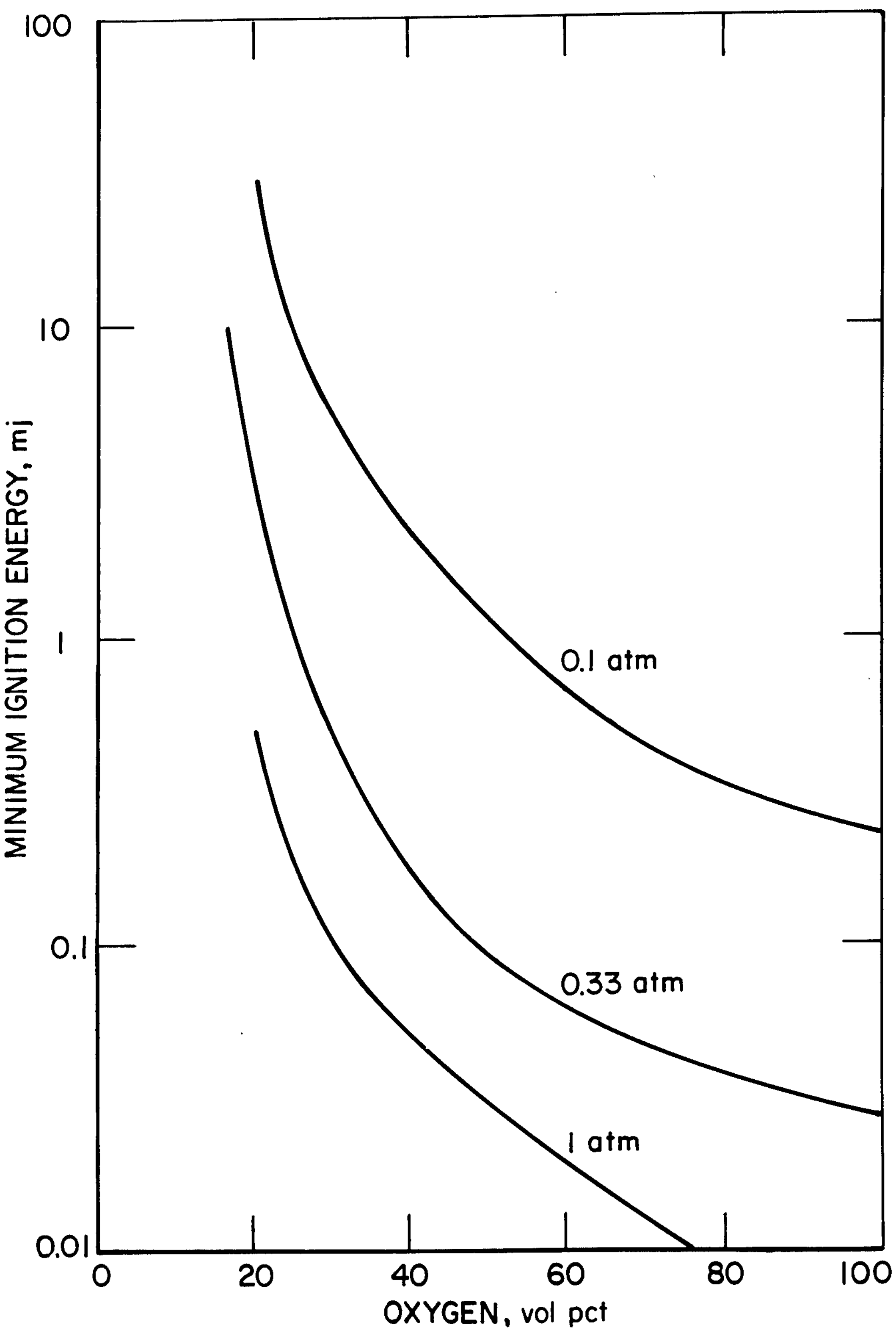


FIGURE 16. Minimum ignition energy of propane-oxygen-nitrogen mixtures as a function of oxygen concentration and mixture pressure.

shown in figure 17 (Ref. 6); these data were obtained prior to 1951. It is of particular interest that the MIE was less than 10 millijoules for all the combustible-oxidant mixtures examined. Thus, the flammable mixtures of most fuels should be capable of being ignited at atmospheric pressure by the common electrostatic discharges discussed in the previous subsection (1).

The ignition energy requirements are greater for <u>fuel sprays</u> than for homogeneous vapor-air mixtures, since a fraction of the available energy must be used in vaporizing a discrete amount of fuel droplets. With increasing temperature, the amount of fuel vapor increases and, therefore, the ignition energy requirements should decrease. The variation of minimum ignition energy with temperature is indicated in figure 18 (Ref. 26) for the sprays ($\leq 10\mu$) of three jet aircraft fuels. The following expressions define the minimum ignition energies (E, mj) as a function of temperature (T, °F):

$$E = 23.2\ e^{-.042T} \quad ; \quad \text{JP-4} \qquad (23)$$

$$E = 139\ e^{-.034T} \quad ; \quad \text{JP-5} \qquad (24)$$

$$E = 111\ e^{-.037T} \quad ; \quad \text{JP-8} \qquad (25)$$

Comparable ignition energies would be expected with emulsified or gelled compositions of these fuels if they were similarly atomized.

(3) <u>Minimum Autoignition Temperatures</u>. The minimum temperature at which a quiescent flammable gaseous mixture will autoignite when uniformily heated in a vessel or fuel tank is commonly referred to as the <u>minimum AIT</u> or <u>SIT</u>. These temperatures are highly apparatus dependent. They vary with such factors as the vessel size and shape, fuel contact time prior to ignition (ignition delay), fuel and oxygen concentration, mixture pressure, and the fuel injection pressure. A vessel of at least 200 cc (12.20 in^3) volume is necessary to obtain the minimum AIT in air (1 atm). Here, the time scale of heating can extend over a wide range but is ordinarily between 1 and 5 minutes at the conditions which yield the minimum AIT value for a fuel in atmospheric air under static conditions. Autoignitions under flow conditions are associated with much shorter heating times but are also of interest in evaluating aircraft fuel hazards.

(a) <u>Static Conditions</u>. The minimum AIT's of organic fuels in air vary noticeably with chemical structure and do not correlate with their corresponding minimum ignition energy values. As noted in table 3-A, the AIT's of the paraffinic hydrocarbons in air (1 atm) are between 400 and 1000° F and decrease with increasing carbon chain length; here, appearance of flame was the criterion of ignition. Also, they are higher for branched chain hydrocarbons (e.g. iso-octane) than for straight chain hydrocarbons (e.g. n-octane). The AIT's of both straight and branched chain paraffins can be correlated with their "<u>average carbon chain length</u>" (Ref. 7). Furthermore, this correlation tends to follow that indicated by the <u>critical compression ratio</u> of the fuels, which provides a measure of their "knock"

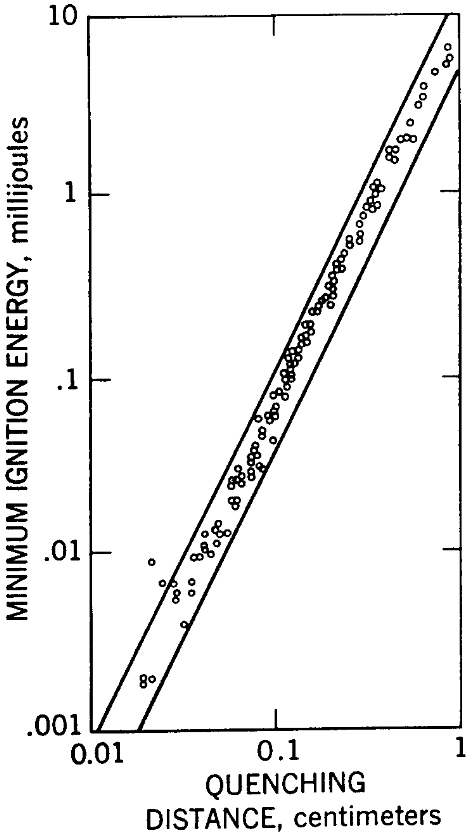


FIGURE 17. Relationship between minimum ignition energy and optimum electrode separation (quenching distance). All mixtures studied, percent O_2 from 21 to 100, pressure from 0.1 to 2.0 atm.

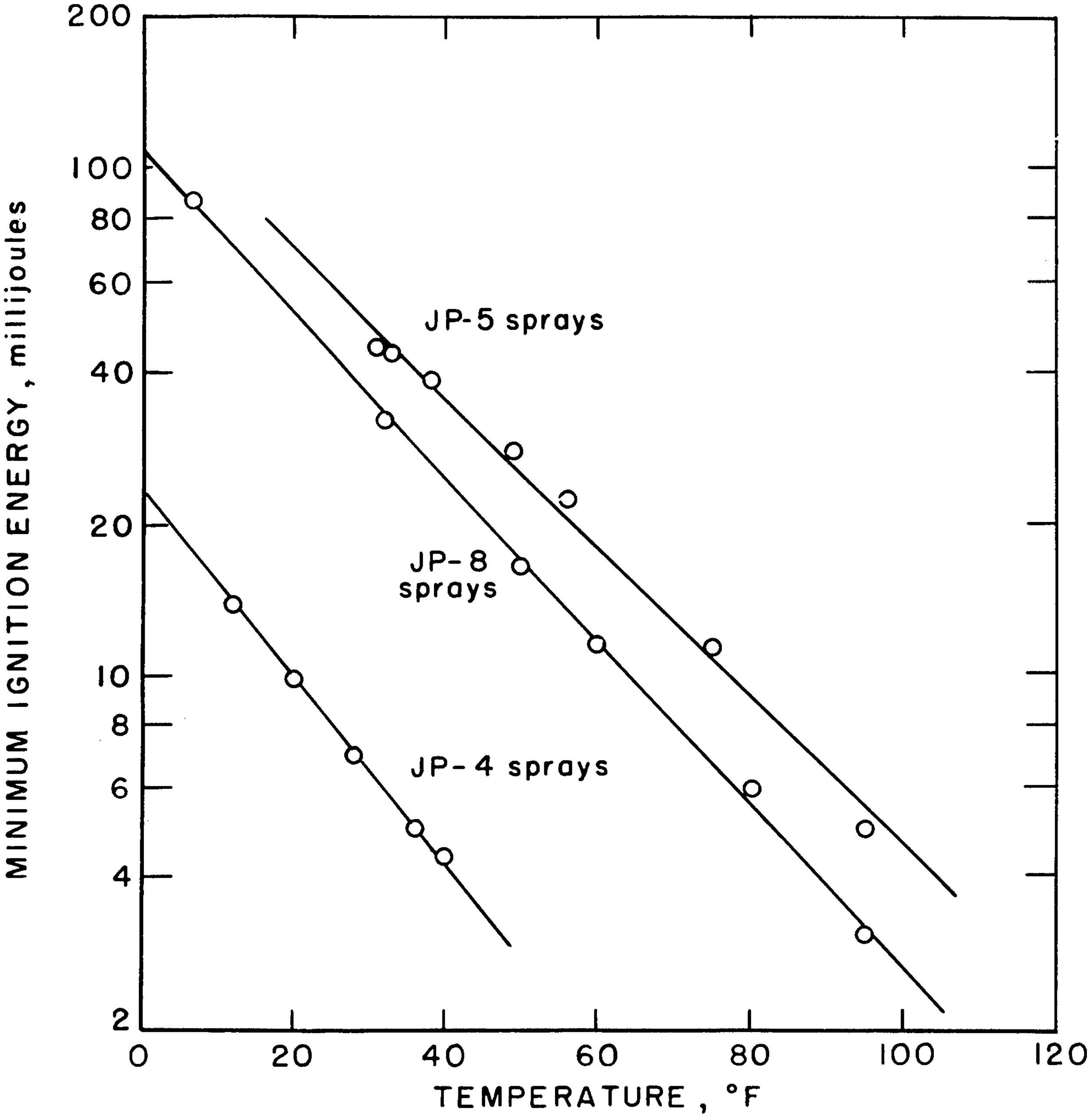


FIGURE 18. Minimum spark ignition energy of the sprays of three jet fuels at various temperatures.

tendency. Thus, fuels of low molecular weight or branched chain paraffins tend to have high critical compression ratios. Note in Tables 3-A and 4-A that AIT's and flash points are not related.

All the jet aircraft fuels have minimum AIT's of less than 500° F in air (Table 4-A). Diesel fuels have AIT's comparable to that of the jet fuels, whereas, those for Avgas (100/130 or 115/145) are in the 800° to 900° F range. As noted earlier, the AIT's vary with the fuel contact time, which tends to be maximum at the lowest temperature at which ignition is possible. The semi-log plot in figure 19 (Ref. 27) shows the expected variation of ignition delay (fuel contact time) with reciprocal temperature for the autoignitions of JP-4, JP-6, JP-150, and kerosene fuels in quiescent air at 1 and 1/2 atmospheres. The delays are sensitive to temperature but the plots at 1 atmosphere are not linear over the entire range of temperature, except for JP-4, because of an apparent change in the reaction mechanism; this trend is typical of many hydrocarbons. For JP-4, the following expression can be used to estimate the variation of ignition delay (τ) with temperature (T) at atmospheric pressure:

$$\ell n\ \tau = 34{,}000/T - 32.2 \qquad (26)$$

where τ is in seconds and T is in °R.

The minimum AIT's are higher at reduced pressures and at reduced oxygen concentrations. In figure 19, the minimum AIT's are about twice as high (Fahrenheit scale) at 1/2 atmosphere than at 1 atmosphere, although this large effect was attributed primarily to the small size of the reaction vessel (12.20 in^3). Generally, pressure effect is not great over a moderate change of pressures or oxygen concentrations, providing the vessel size is sufficiently large to minimize wall effects. Figure 20 (Ref. 27) shows that the AIT's in various O_2-N_2 atmospheres at reduced and elevated pressures ($\leq$5 atms) can be correlated with the oxygen partial pressure. These data were obtained in vessels of at least 120 in^3 capacity. At reduced pressures, the AIT's would be less than indicated if pressure rise instead of appearance of flame were the ignition criterion.

Most hydraulic fluids, engine oils, and lubricants have higher AIT's than the jet aircraft fuels (Table 5-A); mineral oil fluids are an exception. As with the jet fuels, the temperature dependence of ignition delay is much lower at the higher temperatures (Figure 21) (Ref. 18). Although no effect of fluid injection pressure is apparent in figure 21, the AIT's are normally lower when the injection pressure is increased from 0 to 1000 psi. The effects of reduced mixture pressure and increased oxygen concentration on minimum AIT are shown in figures 22 and 23 (Ref. 28) for seven aircraft hydraulic fluids. It is evident that all fluids do not display the same trend. As noted, the AIT of the MIL-H-5606 mineral oil is by far the most sensitive to varying mixture pressure but is insensitive to changes in oxygen concentration from 21 to 100 percent. In comparison, the chlorinated silicone base fluid (MLO-53-446) shows no effect of oxygen concentration or mixture pressure on its AIT, whereas the other synthetic fire resistant fluids display a noticeable decrease in the ignition

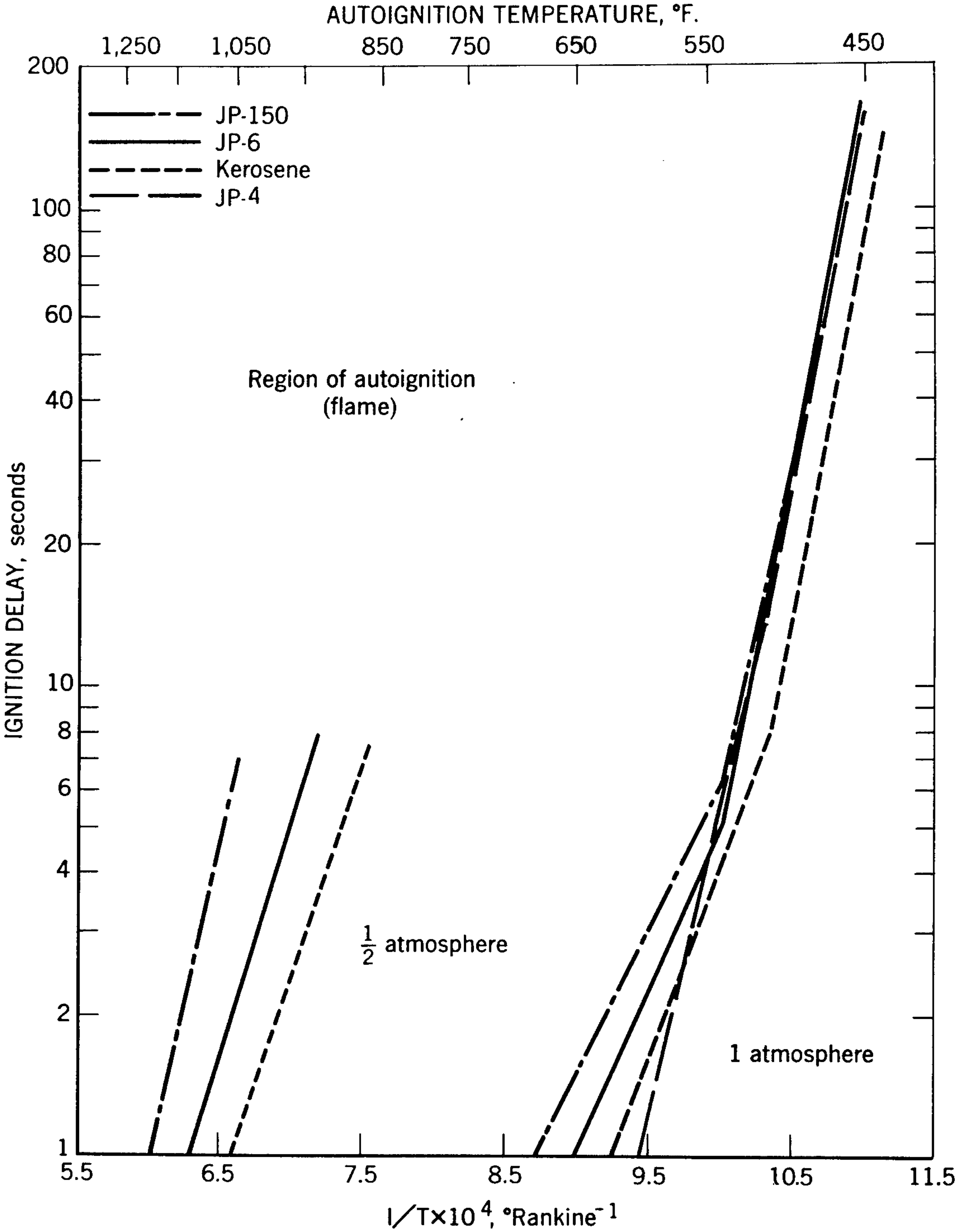


FIGURE 19. Variation of ignition delay with reciprocal temperature in autoignition of four aircraft fuels in stagnant air at 1/2 and 1 atmosphere.

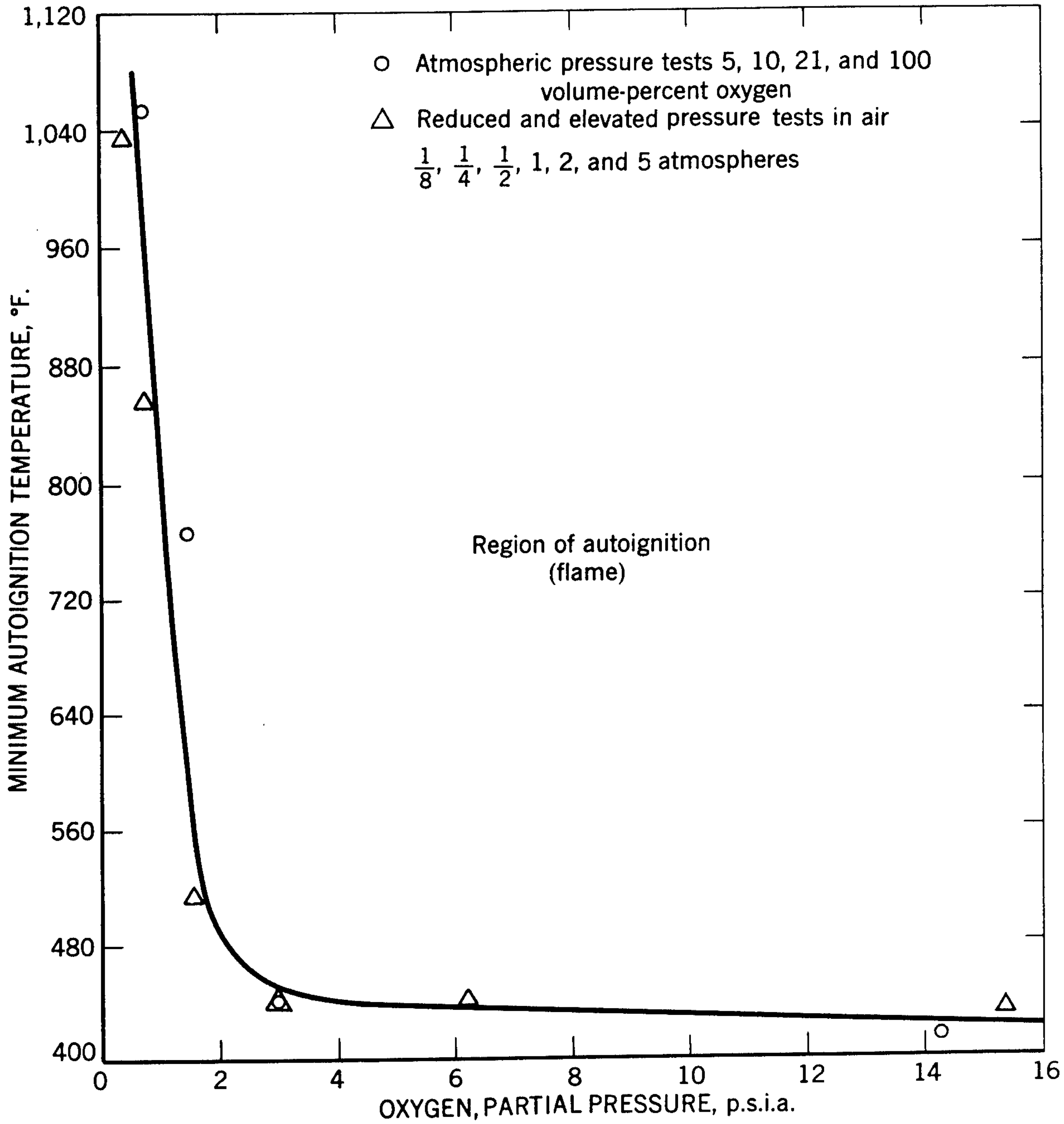


FIGURE 20. Effect of oxygen partial pressure on the minimum auto-ignition temperature of JP-6 fuel vapor-oxygen-nitrogen mixtures at various total pressures under static conditions.

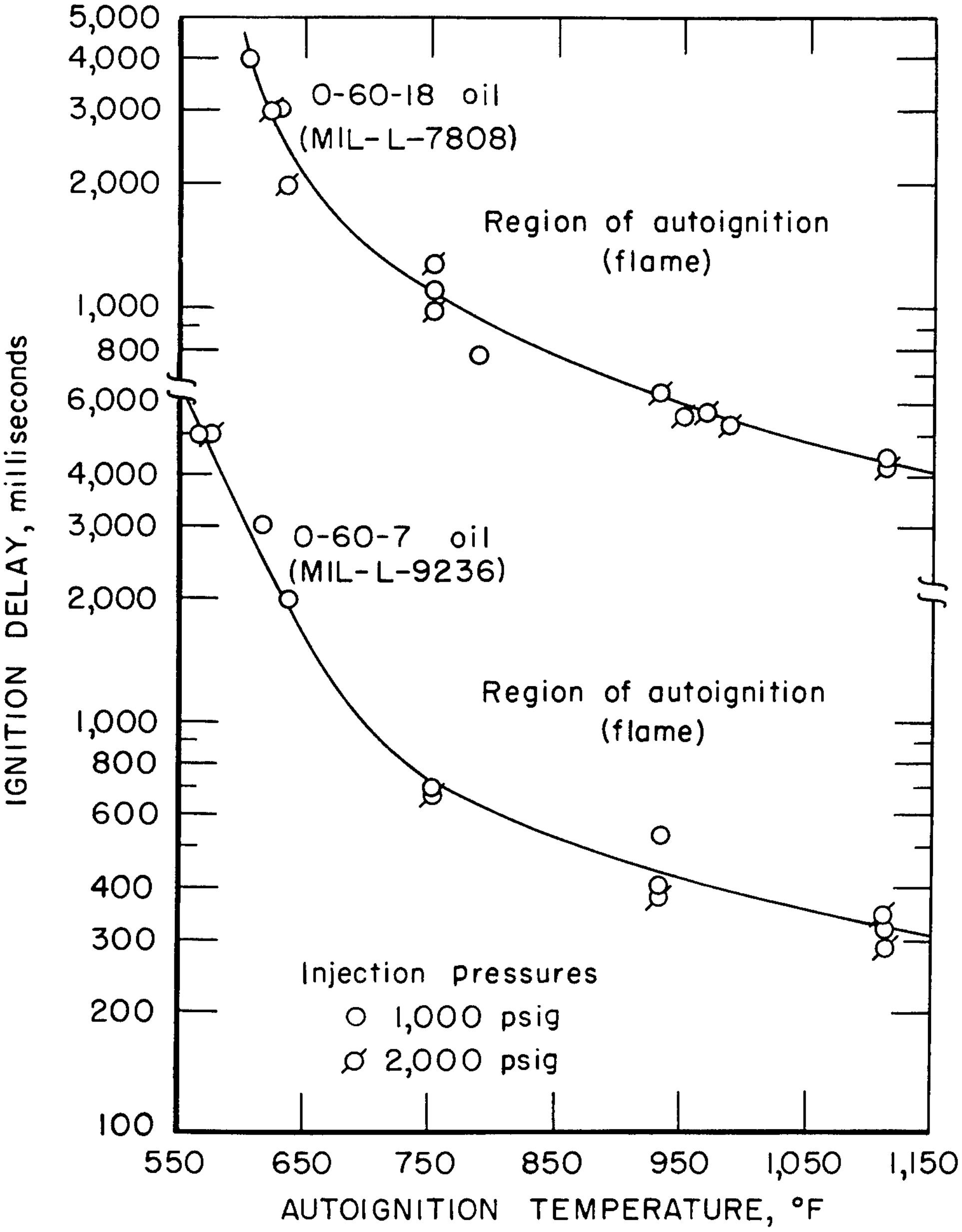


FIGURE 21. Variation of ignition delay with temperature in autoignition of MIL-L-7808 and MIL-L-9236 engine oils in air (1 atm) at 1000 and 2000 psig injection pressures.

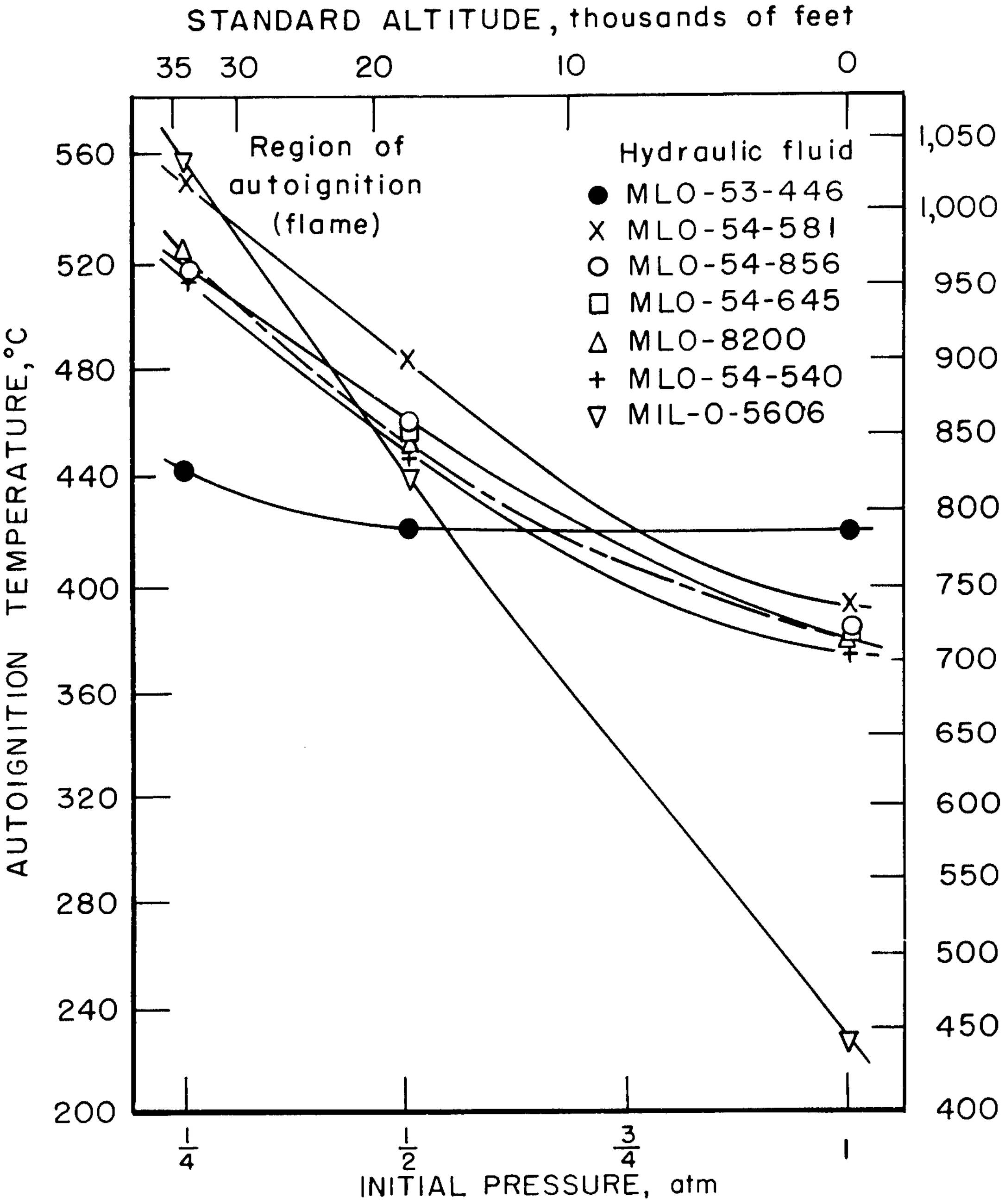


FIGURE 22. Minimum autoignition temperatures of seven hydraulic fluids in air at various initial pressures.

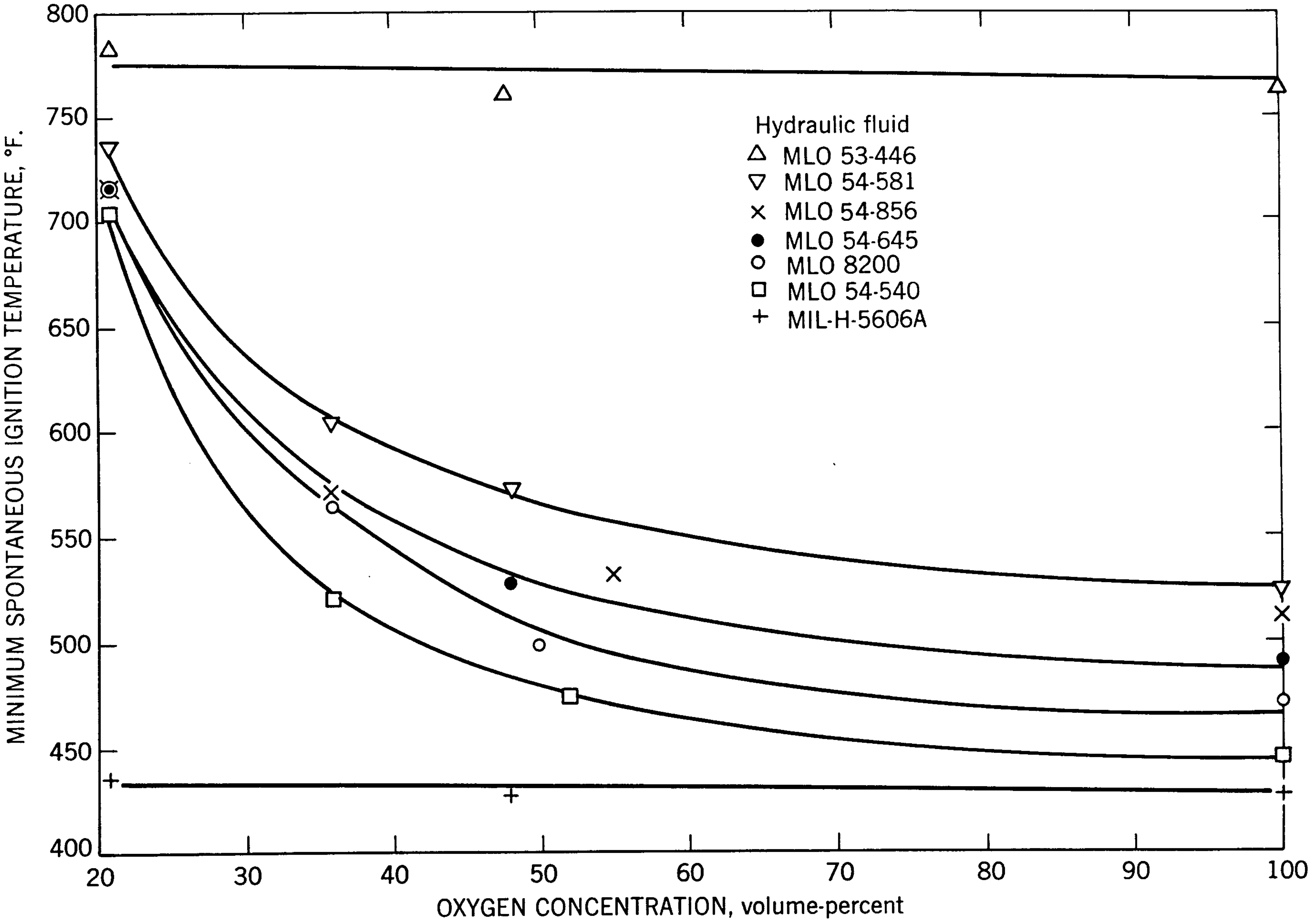


FIGURE 23. Effect of oxygen concentration on the minimum autoignition temperature of seven hydraulic fluids in oxygen-nitrogen mixtures (1 atm) under static conditions.

hazard with decreased pressure or oxygen content.

Where air compressors or other high pressure equipment are used, minimum AIT's of fluids may be needed at pressure of 100 atmospheres or higher. Such data are presented in figure 24 (Ref. 7) for various phosphate ester, mineral oil, and water-glycol lubricants. The AIT's of all the fluids decreased with increased pressure and tended to level off at about 100 atmospheres or more, depending upon the fluid. The extension of such data to 1000 atmospheres (Figure 25) (Ref. 18) for three fluids, including the MIL-L-7808 sebacate ester oil, confirmed the earlier observed trends. In both series of tests, the Houghto-Safe 1055 phosphate ester displayed the highest resistance to autoignition. A review of the ignition and flammability properties of over 90 lubricants and hydraulic fluids is given in reference 18.

(b) Flow Conditions. If a fuel leakage occurs in the engine compartment of an aircraft, the AIT of the fuel in flowing air is of greater interest than that observed under static conditions. The ignition temperature will be largely determined by the air velocity, ambient pressure, and the properties of the fuel, assuming an optimum fuel vapor-air mixture ratio. The air velocity is of particular interest since it will determine the fuel contact time in the heated environment. Figure 26 (Ref. 27) shows the variation of ignition delay with the reciprocal of temperature on a semi-log plot for ignitions of JP-6 in heated flowing air at various pressures. The temperature dependence of ignition delay increases with increased pressure, similar to that observed with other fuels. Furthermore, it is seen that AIT data obtained under flow conditions can be extrapolated to predict autoignition temperatures of the same fuel under static conditions. Note that at 2 atmospheres pressure, the delays or fuel contact time required for ignition decreased from approximately 10 seconds to 0.06 second when the temperature was increased from 500° to 1000° F. This 160 fold decrease in ignition delay for such a variation of temperature appears to be applicable to other similar fuels, such as JP-4, according to other flow ignition data (Ref. 12). By use of such AIT data, one can obtain an estimate of the air velocity required to prevent possible ignition of the fuel vapors when they are flowing in uniformily heated ducts of various lengths.

(4) Localized Hot Surface and Hot Gas Ignitions. In many instances, ignitions may occur where the fuel vapor-air mixture is exposed to a small heated surface or a jet of hot gases and, therefore, the mixture is not uniformily heated. Thus, the ignition temperature will depend greatly upon the size or surface area of the heat source. In any event, the ignition temperature of a flammable mixture with such heat sources will be necessarily higher than that possible in normal vessel autoignitions.

Available data obtained with heated metal targets indicate that the ignition temperature of aircraft fuels or fluids will increase with increasing air velocity and depend significantly upon such factors as the air flow temperature, target dimensions, and target configurations. Figure 27 (Ref. 29) shows the relatively high ignition temperatures that may be

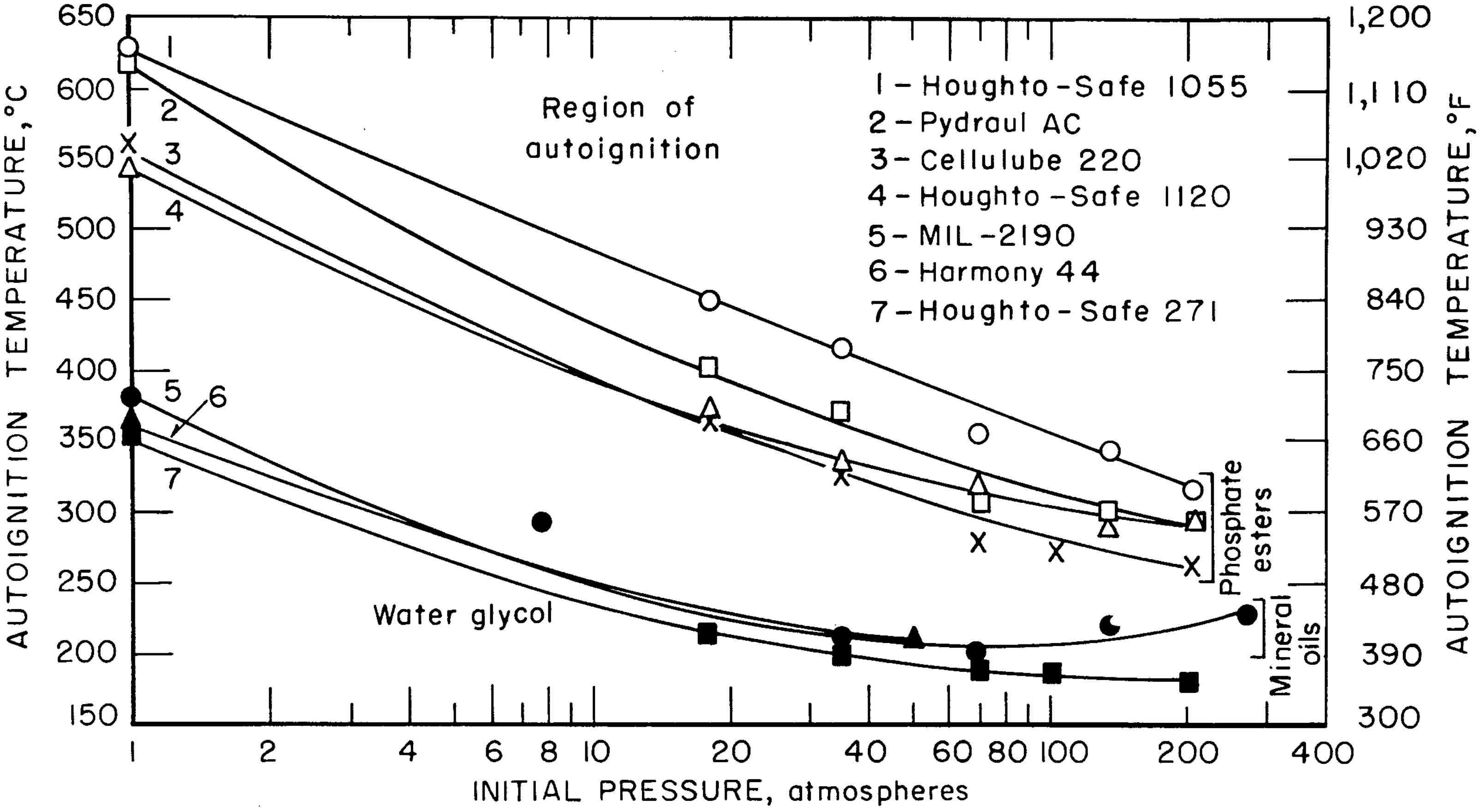


FIGURE 24. Minimum autoignition temperatures of phosphate ester, mineral oil, and water-glycol lubricants in air at various initial pressures.

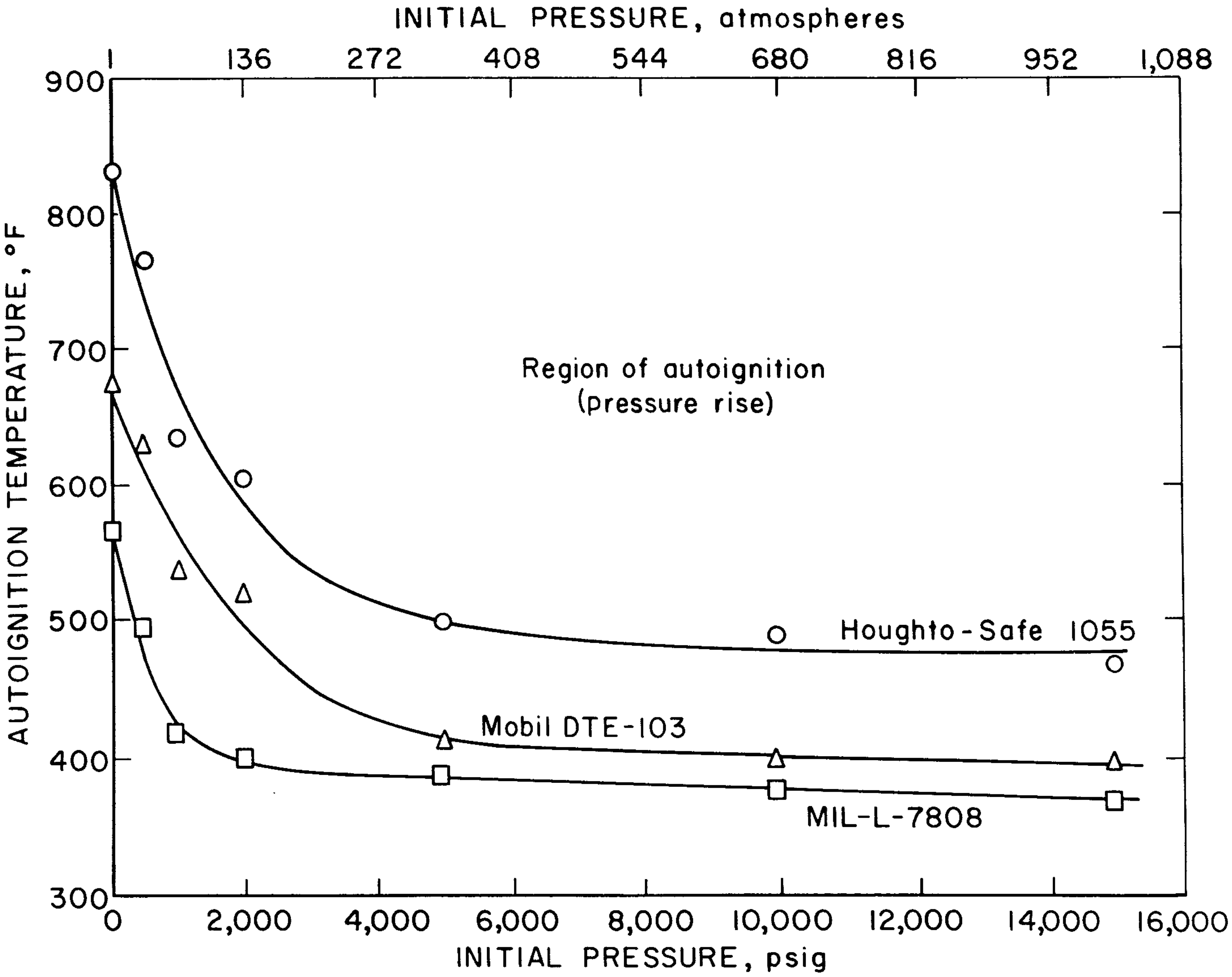


FIGURE 25. Minimum autoignition temperatures of Houghto-Safe-1055, Mobil DTE-103, and MIL-L-7808 lubricants in air at various initial pressures.

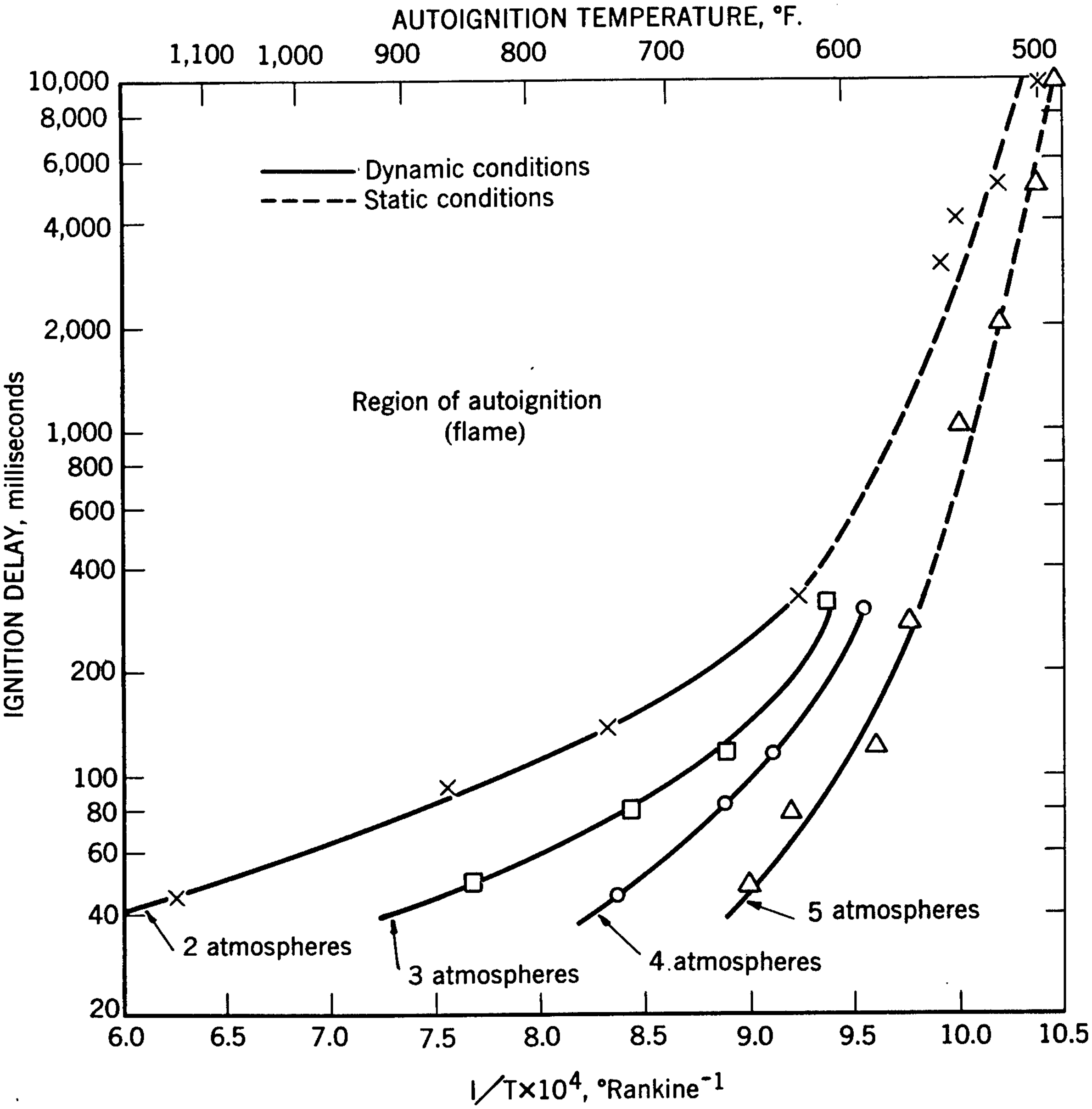


FIGURE 26. Variation of ignition delay with reciprocal temperature in autoignition of JP-6 fuel in air under static and dynamic conditions.

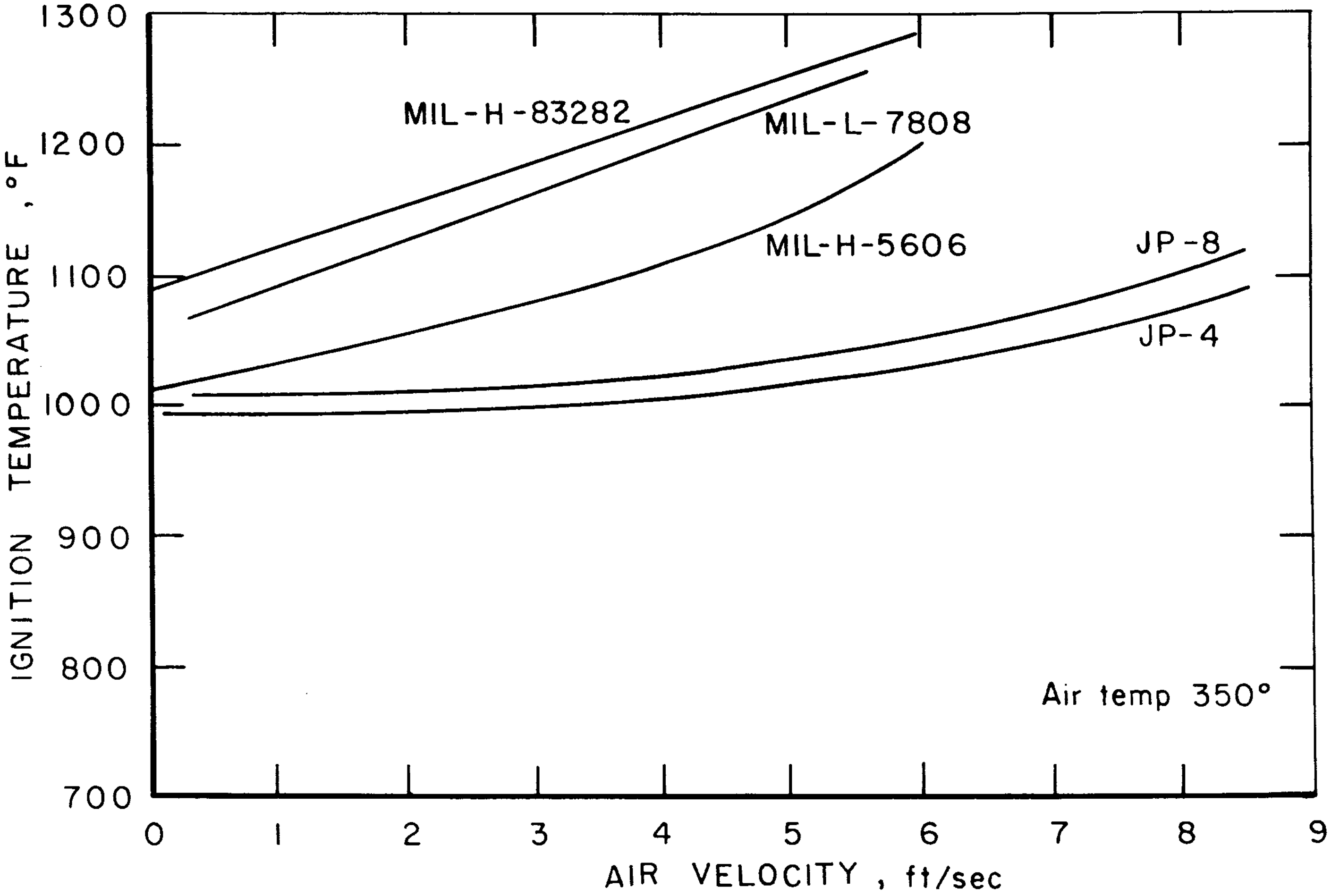


FIGURE 27. Comparison of ignition temperatures of aircraft fuels or fluids at various air velocities with a heated 2-inch diameter by 24-inch long steel target.

expected when jet fuels and aircraft lubricants or hydraulic fluids are injected upon a small heated target, 2 inch diameter by 24 inches long, in a flowing air stream. These ignition temperatures are at least 1000° F and would be much higher under high flow conditions. However, they decrease with increasing target diameter as illustrated in figure 28 (Ref. 29) and tend to approximate ignition temperatures obtained for the fluids with flowing vapor-air mixtures in heated tubes at comparable fuel contact times. Air temperature is particularly important in the case of low volatility fluids, i.e., high flash point fluids. Any heated metal configuration that tends to trap the fuel or provide an increased fuel contact time will yield a lower ignition temperature; an engine cowling is one example.

Another common type of heat source is a heated wire or rod. Ignitions with these sources are dependent upon similar factors to those involving the cylindrical heated targets discussed above. The ignition temperatures with a heated wire will obviously be higher than those resulting from exposure to a heated rod or heated vessel because of the differences in surface area and available heat. Figure 29 (Ref. 18) indicates the dependence of ignition temperature on the surface area of the heat source for several hydrocarbon fuels and an aircraft engine oil. A similar dependence of ignition temperature on heat source diameter would result if the length of the heat source were fixed. The ignition temperature (T, °F) of the JP-6 fuel and MIL-L-7808 engine oil as a function of heat source surface area (A, in^2) is

$$\text{JP-6} \qquad T = 1430 - 201 \ln A \ ; \ A < 11 \tag{27}$$

$$\text{MIL-L-7808} \qquad T = 1175 - 115 \ln A \ ; \ A < 29 \tag{28}$$

The fact that ignition of the engine oil involves predominately high temperature reactions whereas the JP-6 can involve "cool" and "hot" flame reactions at relatively low temperatures accounts in part for the transition observed in the JP-6 curve but not in the curve for the engine oil.

Ignitions by a jet of hot gases are unique in that wall or surface effects are not a factor. Such ignitions may occur as a result of an oil-seal failure or a pinhole leak in various lubricating systems, including those of an aircraft engine. They are also of interest in determining the integrity of flame arrestors and explosion proof equipment. The hot gas ignition temperatures are higher than AIT's or wire ignition temperatures, although the differences depend upon the diameter of the heat source as well as the composition of the combustible mixture (Figure 30) (Ref. 18). It is important to note in both figures 29 and 30 that although the MIL-L-7808 engine oil has a relatively high minimum AIT in air, its ignition temperatures with heated air jets, wires, rods, or vessels are lower than those for JP-6 jet fuel over most of the range of heat source dimensions investigated. This behavior is not unexpected since the jet fuel has the greater thermal stability; the paraffinic hydrocarbons also show this behavior. Generally, the lubricants having aromatic groups will have higher ignition temperatures and decomposition temperatures than the fluids

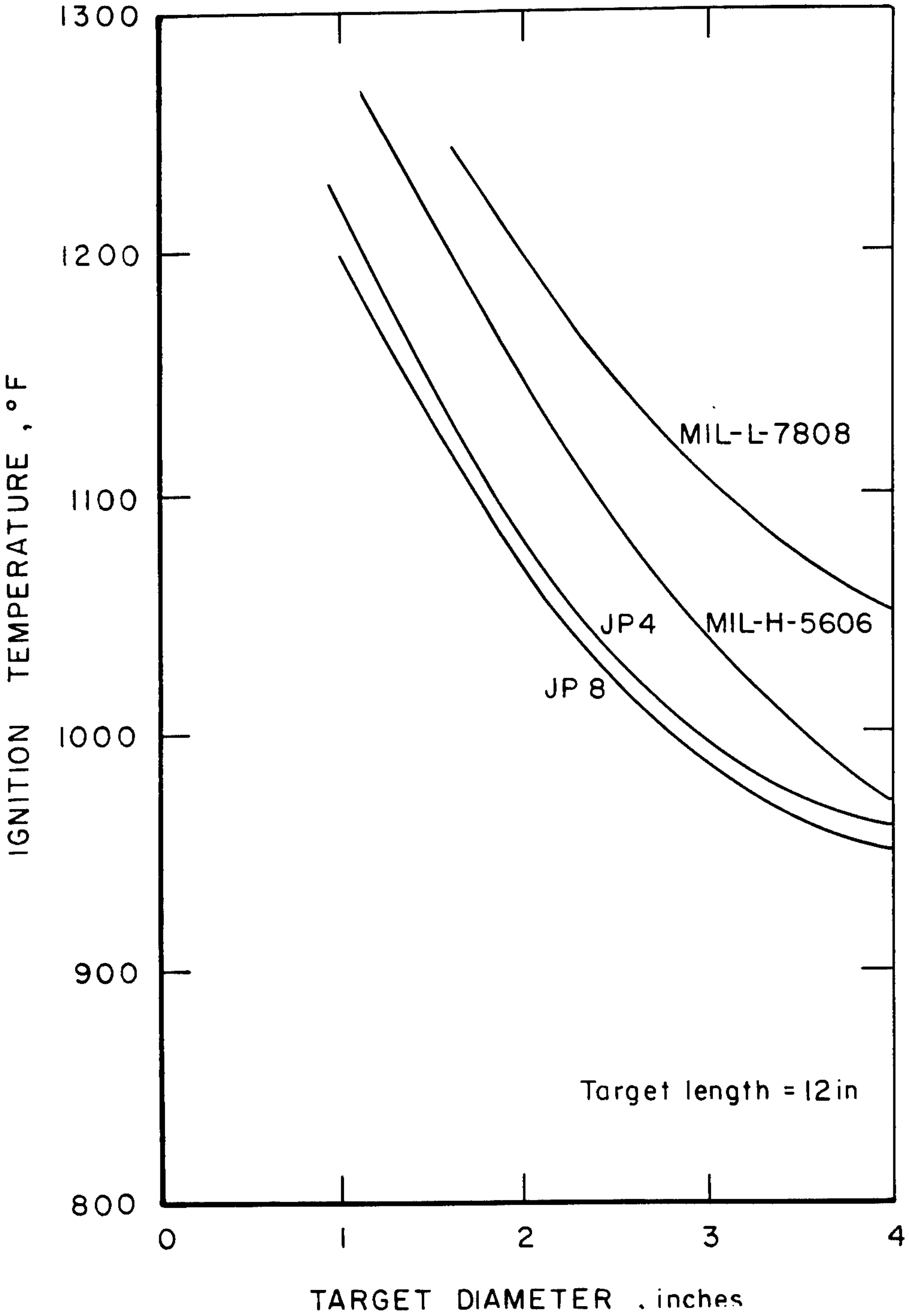


FIGURE 28. Ignition temperature vs target diameter for various aircraft fuels or fluids at an air velocity of 2-ft/sec and air temperature of 80°F.

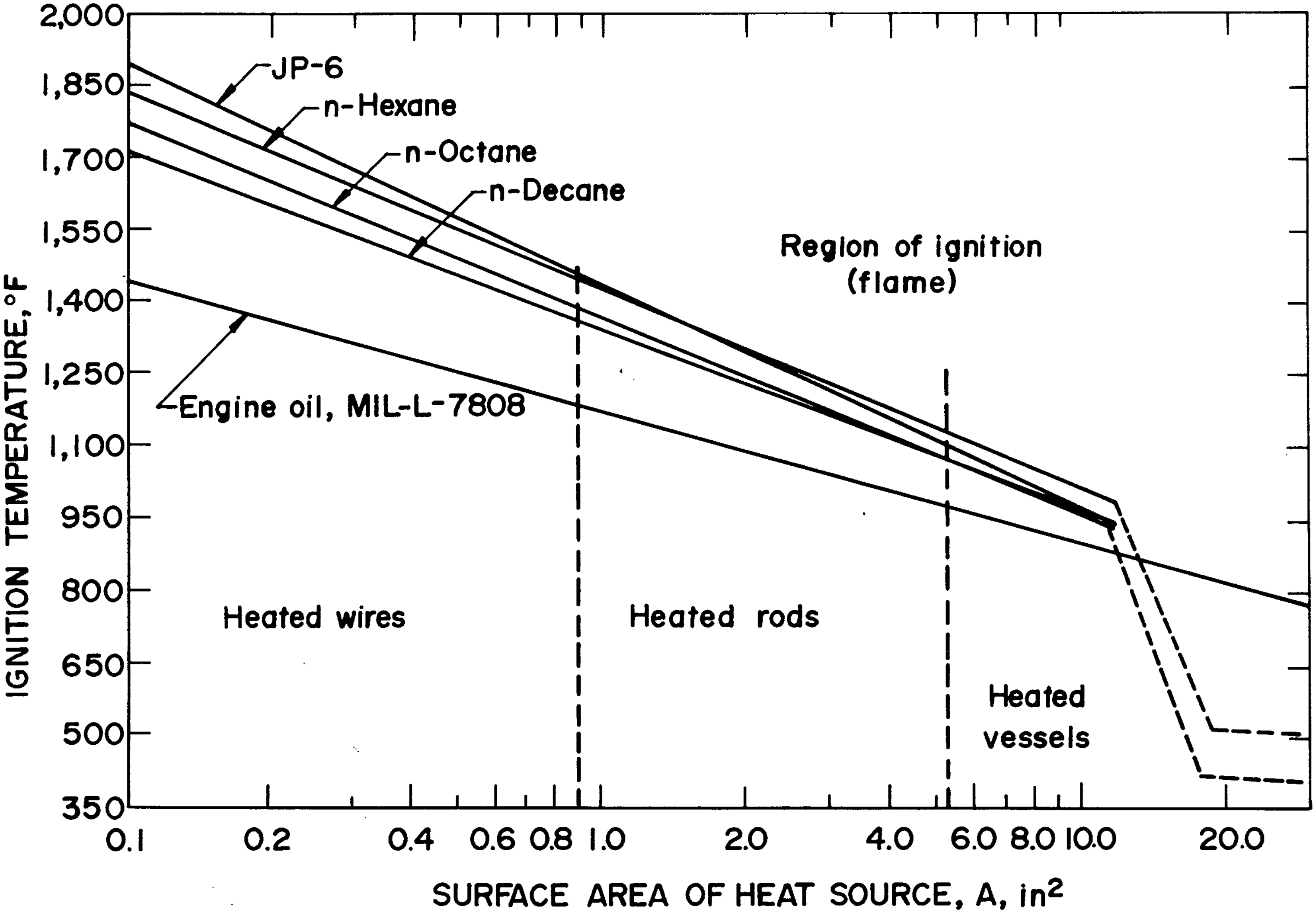


FIGURE 29. Hot surface ignition temperature as a function of the surface area of the heat source for various hydrocarbon fuels and an engine oil in near-stagnant air.

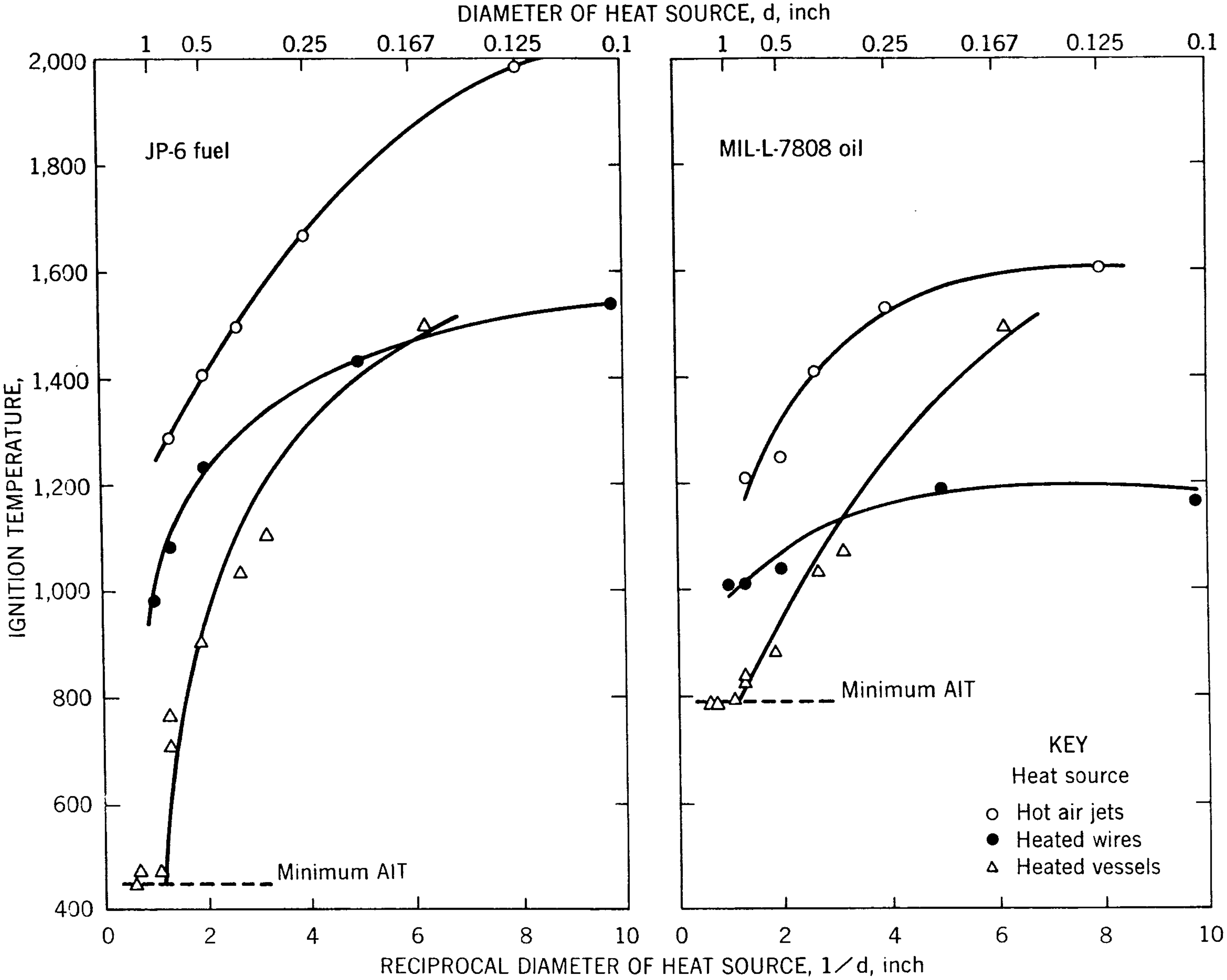


FIGURE 30. Variation of hot gas and hot surface ignition temperatures with reciprocal diameter of heat source for JP-6 fuel and MIL-L-7808 engine oil vapor-air mixtures.

with aliphatic groups. Halogen groups also increase the oxidative stability but not necessarily the thermal stability. The decomposition temperatures of most lubricants are between 600° and 900° F (Ref. 18).

(5) Compression Ignition. The ignition of a combustible mixture can also result from adiabatic or shock compression. This rapid pressurization can occur in reciprocating engines, compressor lines, or in certain systems where quick-opening valves are used. The theoretical gas temperatures (T_2) which can result from shock and adiabatic compression of air at 32° F ambient temperature are compared in table 3 for various compression ratios (P_2/P_1). According to this table, an adiabatic compression ratio of about 50 gives a temperature, T_2 (970° F) that would appear adequate for autoignition of most hydrocarbon fuels in air initially at normal temperature (e.g. 75° F). However, this can only occur if the high temperature condition is maintained for a duration that exceeds the ignition delay. The case of shock compression is more complicated, particularly because of the small volume of gas mixture that is heated and the short duration of the pressure pulse. Thus, a shock wave with a compression ratio of 10 and a T_2 of 810° F would generally be too weak to produce ignition of a mixture having an AIT of 800° F.

Table 3. Shock Wave and Adiabatic Compression Temperatures[a/]

Compression Ratio P_2/P_1	Gas Compression Temperature	
	Shock Wave T_2, °F	Adiabatic Compression T_2, °F
2	144	134
5	406	306
10	810	467
50	3610	970
100	6490	1250
1000	33,940	2615

a/ Reference 6.

B. Flammable Solids

(1) Ignition Energy. The minimum spark ignition energy of most finely dispersed solids, including metal and plastic dusts, is between 10 and 100 millijoules in atmospheric air (Ref. 8, 30). Corresponding values for sheet-type materials that may be involved in an aircraft fire are meager but are expected to be much higher than when the materials are finely divided. Generally, the ignition energy requirements for sheet materials are determined using a thermal radiation source. According to the data in table 8-A, the radiation intensity required for ignition is about 50 Btu/ft^2 for cotton shirt fabrics and between 90 and 120 for wood and paper sheeting (Ref. 31, 32). In comparison, neoprene, nylon, and polyvinyl chloride sheeting appear to be non-ignitable in air with the same radiation source; the radiant heat flux

was 48.7 Btu/ft^2-sec (13.2 cal/cm^2-sec). However, although these data reflect the relative ignitability of the combustibles, they do not indicate threshold radiation intensity requirements for ignition. For example, other investigators have shown that a radiant flux of only about 3 Btu/ft^2-sec is the threshold value for the ignition of wood and certain textile fabrics (Ref. 33).

(2) Ignition Temperatures. The ignition temperatures of combustible solids may refer to bulk or finely divided materials and are apparatus dependent like those of combustible liquids. Table 9-A lists self-ignition temperatures for various metals, synthetic rubbers, wood or fibrous materials, and miscellaneous substances. These were obtained in a heated tube with near-stagnant air by the National Bureau of Standards (Ref. 8) and refer to the lowest temperature at which the material can produce an exothermic reaction that may result in ignition or glow. It is apparent that many materials may present a self-heating hazard between 300° and 600° F under such isothermal conditions; exceptions are metal powders, silk or nylon fabrics, and a few other materials which appear to require temperatures in the 800°-1200° F range. Particle or sample size effects are indicated by the data given for magnesium samples.

Generally, the ignition temperature of a combustible solid is lower when the solid and the ambient atmosphere are uniformly heated, as compared to situations when only the combustible is heated. The minimum AIT and hot plate ignition temperature data of table 4 (Ref. 24) show the effect of the heating condition for several combustibles in sheet form. The greater ease of ignition in oxygen than in air is also illustrated by these data. Other ignition temperature data are given in table 6-A (Ref. 30, 34), in which the relative ignitabilities of metal dust clouds in air and metal slabs or sheets in oxygen are compared. Although both sets of data were not obtained under ideal conditions or in the same oxidant atmosphere, they indicate the greater hazard associated with finely dispersed combustibles. Note that the dust cloud ignition temperatures for aluminum and magnesium are comparable to the melting points of these metals.

Table 4. Minimum AIT's and Hot Plate Ignition Temperatures of Sheet-type Combustibles in Air and Oxygen (1 atm)[a/]

Material	Ignition Temperature, °F		
	AIT	Hot Plate	
	Air	Air	Oxygen
Cotton sheeting	725	870	680
Conductive rubber sheeting	735	895	680
Paper drapes (Sanidrapes)	750	880	770
Plexiglas sheet	840	1105	805
Nomex fabric	960	>1110	970
Blanket wool	1005	"	930
Cellulose acetate sheet	1020	"	795
Polyvinyl chloride sheet	1040	"	735

a/ Reference 24.

A. Fire Temperatures - Gaseous Fuels

The temperatures produced in a fire or explosion are important in determining the potential heat damage and in calculating the explosion pressures that may be developed. In air the maximum adiabatic flame temperatures of saturated hydrocarbon vapor-air mixtures (Stoichiometric) are of the order of 3500° F for constant pressure combustion. In oxygen, the maximum values are over 5000° F. These temperatures can be expected to be higher for unsaturated hydrocarbons or when the combustion is under constant volume conditions. They can be calculated from the heat evolved and the heat capacity of the product mixture, as shown by the following example where adiabatic conditions are assumed.

For the lower limit mixture of methane and air at 80° F (540° R), the reaction for complete combustion of 100 moles may be written as

$$5\ CH_4 + 20\ O_2 + 75\ N_2 \rightarrow 5\ CO_2 + 10\ H_2O + 10\ O_2 + 75\ N_2 \qquad (29)$$

The heat evolved at constant pressure ($\Delta H_{540°}$) is obtained from the heats of formation (ΔH_f) of the products and reactants,

$$\Delta H_{540°} = \Delta H_f\ (\text{Products}) - \Delta H_f\ (\text{Reactants}) \qquad (30)$$

which yields a value of 17,086 Btu/lb-mole. If the molecular weight of the limit mixture is taken as that of air (29 lbs/mole), the heat evolved is approximately 590 Btu/lb which is typical of many hydrocarbon limit mixtures. Note that the heat evolved per mole can also be calculated from the net heat of combustion (Table 3-A) when the latter is converted to a molar (volume) basis and multiplied by the lower limit percentage value.

The maximum temperature rise (ΔT) for the limit mixture is determined from

$$\Delta\ T = \Delta H_{540°}/\bar{C}_p \qquad (31)$$

$$\bar{C}_p = 0.05\ C_p\ (CO_2) + 0.10\ C_p\ (H_2O) + 0.10\ C_p\ (O_2) + 0.75\ C_p\ (N_2) \qquad (32)$$

where $\bar{C}_p$ is the mean heat capacity of the products from 540° R to the flame temperature. If a flame temperature of 2700° R is assumed, $\bar{C}_p$ is 8.16 Btu/lb mole - °R and ΔT is 2095° R, or a calculated final temperature of 2635° R (ΔT + 540°) which agrees well with that obtained by a rigorous treatment. This temperature is referred to as the limit flame temperature and is above 2600° R (2140° F) for most hydrocarbon type fuels in atmospheric air.

Under constant volume conditions, the temperature rise (ΔT) and heat release (ΔE) are

$$\Delta T = \Delta E_{540°}/\bar{C}_v \qquad (33)$$

$$\Delta E_{540^\circ} = \Delta H_{540^\circ} - \Delta n\ RT \tag{34}$$

where $\bar{C}_v$ is the mean heat capacity, Δn is the change in gaseous reactant and product moles, R is the gas constant, and T is the mixture temperature; $\bar{C}_v = \bar{C}_p - R$. The temperature rises are greater by several hundred degrees for constant volume than for constant pressure combustion. In the above case, the maximum flame temperature for constant volume burning of the methane limit mixture is approximately 3300°R (2840°F).

B. Fire Temperatures - Combustible Solids

The flame temperatures of organic combustible solids tend to be comparable to those of the hydrocarbons. Those which yield carbon monoxide, hydrogen, and unsaturated hydrocarbons, particularly acetylene, as their main pyrolysis products will theoretically be capable of producing the highest flame temperatures, e.g., > 4000° F in air at atmospheric pressure. The actual temperatures encountered in a fire will depend greatly upon the supply of air and the adiabatic nature of the fire environment.

Flame temperatures of combustible metals are greatly dependent upon the temperature required to vaporize the metal oxides that are formed on the surface. Since the metal oxide is initially formed when burning metals in air or oxygen, the maximum flame temperatures will not differ greatly in the two oxidant atmospheres. Table 5 lists the adiabatic flame temperatures that have been reported for several metals in oxygen at 1 atmosphere pressure.

Table 5. Adiabatic Flame Temperatures of Various Metals in Oxygen at Atmospheric Pressure[a]

Metal	Adiabatic Flame Temperature, °F	Metal	Adiabatic Flame Temperature, °F
Aluminum	6450	Magnesium	5570
Chromium	5480	Tin	4400
Iron	4940	Titanium	5480
Lead	2780	Zinc	3500

[a] Reference 34

C. Explosion Pressure

The maximum pressure that may result from the deflagration of a flammable gaseous mixture is given by

$$P_2 = P_1 \left({}^{n_2}/_{n_1}\right)\left({}^{T_2}/_{T_1}\right) \tag{35}$$

where P refers to pressure, T to temperature, n to moles of gas, and the subscripts indicate the initial (1) and final (2) states of combustion. Thus, for the constant volume adiabatic combustion of the lower limit mixture of methane (5%) and air at 540° R and 1 atmosphere, the predicted P_2 would be 90 psia since T_2 is 3300° R and n_2/n_1 is 1.0 (see Section A). The corresponding P_2 value for a stoichiometric mixture would be 130 psia. Similar values are found for other hydrocarbons, depending upon their adiabatic flame temperatures.

If the explosion occurs in a <u>spherical chamber</u>, the pressure rise (ΔP) for a centrally ignited mixture is given approximately by

$$\Delta P = K\, P_1\, S_u^{\,3}\, t^3/V \tag{36}$$

where K is an empirical constant, S_u is burning velocity, t is burning time, and V is the chamber volume. This expression is reliable in the absence of large heat losses and particularly for rapid burning mixtures (e.g. stoichiometric) which are least affected by buoyant forces or wall effects that can distort a spherical flame front. Figure 31 shows the pressure history for the explosion of a stoichiometric methane-air mixture (75° F) at atmospheric pressure in a 12-ft diameter sphere ($\sim$920 ft^3). The time required to attain maximum pressure (0.78 sec) agrees well with that from the expression developed by Zabetakis (Ref. 7) for paraffin hydrocarbons or fuel blends,

$$t = 75\sqrt[3]{V} \tag{37}$$

where t is in milliseconds and V is in cubic feet. The maximum explosion pressure for hydrocarbon type fuels occurs slightly on the fuel-rich side of stoichiometric, approximately at an equivalence ratio of 1.2 (Figure 32) (Ref. 35). Note that the pressure rises can be relatively high for both fuel-lean and fuel-rich mixtures which just fall within the flammable range. Thus, the explosion of most gaseous fuel-air mixtures can produce destructive pressures.

The pressure developed during the burning of <u>flammable solids</u> depends upon such factors as the combustible loading, orientation of burning, combustible surface area, and the pressure or oxygen concentration of the ambient atmosphere. Although rates of pressure rise of dust explosions can be even higher than those of gaseous explosions (Ref. 30), the rates associated with the burning of flammable solids in sheet form are ordinarily lower by an order of magnitude or more, depending upon the loading. The pressure history that might be expected from the vertical burning of two common sheet combustibles, paper and cotton, in an enclosure is shown in Figure 33 (Ref. 36), where the combustible loading was 0.035 oz per cubic foot of chamber volume (216 ft^3). Note that the pressure rise of the slower burning material (cotton sheeting) is greatly increased when the burning surface area is increased by the use of two burning racks at the same loading. For this combustible loading of 0.035 oz/ft^3, the pressure rises (ΔP, psi) under the more optimum burning conditions are proportional to approximately the square of time (t, sec). The curves in figure 33 are defined by the following equations:

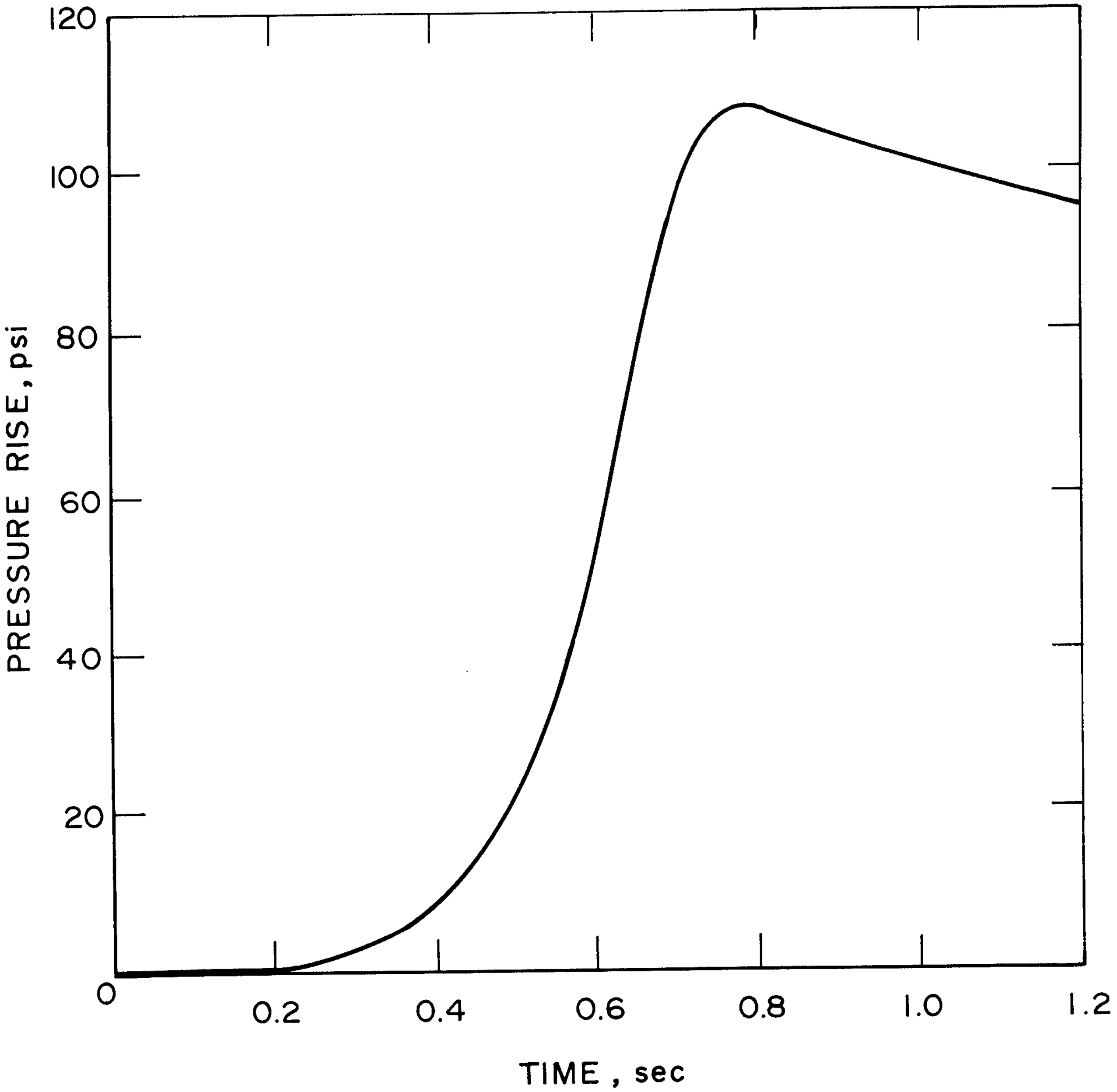


FIGURE 31. Pressure history for the explosion of a stoichiometric methane-air mixture (75°F) in a 12-ft diameter sphere at atmospheric pressure.

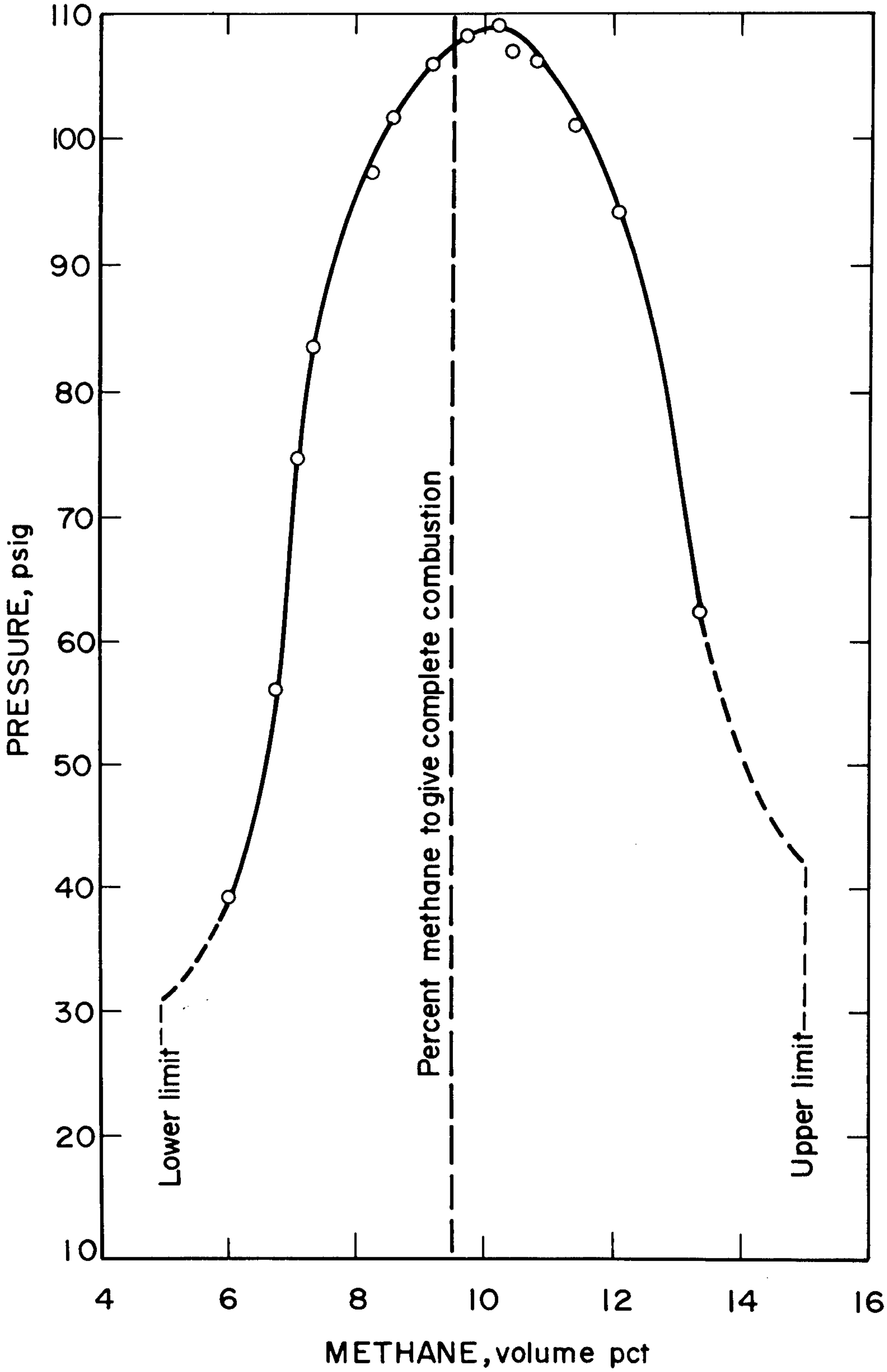


FIGURE 32. Effect of fuel concentration on explosion pressure for methane-air mixtures (75°F) in a 244 in^3 vessel at atmospheric pressure.

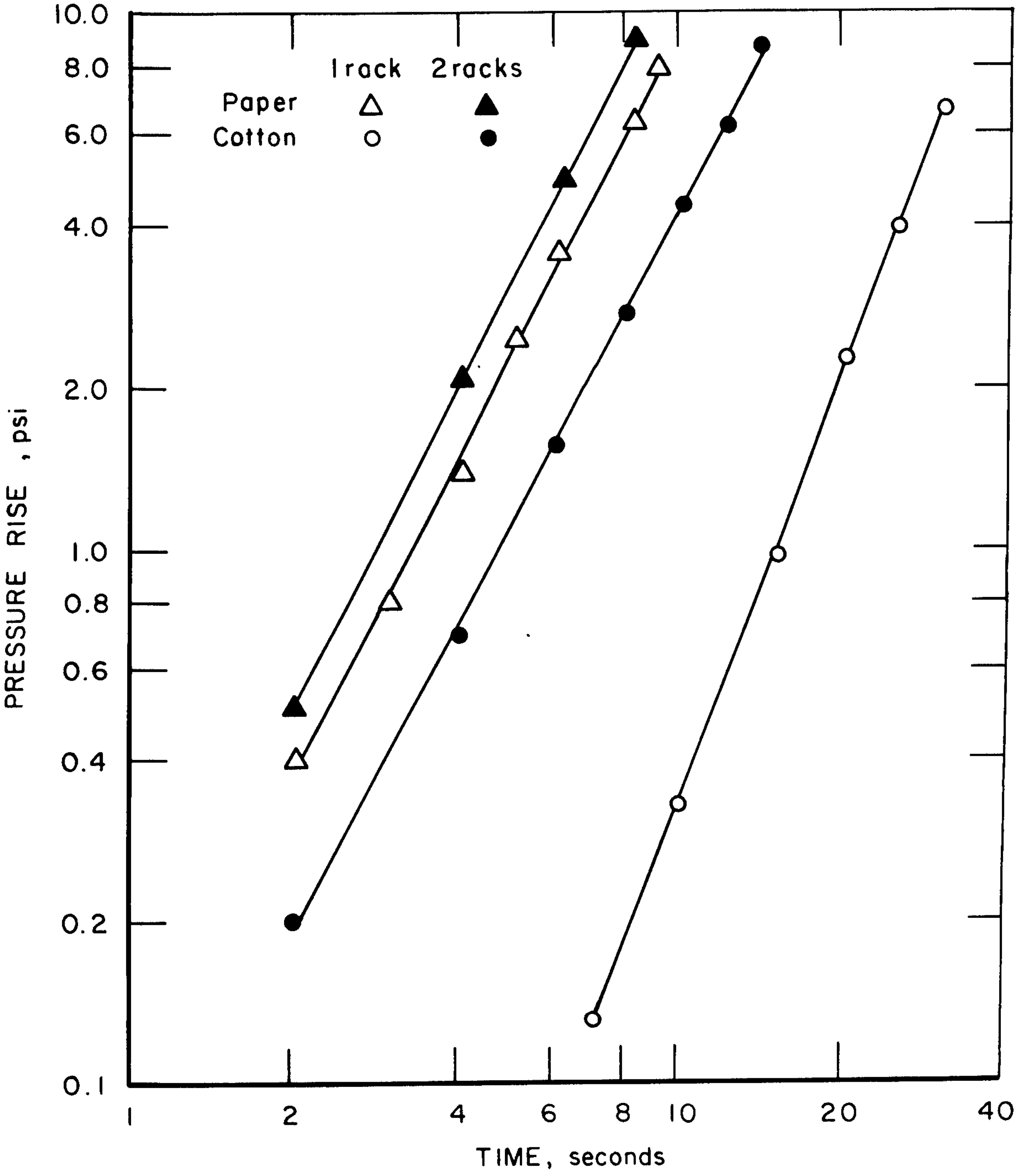


FIGURE 33. Pressure rise vs time for the burning of paper and cotton sheeting (0.035 oz/ft^3) in air on single and double burning racks in a 216 ft^3 chamber (1 atm).

$$\ln \Delta P = 2.054 \ln t - 3.238 \quad \text{Cotton Sheeting} \qquad (38)$$

$$\ln \Delta P = 2.101 \ln t - 2.156 \quad \text{Paper sheeting} \qquad (39)$$

Doubling the combustible loading approximately doubles the rate of pressure rise, at least until the atmosphere becomes significantly deficient in oxygen. "Nap-type burning" also markedly increases the pressure rise rate, since the mass consumption varies exponentially with time; woolen materials are capable of this type of burning, particularly in oxygen-enriched atmospheres.

In the event of a fire or explosion in a partly vented enclosure, the maximum pressure developed will depend upon such factors as the length/diameter ratio, vent area, and the burning velocity of the gaseous mixture or the flame spread rate of the combustible liquid or solid. Relatively large vent areas are necessary to safely vent a confined ignition of flammable gas, although a fuel fire can also develop high pressures which may destroy the enclosure if it is not properly protected. The effect of vent ratio (ft^2/ft^3) on the explosion pressures of 5-percent propane-air mixtures in a 3 ft^3 tank is shown in figure 34 (Ref. 37). A vent area of about 5 ft^2 per 100 ft^3 tank volume is required to keep the explosion pressure below 5 psi for this representative fuel mixture. Higher vent ratios would be necessary for fuels, such as hydrogen or the unsaturated hydrocarbons which have a higher burning velocity than propane. Further discussion is given in the section on explosion venting under safety measures.

D. Heat Damage Criteria

Considering the flame temperatures possible in the burning of organic fuels and the temperature limits of aircraft combustibles or noncombustibles, it is apparent that most materials could not withstand a fully developed aircraft fire without being consumed or severely damaged. The temperature limits of aircraft materials were discussed earlier under the section on physical properties.

In a survivable crash fire accident, the chance of human survival is greatly reduced when a massive fuel spillage occurs. An indication of the fuel dispersion hazard is illustrated in figure 35 (Ref. 26)) where the fire ball size is plotted against impact velocity for vertical fuel drops with 5 gallons of JP-4 and JP-8 liquid or emulsified fuels. Particularly note-worthy is that the fireball hazard tends to be nearly comparable for the low and high flash point liquid fuels if the impact velocity is increased sufficiently (e.g. 60 mph). It is also evident that the fireball associated with the ignition of a relatively small fuel spillage can engulf a large area in flame. With 5-gal metal containers, the fireball diameter (ft) was proportional to over one-half the impact velocity (mph) in fuel drops with the JP-4 jet fuel.

Data obtained by the FAA (Ref. 38, 39) provide an indication of the temperatures and heat fluxes that may be encountered during fully developed aircraft fuel fires. In a severe external jet fuel fire, the aircraft skin

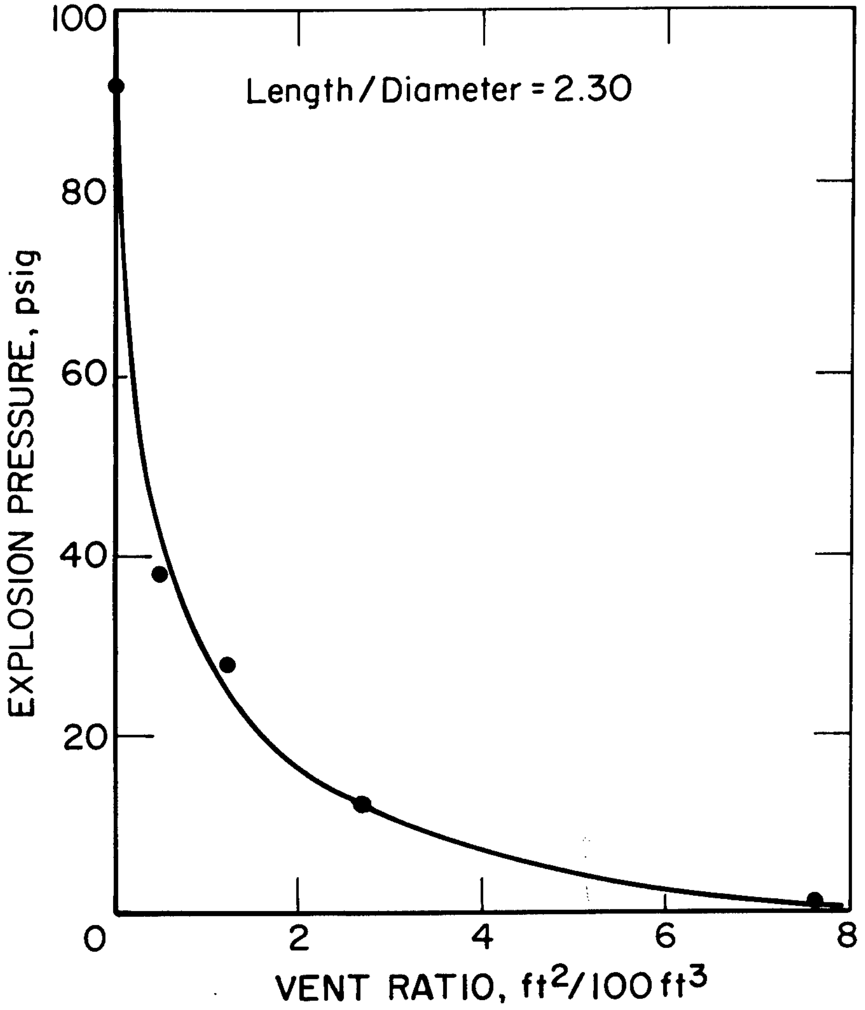


FIGURE 34. Effect of vent ratio on explosion pressure for 5% propane-air mixtures (75°F) in a 3 ft^3 tank at atmospheric pressure.

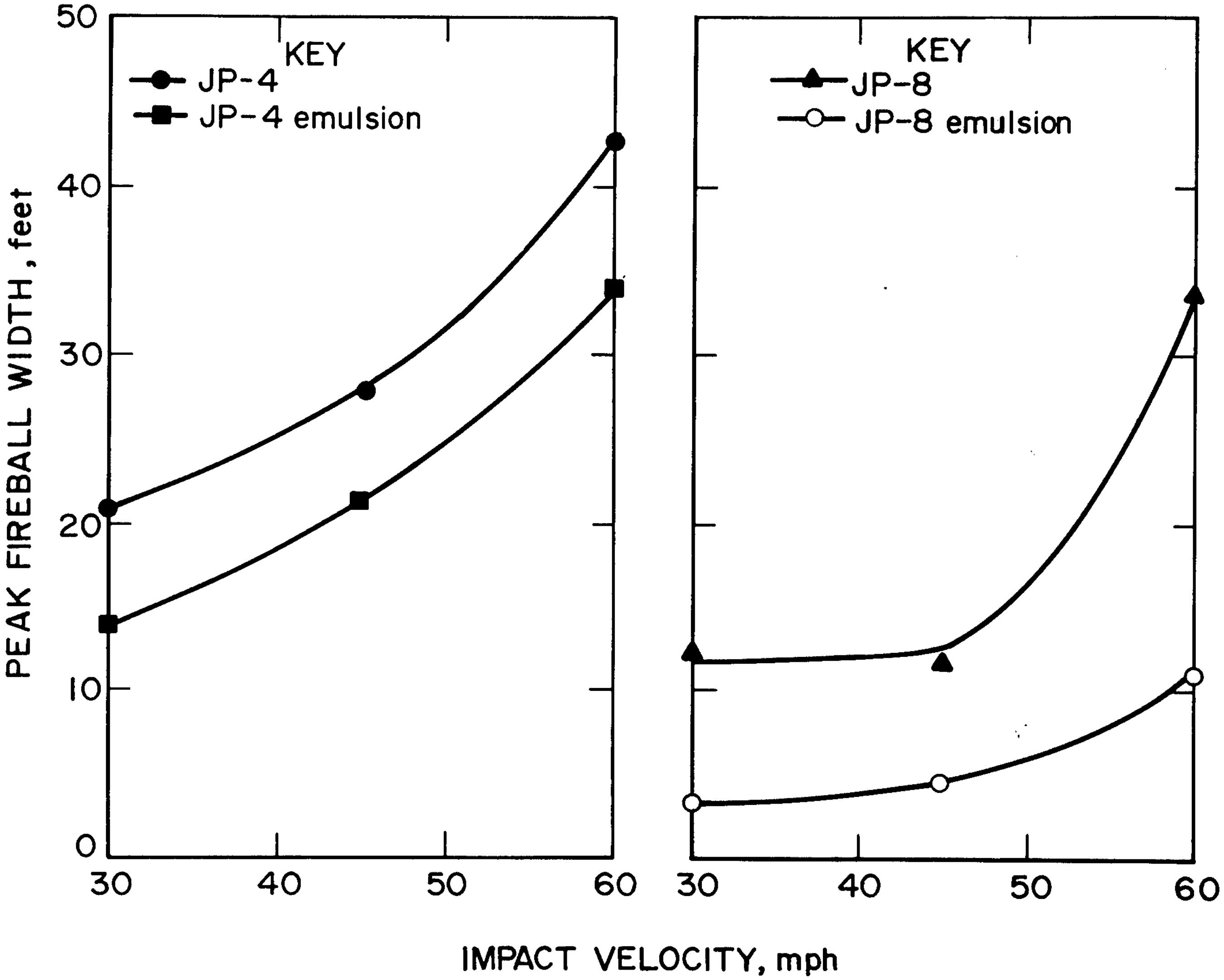


FIGURE 35. Variation of peak fireball width with impact velocity for vertical fuel drops with 5 gallon metal container.

can attain a temperature of at least 1500° F within 1 minute, whereas the cabin air or wall temperature can remain normal during this period or longer, depending upon the skin material, insulation and sealant materials, and the size of cabin vents or unsealed areas. With a sealed titanium fuselage, the safe exposure time could conceivably be as long as about 5 minutes (Figure 36) (Ref. 38); with an aluminum fuselage the time would be much shorter since the melting point of aluminum is much less than that of titanium. Oxygen depletion and toxic product accumulation are also important in determining safe exposure times. Most fatalities in a fire can be considered directly attributable to asphyxiation or carbon monoxide poisoning. At the same time, the degree of heat damage to a victim's respiratory system can provide evidence on the fire development and on the victim's exposure to hot or cooled fire products.

The maximum thermal radiation from liquid-supported diffusion flames occurs at large pool diameters and can be a factor in the spread of fire to adjacent areas. Measured heat fluxes were between 10 and 20 Btu/ft^2-sec in the immediate vicinity of the full-scale aircraft fire (JP-4) of figure 36. Lower values are encountered after short preburn times or early extinguishment of such fires; figure 37 (Ref. 39) shows data obtained in a full-scale test where a simulated JP-4 engine fire was extinguished after a preburn time of approximately 17 seconds. The maximum thermal radiative output at the surface of a large pool fire can be of the order of 40 to 50 kilowatts per square foot (1 kw/ft^2 = 0.95 Btu/ft^2-sec) for gasoline and other hydrocarbon fuels (Table 6) (Ref. 23). As indicated in table 6, the radiative output represents about one-third or less of the total available thermal output, depending upon the fuel. If spherical symmetry is assumed, the radiant heat flux (h_x) at various distances (x) from the center of a burning pool of radius (r) may be calculated as

$$h_x\ (\mathrm{kw/ft^2}) = h_r\ \pi r^2/4\ \pi\ x^2 \qquad (40)$$

where h_r is the value given in table 6 for the fuel of interest. The possibility of igniting textiles, wood and other materials by thermal radiation can be assessed by comparing the calculated heat flux values to the threshold radiation intensities for producing ignition of the materials (Table 7) (Ref. 33). Table 7 also gives a threshold value for producing pain to humans after a short exposure (e.g. ~ 10 seconds).

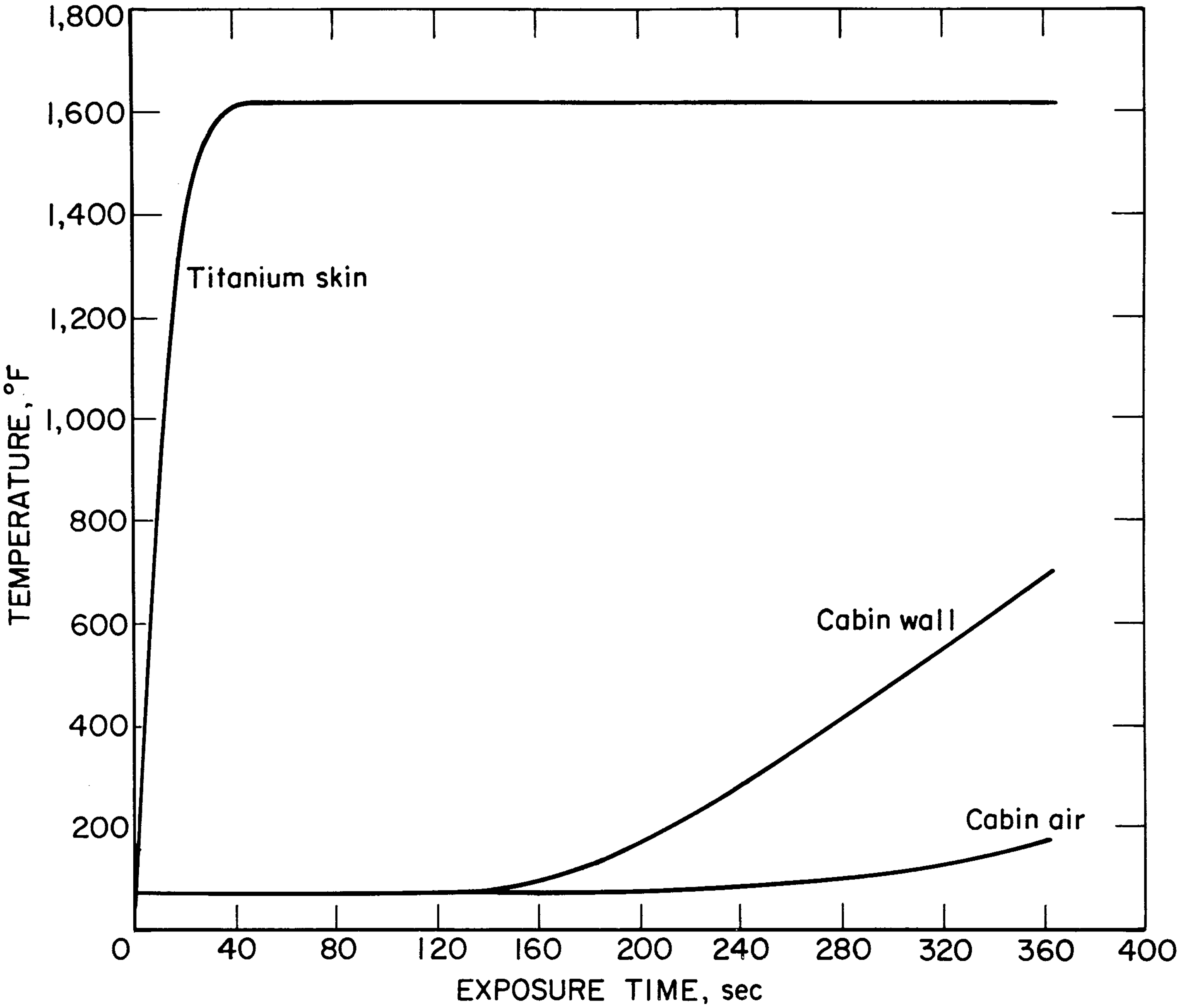


FIGURE 36. Predicted temperature history of a titanium fuselage adjacent to a severe external JP-4 fuel fire.

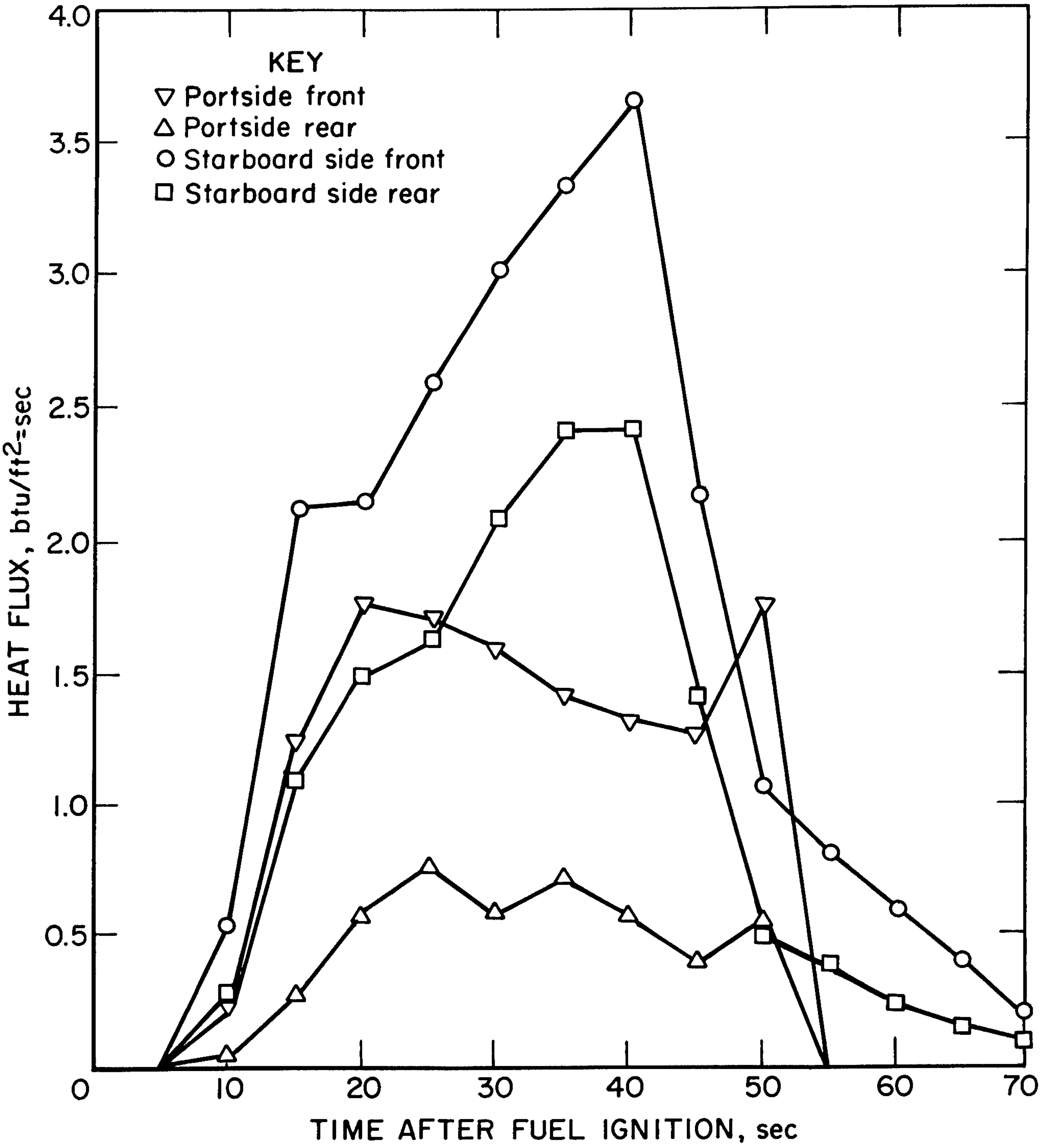


FIGURE 37. Heat flux vs time after fuel ignition in full-scale fire extinguishment test simulating an engine fire (JP-4) on a B-47 aircraft.

Table 6. Comparison of Computed or Experimental Values Bearing on Radiative Hazards of Fire[a]

Fuel	Linear Burning Rate (large diameter) in/min	Thermal Output per Unit Liquid Surface		
		Total kw/ft^2	Radiated kw/ft^2	Radiated %
Hexane	0.29	140	54	38.5
Butane	.31	140	38	27
Benzene	.24	140	49	35
Xylene	.23	135	--	--
Methanol	.067	17	3	17.5
LNG	.26	86	20	14
Gasoline	.35	--	52	23

a/ Reference 23; gasoline burning rates obtained for 10 ft diameter pools; rates for other fuels obtained in small diameter pools and corrected to yield values for infinite diameter pools.

Table 7. Threshold Radiation Intensities for Various Effects[a]

Effect	Threshold Radiation Intensity Cal/sec-cm^2	Btu/hr-ft^2
Wood ignites spontaneously	0.8	10,600
Hemp, jute, and flax (hose) ignite spontaneously	1.0	13,300
Textiles ignite spontaneously	0.85	11,300
Fibreboard ignites spontaneously	0.75	10,000
Wood ignites by flying brands	0.1	1,300
Painted wood ignites by flying brands	0.4	5,300
Humans feel pain after a short time	0.1	1,300

a/ Reference 33.

E. Blast Damage Criteria

The blast damage associated with an explosion includes that produced by the resultant pressure or air blast (as well as flying fragments) which may propagate at sonic or supersonic rates, depending upon the severity of the explosion. In the preceding sections, the discussions on combustible gases, liquids, or solids have been largely limited to reactions (deflagrations) in which flame propagation rates are subsonic. Under certain ignition and confinement conditions, the reaction of many gaseous combustible mixtures can result in detonation, that is, one in which propagation through the reacting medium is at a supersonic rate relative to the unburned material. Some energetic materials, particularly primary high explosives (Table 11-A), detonate readily even in the absence of confinement. Detonations are generally characterized by the formation of a shock front which precedes the flame front and is sustained by the energy of the flame front. A brief discussion of some of the terms essential to the application of blast wave theory (Ref. 40) is contained herein.

An explosion is defined as a sudden release of pressure or energy and, therefore, can result from any chemical or physical reaction that produces a sharp pressure discontinuity. The pressure discontinuity or shock wave propagates at a velocity determined largely by the energy of the driving force and the properties of the inert or reactive medium through which the wave propagates. Thus, the shock wave or blast wave produced following the failure of an enclosure will degenerate into a sonic wave more rapidly in the case of a deflagration than in the case of a detonation. The <u>Mach number</u> (M) of a shock wave in air is

$$M = \frac{u}{a} = \frac{u}{\sqrt{\gamma R T}} \tag{41}$$

where us is shock velocity, a is sound velocity of air, γ is ratio of specific heats ($^{C}p/C_v$), R is molar gas constant, and T is initial temperature. Mach numbers for flowing air at various pressure differentials are available in the literature (Ref. 9). The pressure drop (Δp_s) across a shock front is equal to the difference between the shock pressure (P_s) and the ambient pressure (P_o) ahead of the shock. This pressure drop is referred to as the <u>side-on overpressure</u> and is defined by

$$\Delta p_s = P_o \frac{2 \gamma (M_o^2 - 1)}{\gamma + 1} \tag{42}$$

To obtain the total pressure rise that an object will sense when placed in the path of a shock, it is also necessary to add the dynamic pressure component (q_p) associated with the wind velocity (u_p):

$$q_p = 1/2 \rho u_p^2 \tag{43}$$

where ρ refers to air density. For weak shocks, the <u>reflected overpressure</u> tends to be about twice the side-on overpressure but approaches a value of $8\Delta p_s$ for very strong shocks (Ref. 40).

As previously noted, the pressure rise ratio in a deflagration of gaseous mixtures can be at least 8. In the case of a gaseous detonation, the detonation pressure is about twice the maximum pressure of constant volume combustion; thus, the reflected overpressures in such cases could be at least 40 atmospheres. Detonation pressures (P_2) can be calculated by the following expression (Ref. 41):

$$P_2/P_1 = \frac{1 + \gamma_1 (D/C_1)^2}{1 + \gamma_2} \tag{44}$$

where D is the detonation velocity and the subscripts refer to the unreacted (1) or reacted (2) state.

A cube root scaling law has proved to be useful in predicting the blast wave characteristics of various charge weights of an explosive. Of particular interest is the correlation of distances (D) at which the same overpressure is obtained with different quantites (W) of a given explosive. This is given by

$$\left({}^{D}/{D_o}\right) = \left({}^{W}/{W_o}\right)^{1/3} \qquad (45)$$

where D_o and W_o pertain to the reference explosion conditions. If the reference explosion has an energy yield equivalent to 1-lb TNT (W_o=1), D is equal to $D_o W^{1/3}$ and one can thus obtain TNT equivalents for explosions of various energy yields. The peak overpressures which can be produced are normally plotted as a function of the scaled distance (λ),

$$\lambda = D/\ W^{1/3} \qquad (46)$$

as in figure 38 (Ref. 42), where the data were derived from TNT surface explosions of hemispherical charges. In this figure, it is seen that the peak overpressure for a 1-lb TNT charge decreases from 10 psi to 1 psi when the distance is varied from 10 ft (λ=10) to about 40 ft (λ=40). A similar plot is shown in figure 39 (Ref. 43) where approximate overpressures for certain biological effects and material failures are also indicated. However, it should be noted that the lethal overpressure values are for a 400 millisecond pulse duration; both lethal and lung damage values can be expected to be higher with shorter pressure pulse durations since they are impulse sensitive.

In the case of parked aircraft, a blast overpressure of approximately 3 psi would cause severe damage to an average-sized transport and 1 psi would cause only light damage (Ref. 40). Lower pressures would be necessary to produce the corresponding damage to smaller aircraft. Tables 8 and 9 give additional blast damage criteria for structural materials; the data in table 9 should be more reliable since they are based on a statistical survey.

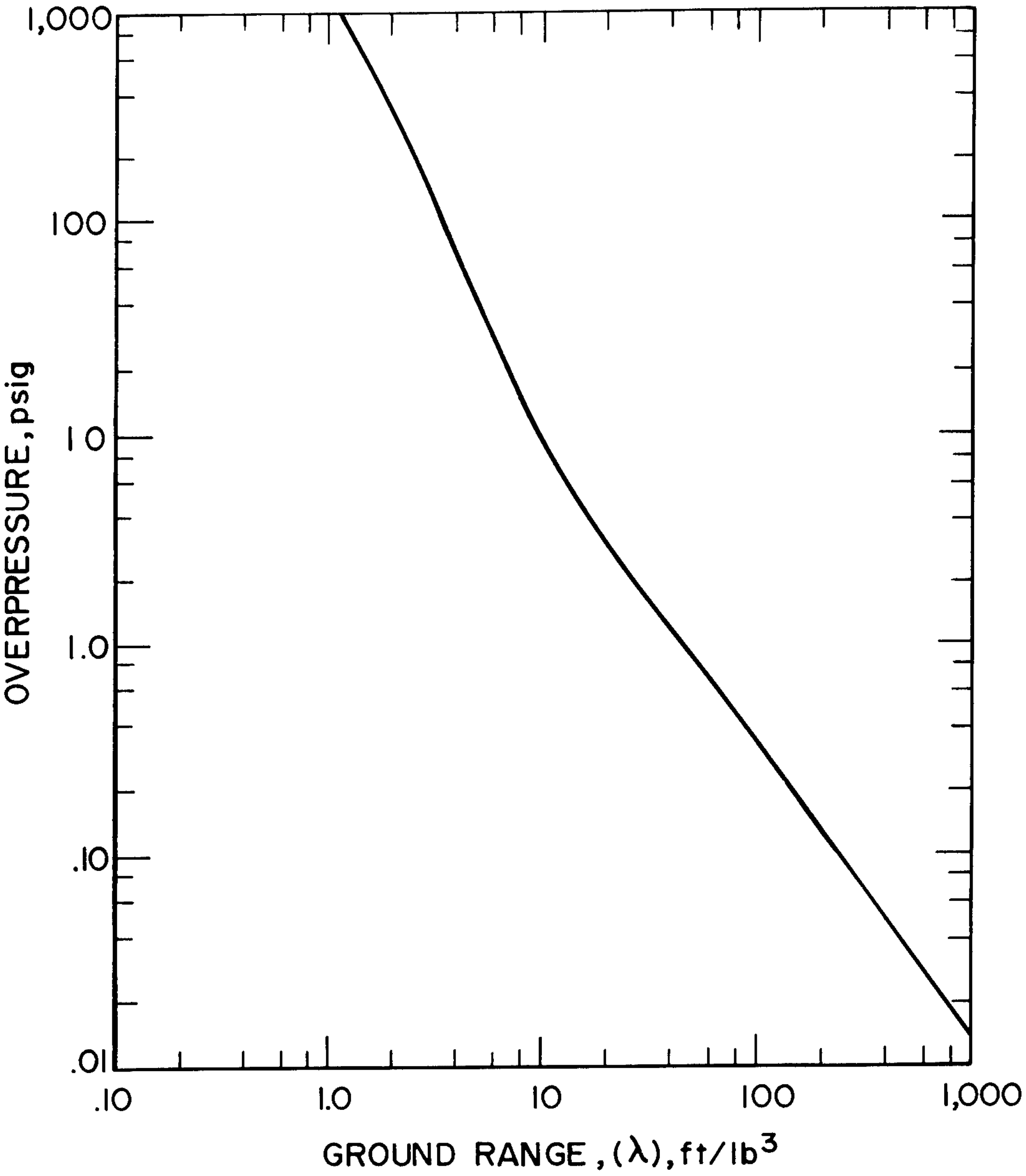


FIGURE 38. Peak overpressure vs scaled distance for hemispherical TNT surface bursts.

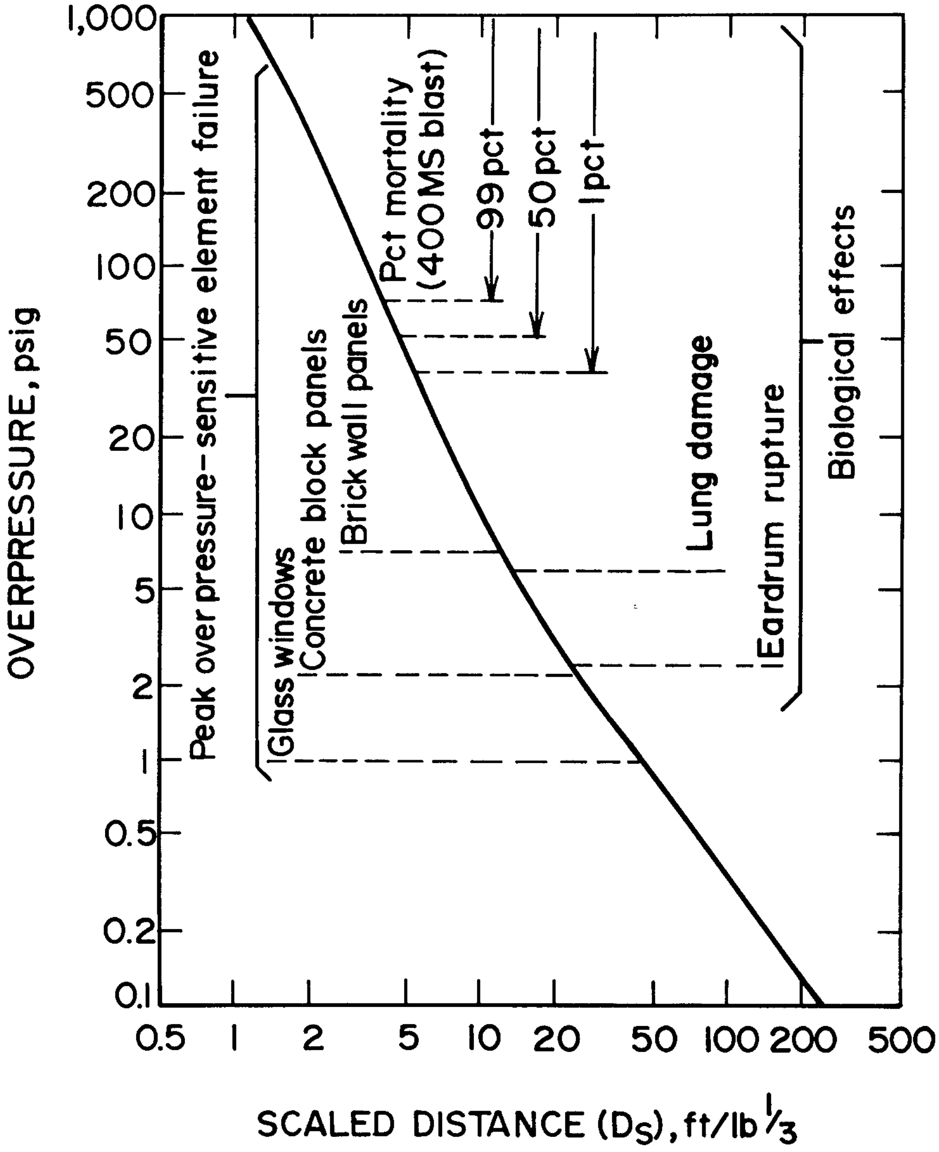


FIGURE 39. Peak overpressure and approximate damage potentials from hemispherical TNT surface bursts.

Table 8. Peak Overpressures for Failure of Structural Materials[a]

Structural Material	Usual Failure	Peak Blast Overpressure, psi
Glass windows	Shattering	0.5 - 1.0
Corrugated asbestos siding	Shattering	1.0 - 2.0
Corrugated steel or aluminum paneling	Connection failure and buckling.	1.0 - 2.0
Wood siding panels (standard house constr.)	Connection failure and buckling.	1.0 - 2.0
Concrete or cinderblock walls, 8 or 12 inches thick (not reinforced)	Shattering	2.0 - 3.0
Brick walls, 8 or 12 inches thick (not reinforced)	Shearing and flexure failures	7.0 - 8.0

a/ Reference 40.

Table 9. Scaled Distance for Building Damage from Statistical Survey of Chemical Explosions[a]

Category	Building Damage	Scaled Distance, (λ) ft/lb$^{1/3}$
A	Demolished, not standing	7.4
B	Severe damage; standing but substantially destroyed, some walls gone	16.6
C	Moderate damage; walls bulged, roof cracked or bulged, studs and rafters broken	25.0
D	Slight damage; doors, sashes, or frames removed; plaster or wallboard broken; shingles or siding off.	28.1
E	Minor damage to glass or miscellaneous small items (similar to that resulting from high wind)	42.7

a/ Reference 44.

The application of TNT equivalents to the explosions of other solid or liquid explosives is fairly reliable since their energy yield is closely related to their calculated heats of explosion (ΔH).* However, in the case of gaseous explosions, the fraction of available chemical energy that is converted into blast energy or "pressure energy" can vary greatly depending upon the confinement conditions and whether the gas mixture is detonable (Ref. 45). If the gas expansion following an explosion or tank rupture is assumed to be isothermal, ($P_1V_1 = P_2V_2$), the work (output) is defined as:

$$W = - nRT \ln (P_1/P_2) \qquad (47)$$

where P_1 is the elevated pressure or tank pressure at rupture and P_2 is the final pressure after expansion. However, this expression greatly overestimates the work for most explosions since isothermal conditions are not maintained. The following expression, which assumes adiabatic expansion, ($P_1V_1\gamma_1 = P_2V_2\gamma_2$) gives more realistic values for the work or "pressure energy":

$$W = \frac{P_1 V_1 - P_2V_2}{1 - \gamma} \qquad (48)$$

where V is volume and γ is the ratio of specific heats. Thus, if a gaseous deflagration occurs in an unconfined system, P_1 will be very low and the TNT equivalent will be close to zero. In a weakly confined deflagration, P_1 will not attain the maximum constant volume explosion pressure and, therefore, the TNT equivalent will be determined by the "pressure energy" (W) rather than the available chemical energy (ΔH). In comparison, the TNT equivalent of strongly confined gaseous deflagrations (or most any detonation) will tend to relate closely to the energy yield given by their heats of combustion (ΔH). Aircraft fuel tank explosions would fall in the weak confinement category with relatively low "pressure energy", whereas those in the combustion chamber of a reciprocating engine would be in the strong confinement category. As a guideline, one can assume that the "pressure energy" of weakly confined gas explosions will be about 10 percent of the heat of combustion of the mixtures.

F. Crater and Missile Damage

In an aircraft accident, ground craters can result from the violent impact of the aircraft. They can also occur from the detonation of large charges of explosives that may be carried by the aircraft. By use of the cube root scaling law, the crater diameter for the detonation of high explosives (Table 11-A) can be expressed as

$$d = d_o \; W^{1/3} \qquad (49)$$

---

*/ A ΔH value of 1100 cal/g (1980 Btu/lb) is generally used to define the energy yield of 1-lb of TNT. The heat of detonation given in table 11-A for TNT (2520 Btu/lb) is high partly because H_2O (ℓ) instead of H_2O (g) was assumed as an explosion product.

where W is the charge weight and d_o is the scaled diameter for a unit weight of charge. If W is in pounds, d_o for a 1-lb TNT charge or equivalent will be about 1.5 or more, depending upon the nature of the surface and the depth to which the charge is buried. The depth of the crater is usually not more than about 1/4 the diameter. Figure 40, (Ref. 46) shows the predicted crater dimensions for explosions at various charge depths in dry soil with the dimensions scaled to 1-ton charges of TNT. Generally, surface explosions of deflagrating materials, e.g., smokeless gun powders, do not produce craters.

The damage by missiles or fragments from an explosion will depend upon their mass and velocity. Approximately 10 percent of the available chemical energy (strong confinement) or pressure energy (weak confinement) in a gaseous explosion may be assumed to be required for rupturing a vessel or tank (Ref. 47). Also, about 20 percent of the available energy can be taken as the kinetic energy of the fragments ($1/2\ m\ v^2$). Thus, if the mass (m) of a fragment and chemical energy (ΔH) of the explosive mixture are known, the fragment velocity (v) can be calculated. For cased explosive charges, more complicated expressions are necessary for calculating the fragment velocities. The depth of penetration into mild steel that can be produced with small metal missiles ($\lesssim$ 1 oz) at various velocities is shown in figure 41 (Ref. 48). Note that any of the missiles with a striking velocity of 2000 ft/sec could penetrate steel vessel walls of at least 0.15 inch thickness; this velocity is in the same range as that obtained from firing a 30-caliber weapon (e.g. 2-3000 ft/sec). The human damage levels that could result from head or total body impacts (tertiary effects) at various velocities are indicated in figure 42 (Ref. 49); this figure also describes blast-induced translational velocities for a nylon sphere as a function of time. It should be noted that the threshold impact velocity for a skull fracture is slightly over 10 ft/sec, as compared to about 30 ft/sec for the lethal level with a 100 percent probability. The "safe" threshold of 10 ft/sec for head impacts is also comparable to the "safe" limit reported for total body impacts and for head impacts produced by a 10 lb blast fragment (secondary effect); the kinetic energy of such a fragment would be equal to about 16 ft-lbs.

The initial velocity (v_o) of an explosion fragment can be estimated from its distance from the explosion site, i.e., its range (R). The maximum range is obtained when the trajectory angle (α) of the missile is 45°:

$$R = \frac{v_o^2 \sin 2\alpha}{g} \tag{50}$$

where g is the gravitational constant (32 ft/sec^2). One can also estimate the striking velocity (v_s) if V_o, R, and the drag coefficient (K_D) for the object are known:

$$v_s = v_o\ e^{-kR} \tag{51}$$

Here, the constant $k = K_D\ A/m\rho$, where ρ is air density, and A (area) and m (mass) refer to the fragment. Further discussion on this topic is given in reference 50.

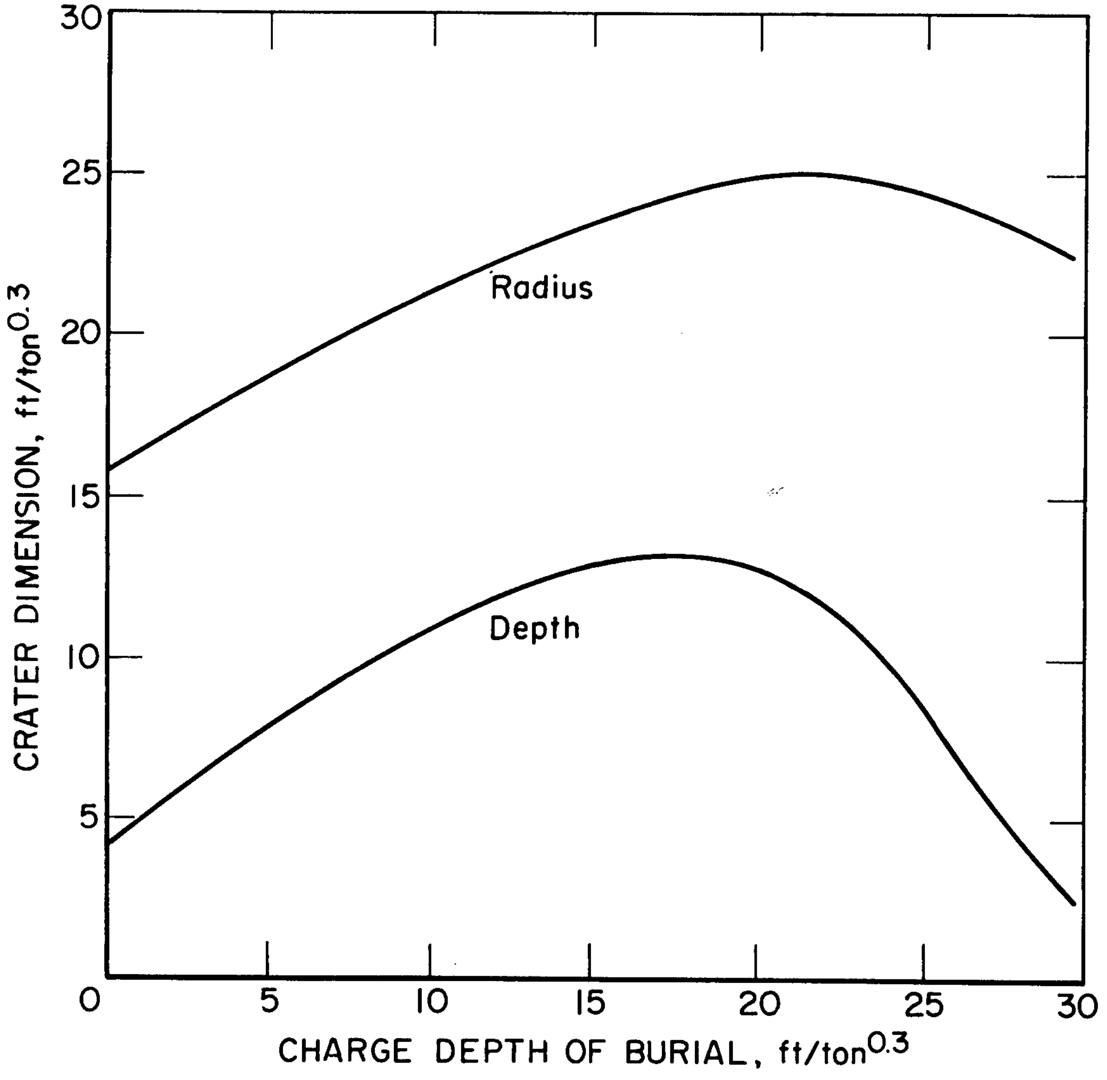


FIGURE 40. Crater dimensions scaled to 1-ton charges of TNT or equivalent buried in dry soil.

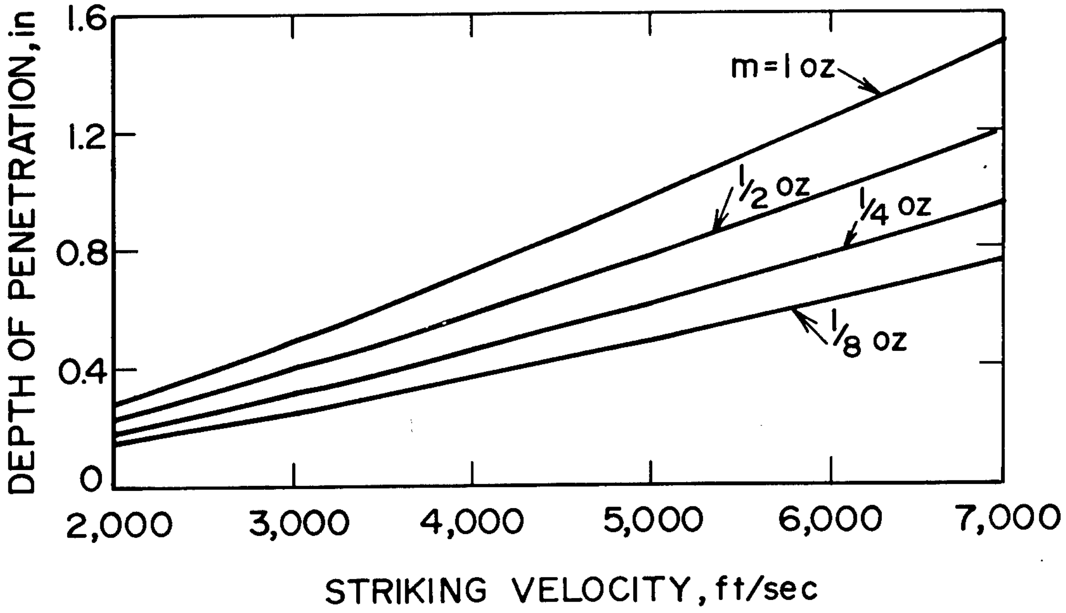


FIGURE 41. Depth of penetration of mild steel vs striking velocity for steel fragments of various weights (m).

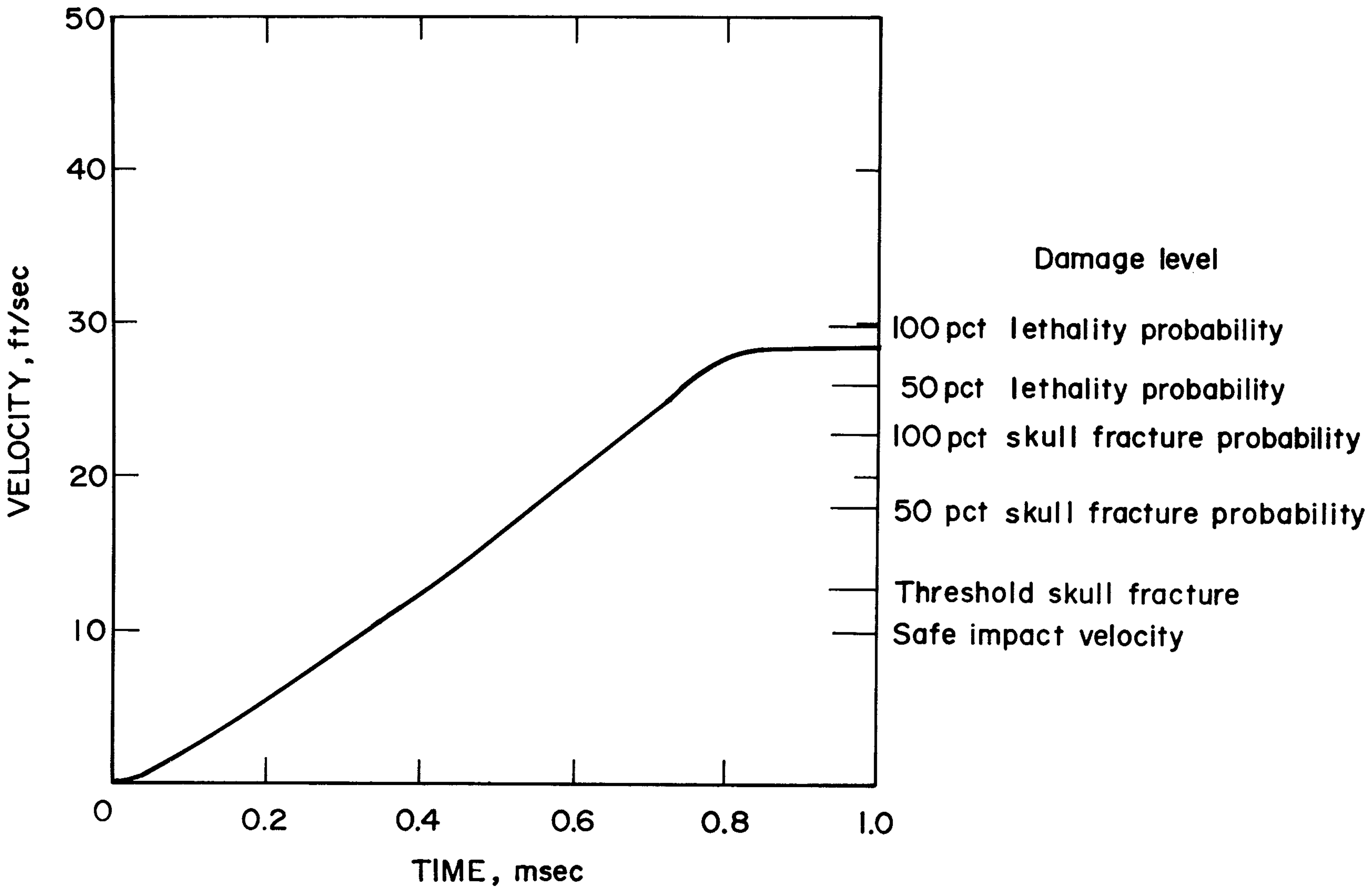


FIGURE 42. Velocity-time profile for translation of 1/8-inch diameter nylon sphere.

SAFETY PROTECTIVE MEASURES

The most important part of an accident investigation report is the recommendation of safety measures to prevent the recurrence of a similar mishap. Both equipment and operational procedures or conditions must be included in such evaluations. This section describes some of the safety protective measures that require consideration where fire or explosion is a possible occurrence.

A. Explosion Venting

If the hazard of a gaseous explosion cannot be eliminated, protective measures must be taken to minimize the damage that may result from an accidental ignition. In many situations, some level of pressure build-up can be tolerated and a suitable explosion venting system can be installed to prevent structural failures. Although one cannot rely upon explosion venting for use on aircraft, the fact that the engine bays of fighter aircraft are vented has prevented many explosion disasters. The venting requirements depend greatly upon the burning velocity of the combustible mixture (gas or dust), as well as the size and geometry of the confining medium. For example, the venting requirements are more stringent for hydrogen air explosions than for methane-air explosions because of the higher propagation rates and pressure rise rates that are possible with hydrogen.

The venting requirements are generally defined in terms of a vent ratio (K) such as the ratio of the cross-sectional area of the duct or chamber to that of the vent. For ordinary hydrocarbon fuel-air mixtures, the maximum pressure (P_2, psig) for explosions in large, weakly confined enclosures (≤ 100 ft^3) is

$$P_2 = K \tag{52}$$

where K is small (e.g. 1-2) and the length/diameter ratio is less than 3 (Ref. 51). For explosions of similar mixtures in open ducts or long vessels, the maximum pressure is given by

$$P_2 = 0.035\ {}^{L}/_{D} + 0.9\ K \quad ; \quad K = 1 \text{ to } 2 \tag{53}$$

$$P_2 = 1.8\ K \quad ; \quad K = 2 \text{ to } 32 \tag{54}$$

where the length/diameter ratio is from 6 to 30 (Ref. 52). Higher maximum pressures can occur when obstacles are present that induce turbulence in the ducts or enclosures, such that flame speeds are substantially higher than 10 ft/sec. Similarly, the venting requirements will be more stringent if a vent cover or closure is used that offers considerable resistance.

Venting requirements may also be expressed as a ratio of the area of the vent and the volume of the protected enclosure. According to NFPA recommendations (Ref. 8), the vent ratio should be 1 square foot/10 to 30 cubic feet for small enclosures (<1000 ft^3) of light construction and 1 square foot/30 cubic feet for those having reasonably high bursting strength. For relatively large enclosures (1000 - 25,000 ft^3), such as bins, rooms, storage tanks, etc., the recommended ratio is 1 square foot/30 to 50 cubic feet. Again, it is emphasized that these venting guidelines are primarily applicable to explosions in which rates of pressure rises are not exceptionally high.

B. Explosion Inerting

Inerting can be used to protect against ignitions in fuel tanks and other enclosures or compartments that are not ordinarily occupied. If it is impractical to inert a hazardous area for long periods because of leakage or venting conditions, such as in a "breathing" aircraft fuel tank, a triggered ignition suppression system can be used. Such systems are normally equipped with an optical flame sensor or other suitable detector which triggers an explosive actuator that releases a pressurized inerting agent. Since some aircraft compartments can withstand only a few pounds pressure, the triggered inerting system must be designed to detect and quench an incipient ignition within a fraction of a second, depending upon the compartment volume.

The efficacy of any inerting system is usually defined by the minimum concentration required to prevent flame propagation through all possible mixtures of the given fuel and oxidant. Nitrogen (N_2) is a more effective inert than helium but less effective than carbon dioxide (CO_2), whereas water vapor or engine exhaust gases tend to rank between N_2 and CO_2. Inerting values obtained with upward flame propagation and with relatively large diameter apparatus (≥ 2 inch) should be relied upon since these conditions yield the more conservative values. For hydrocarbon fuels such as gasoline (73-100 octane), the minimum inerting concentrations in atmospheric air (80° F) are about 42 percent with N_2 and 29 percent with CO_2 (Figure 43) (Ref. 19). In comparison, with chemical flame inhibitors such as Halons 112 ($CHCl_2F$), 113 (CCl_3F), and 122 (CCl_2F_2), the inerting concentrations are as low as 10 to 16 percent. The most effective halogenated inhibitors are those containing bromine. As noted in figure 44, (Ref. 53), the minimum concentrations required for inerting methane-air mixtures at atmospheric pressure (75° F) range between 3.8 and 5.3 percent for Halons 1202 (CF_2Br_2), 1211 (CF_2BrCl), and 1301 (CF_3Br). Table 12-A (Ref. 68) lists the physical properties of various halogenated hydrocarbon fire extinguishants.

In determining safe design concentrations for inerting, a safety factor of about 20 percent should be applied to the experimental threshold values to allow for any uncertainties. Table 10 lists Halon 1211 (Ref. 54) and 1301 (Ref. 55) inerting design concentrations that are recommended by the NFPA for various combustibles; a 10 percent safety factor is included. The NFPA recommended values of 2.0 percent Halon 1301 and 4.3 percent Halon 1211 for methane are not sufficiently conservative, considering the higher values obtained by the Bureau, as well as other investigators. Table 10 also

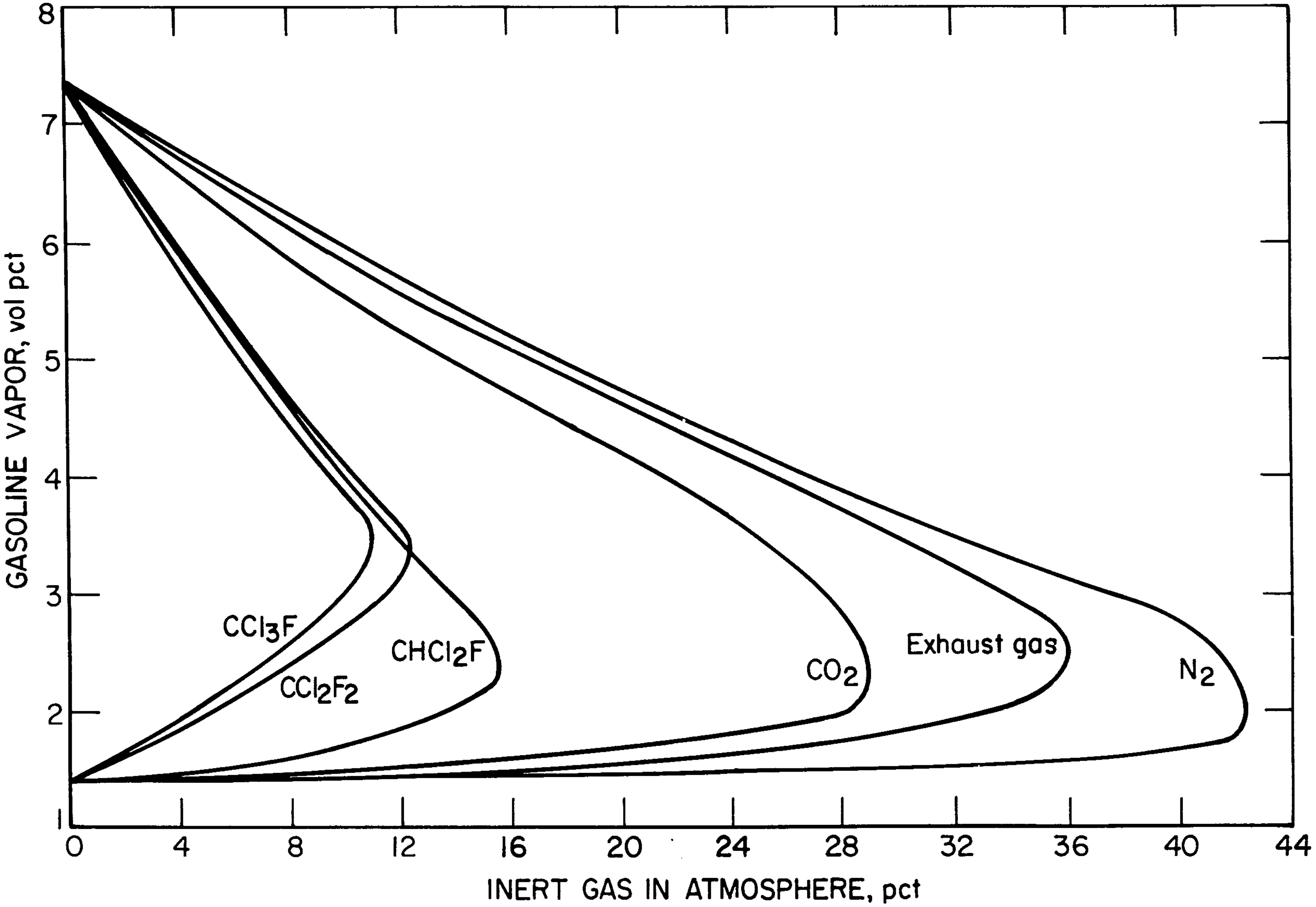


FIGURE 43. Effectiveness of various inerting agents on limits of flammability of gasoline vapor-air mixtures at 80°F and atmospheric pressure.

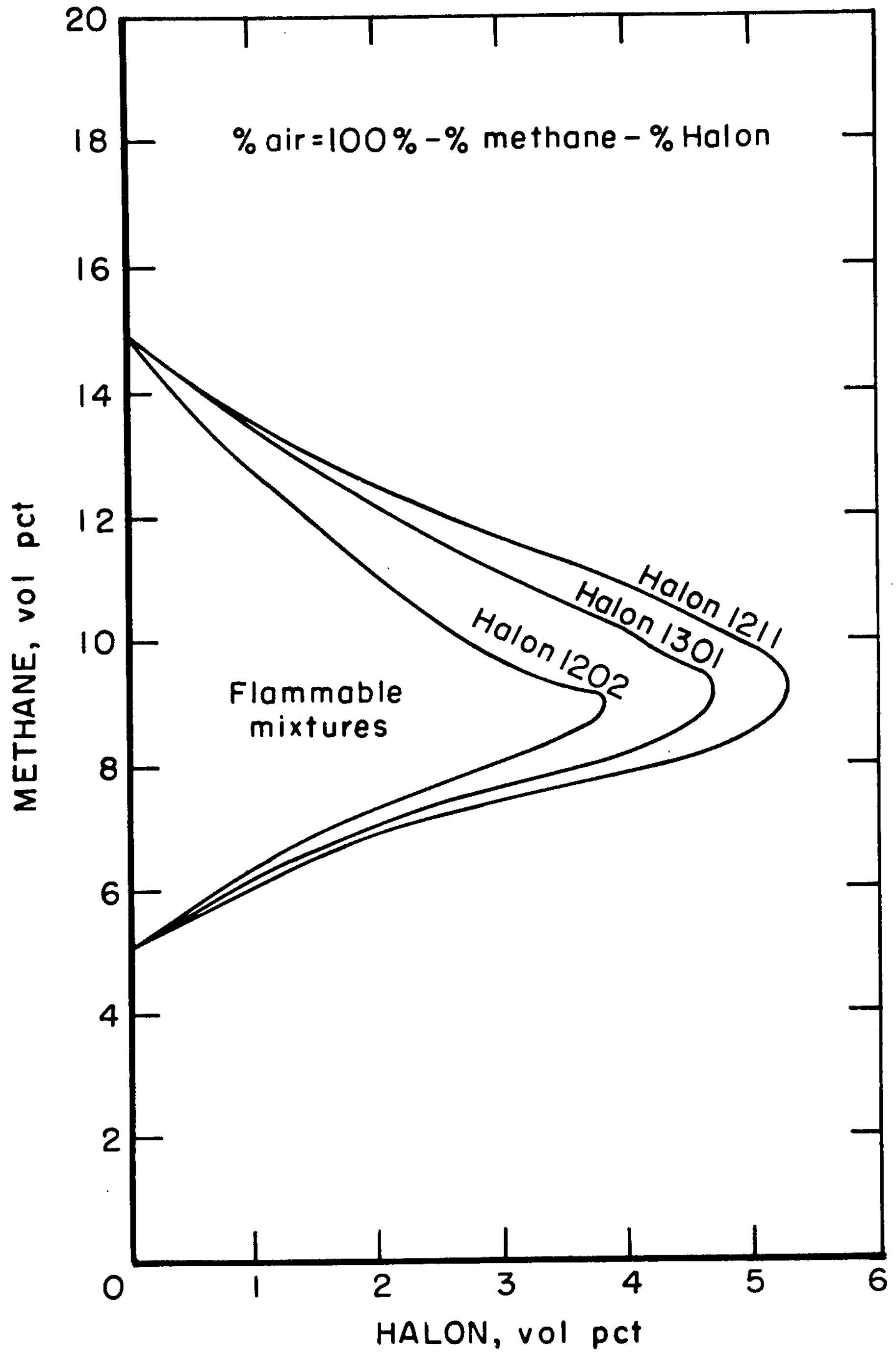


FIGURE 44. Limits of flammability of methane-air mixtures inhibited with Halons 1202, 1211, and 1301 at 75°F and atmospheric pressure.

includes CO_2 and N_2 inerting requirements that were obtained by the Bureau for the various combustibles. Corresponding minimum O_2 values for some of the combustibles are given in the flammability section of this manual, which also discusses the effects of ambient temperature and pressure on such limits.

The inerting requirements are influenced not only by vessel diameter and direction of propagation, but also by ignition source energy. The values in table 10 were obtained with a single spark energy source and would tend to be higher with multiple or other more severe sources which increase the temperature and heat flux throughout the gas mixture.

Table 10. Inerting Requirements for Various Combustibles in Air at Ambient Temperature (~70 °F) and Atmospheric Pressure

Combustible	Inerting Agent, volume percent			
	CO_2 [a]	N_2 [a]	Halon 1211 [b]	Halon 1301 [c]
Methane	23	36	4.3 (5.3 [a])	2.0 (4.7 [a])
Ethane	31	44	5.6	-
Propane	28	42	4.8	6.5
Butane	27	40	4.1	-
i-Butane	26	40	3.9	8.0
n-Pentane	28	43	4.5	-
n-Hexane	28	42	4.1	-
n-Heptane	28	42	4.3	8.0
Ethylene	40	49	6.5	11.0
Propylene	28	42	-	-
Benzene	28	43	3.9	4.3
Gasoline	29	42	4.2	-
JP-4	29	43	-	6.6
Methyl alcohol	33	47	9.1	-
Ethyl alcohol	32	44	5.0	4.0
Acetone	27	42	4.2	5.3
Carbon monoxide	41	58	-	-
Hydrogen	57	72	22.6	20.0

a/ BuMines data
b/ Reference 54; include 10 percent safety factor
c/ Reference 55; include 10 percent safety factor

Figure 45 (Ref. 56) shows the increased Halon 1301 requirements (9-10%) for quenching stoichiometric n-pentane-air mixtures that were ignited with an incendiary charge and 30 caliber incendiary ammunition; 5 to 6 percent Halon would normally be required with a spark ignition source.

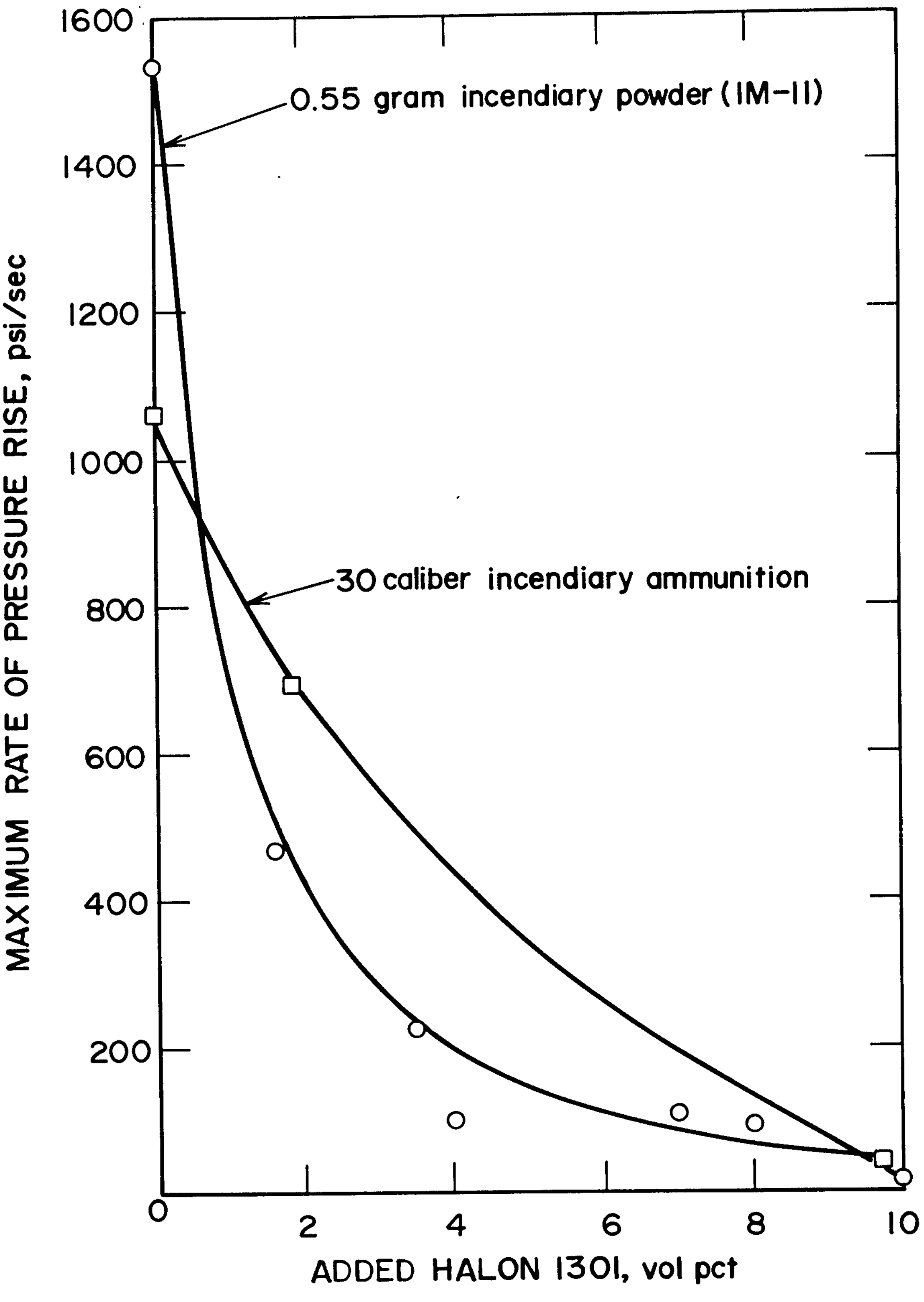


FIGURE 45. Effectiveness of Halon 1301 in quenching incendiary ignitions of near-stoichiometric n-pentane-air mixtures (1 atm) in a 74 gallon fuel tank at 75°F.

C. Fire Control

Time is the most critical factor in fighting aircraft fires, particularly during flight or following a survivable crash there the fire must be controlled within seconds. All compartments in which a fire hazard may exist must be equipped with fire detectors; these can include fixed pressure or temperature, rate of temperature rise, or optical flame sensors, depending upon the desired response. Automatic flame suppression systems, similar in principle to triggered inerting systems, are necessary when providing fire protection to engine compartments and other high fire risk areas. Cargo bays and other unoccupied areas may be similarly protected depending upon the ignition hazard level and practical considerations. Halon systems are preferred for at least the fire zone areas because of their greater effectiveness. Table 11 summarizes the military specifications for two types (fixed) of aircraft engine fire extinguishing systems that employ Halons as the agents (Ref. 68). The extinguishing design requirements for aircraft fuels and other combustible liquids should be no less than their inerting requirements, such as those listed in table 10. For the crew and passenger compartments, CO_2 or water portable extinguishers should be provided as outlined by the NFPA (Ref. 8).

Although halogenated agents present toxicity problmes, Halon 1301 (undecomposed) is not highly toxic and may be used in occupied areas providing the concentrations are not over 10 percent (Ref. 55). In such instances, the dispersion should be by the total flooding mode to insure rapid extinguishment without a hazardous accumulation of toxic decomposition products. If properly designed, Halon 1301 total flooding systems can be effective even against certain Class A surface fires e.g. paper or cotton sheeting (Ref. 36); however, the combustible loading and human exposure time to toxic products must be considered in contemplating such applications with this extinguishant. Furthermore, gaseous agents are not considered suitable for deep-seated fires because of the penetration and cooling limitations with gases.

In a survivable crash situation, it is of utmost importance to envelope the aircraft with a fire extinguishant as rapidly as possible to permit safe egress of the crew and passengers. Thus, an aqueous foam is preferred for such situations. With a high expansion foam, the minimum application rate for obtaining fire control of small pool fires appears to be of the order of 0.02 $lbs/sec\text{-}ft^2$ for benzene or xylene and 0.04 $lbs/sec\text{-}ft^2$ for hexane (Figure 46) (Ref. 57); the foam in figure 46 was an ammonium lauryl sulfate type (0.21 percent) with an expansion ratio greater than 600. In comparison, the minimum application rate for extinguishment of a 50-by 50-ft gasoline fire by high expansion foam is reported to be only about 0.005 $lb/sec\text{-}ft^2$ (Ref. 57). Minimum application rates of this magnitude also appear to be required when relatively large-scale fires of these fuels are extinguished with dry chemical agents; the curve in figure 46 for dry chemicals was taken from reference 58. This scale effect is believed to be partly attributable to the screening of thermal radiation from the flame to the liquid surface, which should be more noticeable with increasing pool diameter.

Table 11. Aircraft Fixed Fire Extinguishing Systems[a]

System Type	Specification	Agent	Agent Quantity,[b] Lbs	Discharge Duration	Discharge Outlets
Conventional	MIL-E-5352	Bromochloromethane Dibromodifluoromethane	$0.56(W_a) + (0.16)^a(V)_*$	2 Seconds or Less	Perforated Tubes
High Rate	MIL-E-22285	Bromotrifluoromethane Dibromodifluoromethane	$W= 0.05V$ $W= 0.02V + 0.25W_a$ (Whichever is greater) Design Guide	1 Second or Less	Open Ended Lines

[a] Reference 68

[b] *V = Net Volume of Zone in Cu. Ft.
W_a = Air Flow (Normal Cruise) in Lbs. Per Second

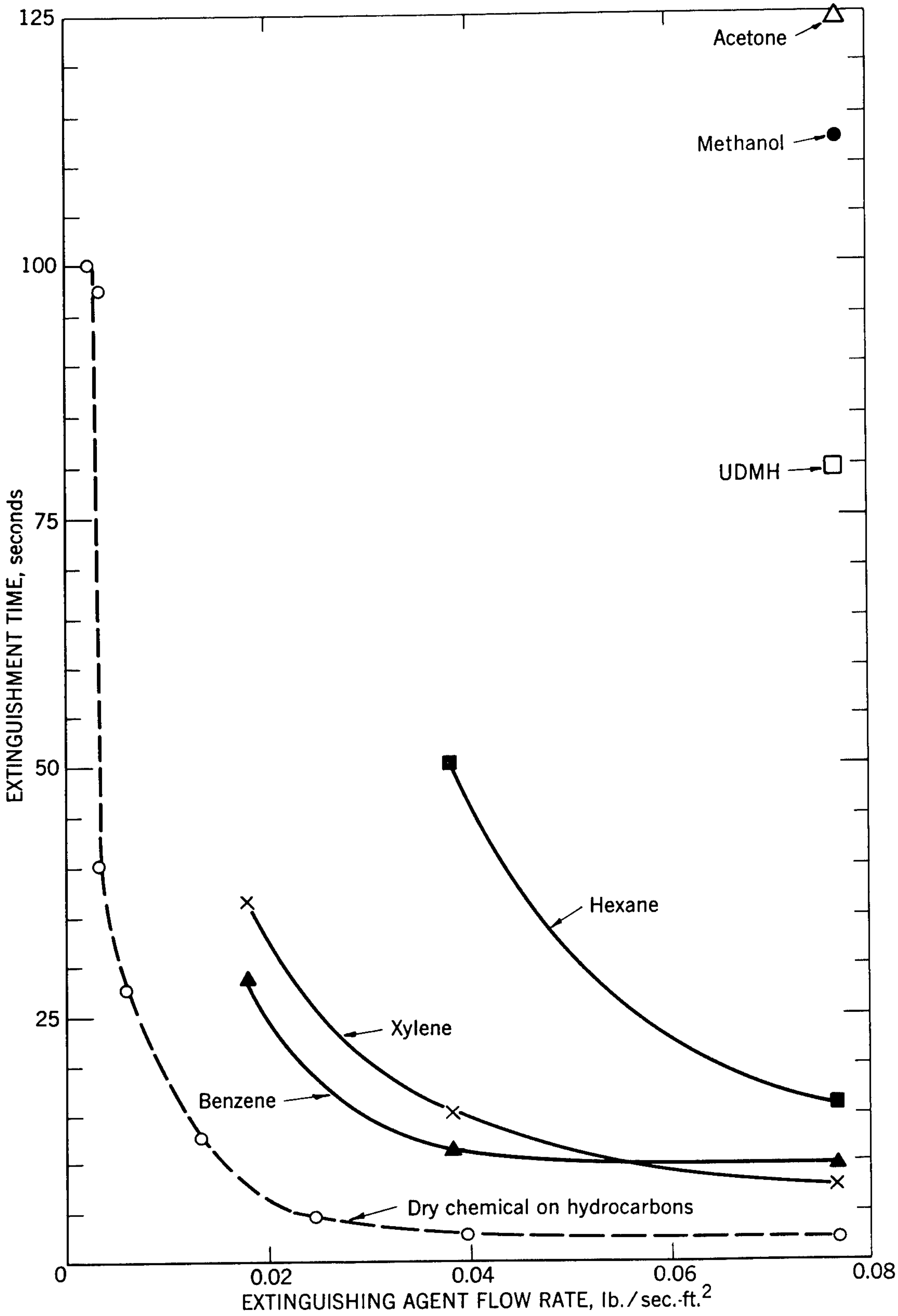


FIGURE 46. Minimum application rates of foam and of dry chemical for extinguishment of hydrocarbon and nonhydrocarbon fuel fires.

A low expansion foam is preferable to a high expansion foam from the standpoint of achieving greater cooling capacity and greater penetration to the "seat" of the fire. A fluoroprotein agent (6 percent) is widely used for large-scale fires and is compatible with potassium bicarbonate powders, such as Purple K. This agent and an aqueous film forming foam (AFFF), which is similar to "light water", are considered by the FAA to be among the most superior fuel vapor securing and blanketing agents; their expansion ratios are less than 100. Full-scale fire extinguishing tests by the FAA have shown that Jet A fuel fires can be controlled with the AFFF agent at an application rate of about 0.02 gal/min-ft^2 (Figure 47) (Ref. 39). Furthermore, if the application rate is greater than 0.1 gal/min-ft^2, fire extinguishment can be achieved in less than 30 seconds with either U. S. Air Force or U.S. Navy fire fighting vehicles. Such extinguishing times are necessary to minimize fatalities in survivable aircraft crash accidents. After each accident, the time response and effectiveness of the fire fighting equipment should be evaluated.

D. Flameproof Equipment and Flame Arrestors

Electrical equipment on aircraft must meet Air Force design specifications and the National Electrical Code. This code divides hazardous locations into three classes, depending upon the flammable material in the given environment; Class I - flammable gases and liquids, Class II - combustible dusts, and Class III - ignitable fibers or flyings. Of particular interest here is Class I, which includes atmospheres containing the following groups of representative flammable materials:

Group A - Acetylene
Broup B - Hydrogen or manufactured gas
Group C - Ethylene, diethyl ether, acetaldehyde, or isoprene
Group D - Paraffins, paraffinic alcohols, acetone, benzene, xylenes, gasoline, naphtha, or organic solvents.

Since flameproof enclosures must generally be used when electrical equipment may be exposed to flammable gases or vapors, it is important to know the maximum gap between enclosure flanges that will prevent transmission of flames or hot gases which can ignite a flammable atmosphere. The Underwriters' Laboratories (UL) has published this information for a limited number of flammable gas or vapor-air mixtures and is currently extending these measurements to other materials that fall under the above four groups (Ref. 59). The British have been similarly active in this area. Figure 48 (Ref. 60) shows a correlation which they obtained between the maximum experimental safe gap and minimum igniting current (break spark) for various gases or vapors; the minimum igniting current is of interest in designing intrinsically safe equipment. Although some of the gap data are higher than those obtained by UL, this figure clearly illustrates the more severe gap requirements for hydrogen and acetylene as compared to those for the paraffins or Group D fuels. The Group D fuels are included under the British Standard 229 as Groups I (methane) and II. Jet fuels fall under Group D unless the fuel temperature presents an autoignition hazard.

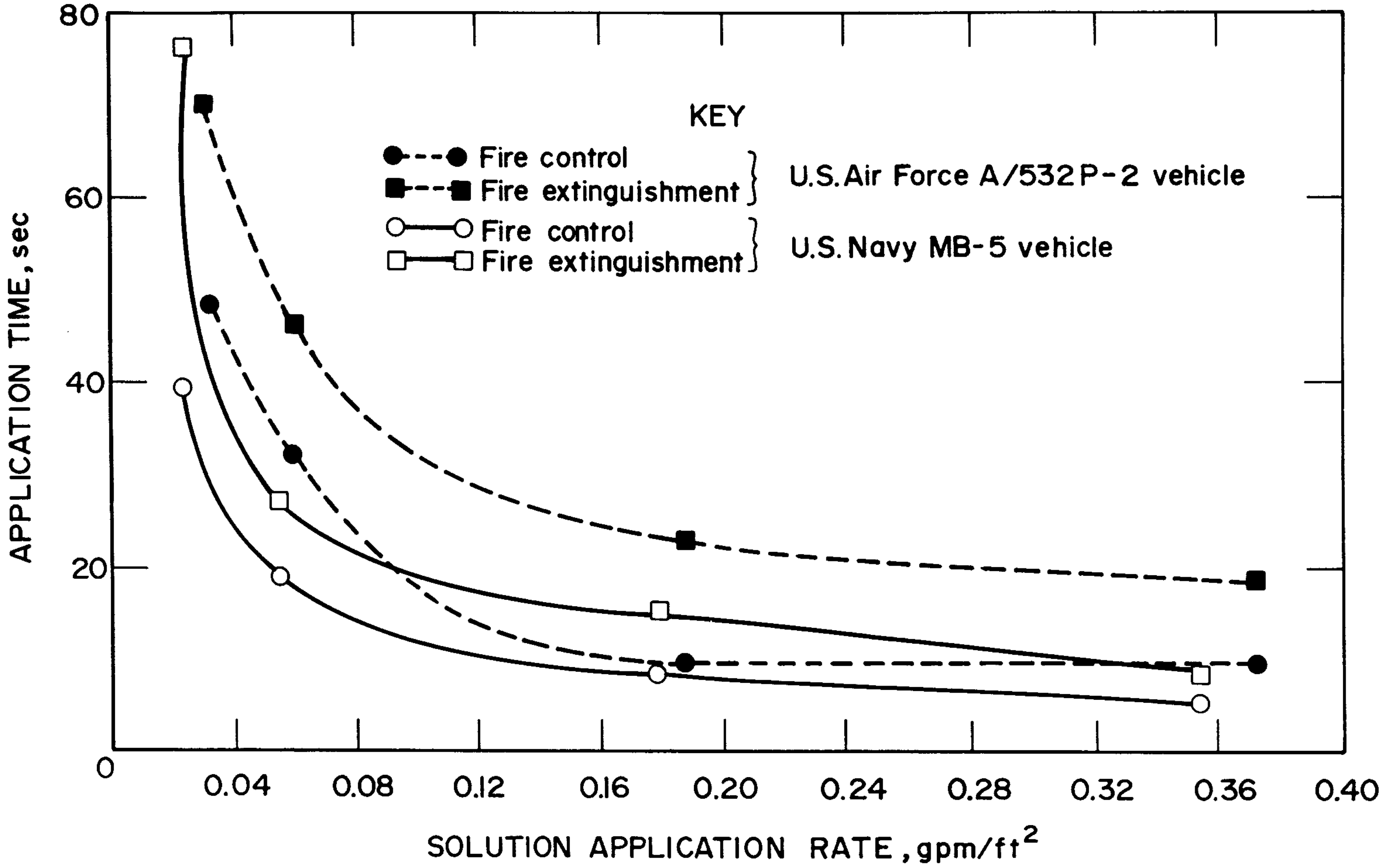


FIGURE 47. Fire control and extinguishing times as a function of AFFF solution application rate for Jet A fuel fires using the Air Force A/S32P-2 and U. S. Navy MB-5 trucks.

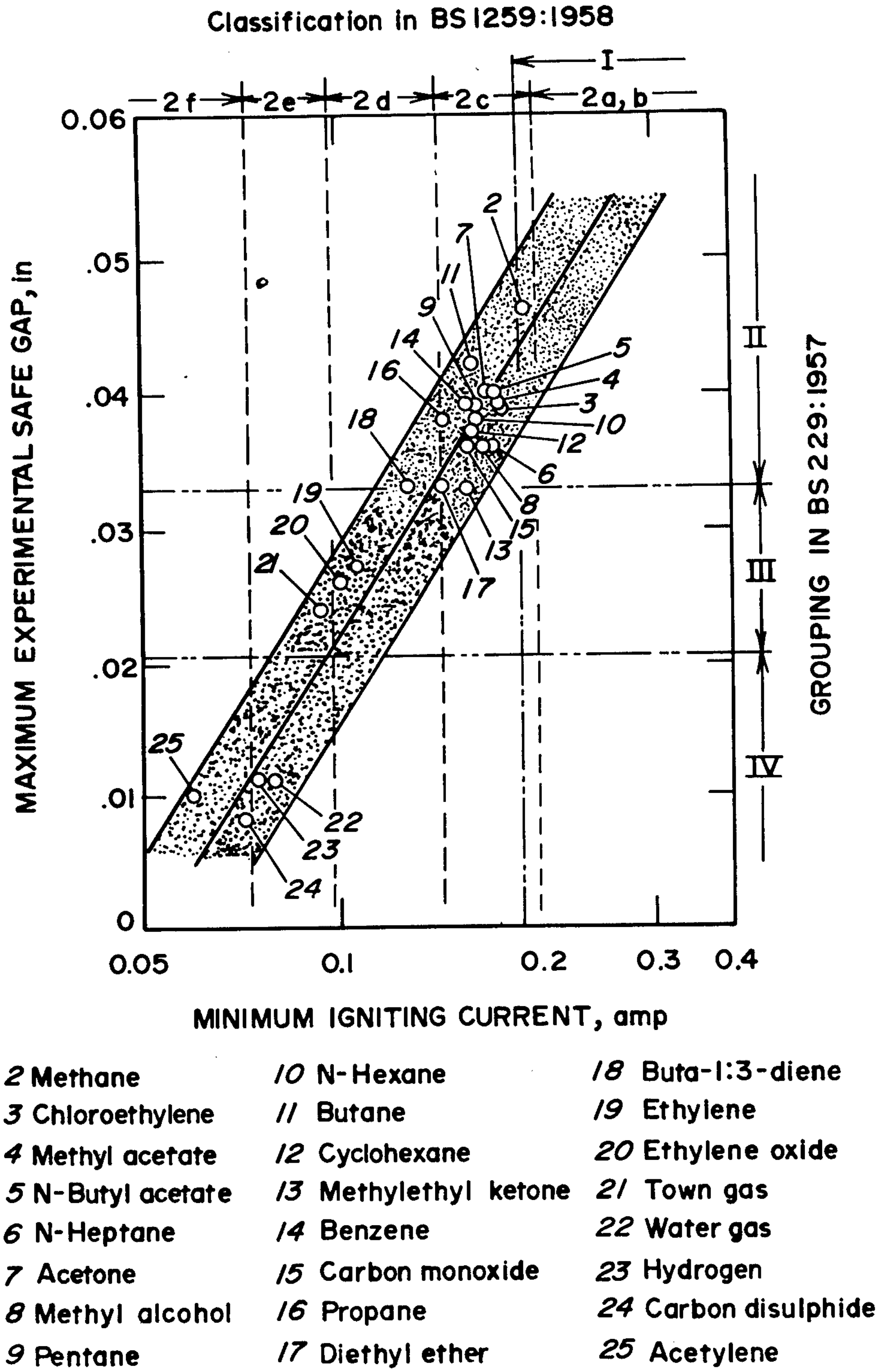


FIGURE 48. Correlation of maximum experimental safe gap with minimum igniting current (limits of 95% confidence shown shaded).

Flame arrestors are another explosion protection device and are normally installed in lines through which an explosion may propagate or spread to other areas. The following equation predicts the maximum speeds of flames (excluding detonations) that can be quenched by crimped metal, wire gauze, and perforated flame arrestors (Ref. 52):

$$v = 0.5\ a\ y/d^2 \tag{55}$$

where v is flame speed (ft/sec), a is the proportion of arrestor surface area not blocked by arrestor material, y is thickness of arrestor (inch), and d is diameter of aperture (inch). In the case of gauze arrestors, this equation is limited to single layers and y is equal to twice the wire diameter. Also, d should not exceed 50 percent of the quenching diameter and y should be increased or d decreased if the pressure is substantially above atmospheric. The minimum quenching diameter for a given flammable mixture is about 1.5 times greater than the minimum quenching distance obtained with flat plates.

Flame arrestors can also be used to protect against fuel tank explosions. A reticulated polyurethane foam has been installed in the fuel tanks of some military aircraft for this purpose. The effectiveness of such flame arrestors is strongly dependent upon the foam porosity, free tank volume or flame run-up distance, and the fuel tank pressure (Figure 49) (Ref. 61). A 10 pore/inch foam is adequate at atmospheric pressure if the fuel tank is fully packed, but a higher porosity rating (e.g. 20 pores/inch) is necessary for a partially packed tank, particularly if multiple ignition sources are possible. Since this type of flame arrestor is combustible and decomposes at about 500° F, its use must be limited to applications where the exposure time to flame is relatively short. In all cases, the arrestor should be designed to quench the propagation of flame and to reduce the temperature of the gaseous products below the hot gas ignition temperature (see figure 30) of any flammable gas in the given system.

E. Fire Resistant Materials and Toxicity

To reduce the ignition and flame spread hazard, materials of high fire resistance should be used in the fire zone areas and passenger or crew cabins of an aircraft. If a fabric or other solid material is specified by the vendor as being fire resistant, it should be recognized that this represents only a relative rating which may not reflect the flammability hazard in a large-scale fire. Certainly, one should not rely upon any ratings based upon downward or horizontal burning since the ratings will be much less conservative than those based upon upward burning (Ref. 69).

Unfortunately, the use of fire resistant materials can result in the release of toxic vapors when these materials are involved in a fire. In fact, materials like polyvinyl chloride and neoprene can decompose and evolve toxic vapors (e.g. HCl) when heated to only a few hundred degrees above ambient; also, the fire resistant plastics tend to produce more

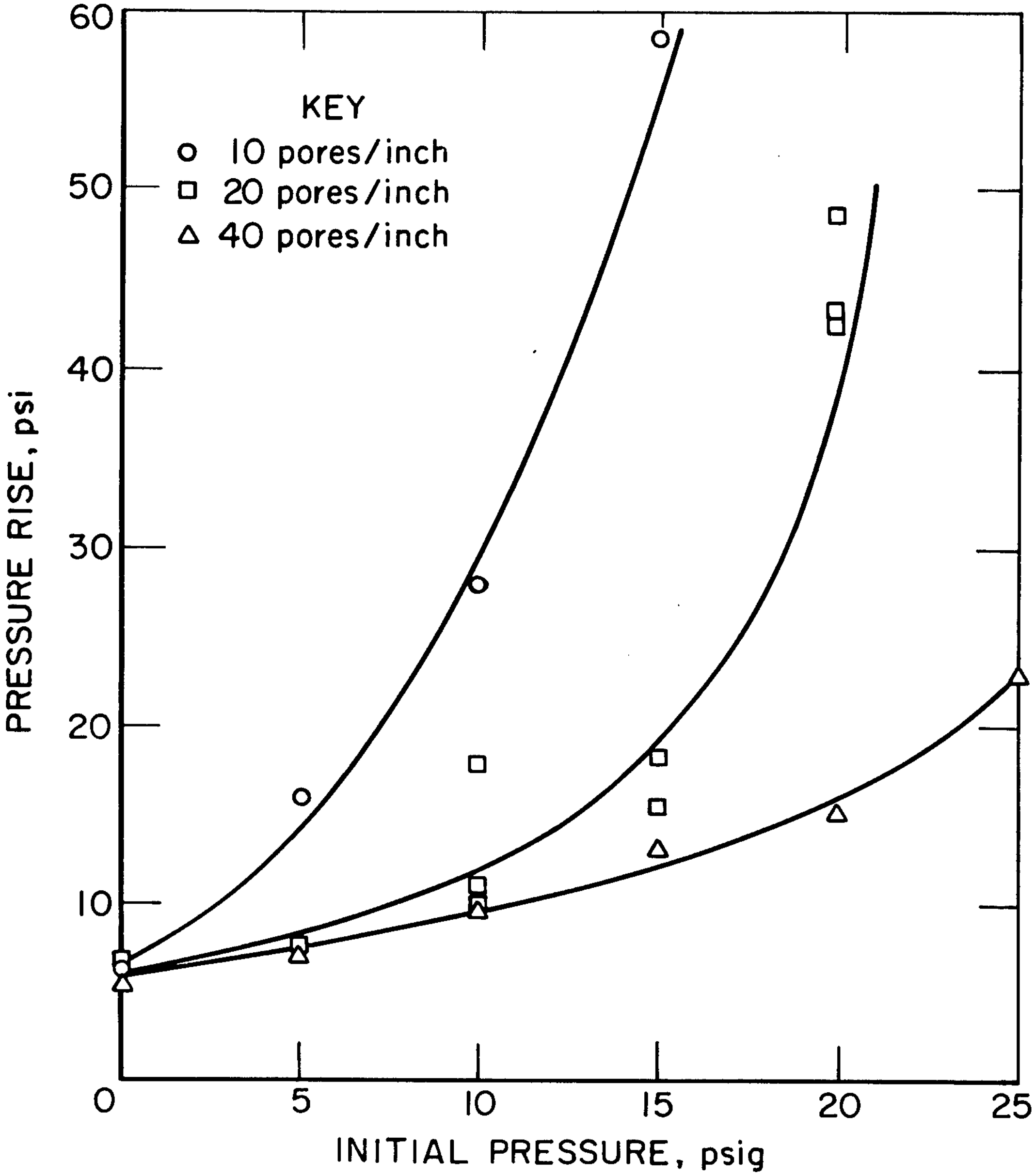


FIGURE 49. Effectiveness of 10, 20, and 40 pore/inch polyurethane foam in quenching ignitions of near-stoichiometric n-pentane-air mixtures (1 atm) in a 1-ft^3 cylindrical vessel. Arrestor length (30-in)/Ignition void (18-in) = 1.67.

smoke during burning than do the cellulose-derived materials (Ref. 69). Thus, the presence of the fire-resistant materials in a cabin fire could present an early toxicity hazard.

Table 12 lists the approximate lethal concentrations (ALC's) of various toxic gases for an exposure period of 15 minutes; the ALC's for possible toxic products from halogenated hydrocarbon extinguishants are included in this table. For shorter exposure times, the ALC values in table 12 would be greater. The level of toxic product formation in a fire will depend greatly upon the amount of material consumed and the air ventilation rate. If the mass burning rate (dw/dt) and specific toxic product formation per unit mass (v_g) of material are known, the concentration of a particular toxic vapor (C_g) in a ventilated chamber can be obtained from the following expression:

$$C_g = 100 \frac{v_g \ dw/dt}{Q_{air} + Q_{gas}} \cong 100 \frac{v_g \ dw/dt}{Q_{air}} \quad (56)$$

where C_g is in volume percent, v_g is in in^3/lb, dw/dt is in lbs/min, and the flow rates ($Q_{air} \gg Q_{gas}$) are in in^3/min. Since v_g is equal to the ratio of the total volume of specific toxic vapor to the total mass of consumed material, the amount of fire resistant material that would avoid toxic levels, such as those in table 12, can then be calculated.

The accident investigator should always bear in mind that synergistic effects are possible and that most lethal thresholds of toxicity have been based on animal exposures rather than human exposures. Also, since the exposure time to fire products is a highly critical factor, he should make certain that the aircraft is equipped with adequate exits to provide rapid egress and that the chances of survival are not reduced because of poor response of the fire fighting equipment (ground or inflight).

Table 12. Approximate Lethal Concentrations of Various Toxic Gases or Vapors for 15 Minute Exposure Periods.[a/]

Toxic Vapor	ALC (15 minute) ppm
Carbon dioxide (asphyxiant)	> 5 percent
Carbon monoxide	1500
Hydrogen fluoride	2500
Hydrogen chloride	4750
Hydrogen bromide	4750
Fluorine	375
Chlorine	350
Bromine	550
Carbonyl Fluoride	1500
Carbonyl Chloride	100-150

a/ Data for halogens and halides from reference 54.

REFERENCES

1. USAF Aircraft Investigators Handbook, AFM 62-5, May 1950.

2. Federal Aviation Administration, Aircraft Accident Investigation and Reporting, Handbook 8020.1 A, September 1968, 62 pp.

3. U. S. Naval Aviation Center, Handbook for Aircraft Accident Investigators, NAVWEPS, 00-80T-67, 1961, 128 pp.

4. International Civil Aviation Organization, Manual of Aircraft Accident Investigation, Doc 6920 - AN/855/4, 1970.

5. National Fire Protection Association, Aircraft Fire Investigators Handbook, Proposed NFPA 422M, 1972.

6. Van Dolah, R. W., M. G. Zabetakis, D. S. Burgess, and G. S. Scott, Review of Fire and Explosion Hazards of Flight Vehicle Combustibles, BuMines IC 8137, 1963, 80 pp.

7. Zabetakis, M. G., Flammability Characteristics of Combustible Gases and Vapors, BuMines Bulletin 627, 1965, 121 pp.

8. National Fire Protection Association, Fire Protection Handbook, 13th Edition, 60 Batterymarch Street, Boston, Mass., 1969.

9. Keenan, J. H. and J. Kaye, Gas Tables, 2nd Printing, John Wiley & Sons, Inc., New York, N.Y., 1949, 238 pp.

10. Shelton, E. M., Aviation Turbine Fuels, 1970, BuMines Bartlesville Petroleum Res. Center, Survey No. 69, February 1971, 13 pp.

11. Botteri, B. P., R. G. Clodfelter, J. R. Manheim, and Lt. E. E. Ott, Evaluation of JP-8 vs JP-4 Fuel for Enhancement of Aircraft Survivability, Air Force Aero Propulsion Laboratory, APFH-TM-70-34, June 1970, 38 pp.

12. Zabetakis, M. G. et al, Research on the Flammability Characteristics of Aircraft Fuels, Wright Air Development Center, WADC Tech Report 52-35, Supp. 1, 1956.
    Ibid, WADC Technical Report 52-35, Supp. 4, January 1956, 85 pp.

13. Diekman, W. R., Aircraft Fire Damage - In Flight and After Impact, Air Force Aircraft Industry Conference on Aircraft Accident Investigation, Santa Barbara, Calif., May 1957.

14. Mullins, B. P. and S. S. Penner, Explosions, Detonations, Flammability and Ignition, Pergamon Press, (London), 1959, 287 pp.

15. Affens, W. A., Flammability Properties of Hydrocarbon Fuels, Part I, U. S. Naval Res. Lab., NRL Report 6270, May 1965, 22 pp.

REFERENCES (cont'd)

16. Barnett, H. C. and R. R. Hibbard, Properties of Aircraft Fuels, Lewis Flight Propulsion Center, NACA TN 3276, August 1956.

17. Kuchta, J. M., R. J. Cato, G. H. Martindill, and W. Gilbert, Ignition Characteristics of Fuels and Lubricants, Air Force Aeropropulsion Laboratory, Technical Report AFAPL-TR-66-21, March 1966, 71 pp.

18. Kuchta, J. M. and R. Cato, Ignition and Flammability Properties of Lubricants, SAE Transactions Vol 77, 1968, p. 1008 and Air Force Aeropropulsion Laboratory, Technical Report AFAPL-TR-67-126, January 1968, 61 pp.

19. Kuchta, J. M., Oxygen Dilution Requirements for Inerting Aircraft Fuel Tanks, Second Conference on Fuel System Fire Safety, Federal Aviation Adm., Washington, D.C., May 1970, p. 85.

20. Stewart, P. B. and E. S. Starkman, Inerting Conditions for Aircraft Fuel Tanks, Univ. of California, WADC Tech. Report 55-418, September 1955, 0-4 pp.

21. Coordinating Research Council, Ad Hoc Group on Aviation Fuel Safety, CRC Project No. CA-37-64, June 1964, 72 pp.

22. Andrews, G. E. and D. Bradley, The Burning Velocity of Methane-Air Mixtures, Combustion & Flame, Vol 19, 1972, p. 275.

23. Burgess, D. and M. G. Zabetakis, Fire and Explosion Hazards Associated with Liquefied Natural Gas, BuMines RI 6099, 1962, 33 pp.

24. Kuchta, J. M., A. L. Furno and G. H. Martindill, Flammability of Fabrics and Other Materials in Oxygen-Enriched Atmospheres, Fire Technology, Vol 5, August 1950, p. 203.

25. Litchfield, E. and A. L. Furno, Flammability of Propellant Combinations Annual Report No. 1, BuMines ERC Report No. 3598, 30 June 1965, 83 pp.

26. Kuchta, J. M., J. N. Murphy, A. L. Furno, and A. Bartkowiak, Fire Hazard Evaluation of Thickened Aircraft Fuels, AGARD Conference Proceedings No. 84 on Aircraft Fuels, Lubricants and Fire Safety, The Hague, Netherlands, March 1971, p. 22-1.

27. Kuchta, J. M., A. Bartkowiak, and M. G. Zabetakis, Autoignition Characteristics of JP-4 Jet Fuel, Aeronautical Systems Division, ASD Tech. Documentary Report 62-615, June 1962, 35 pp.

REFERENCES (cont'd)

28. Zabetakis, M. G. et al, Research on the Flammability Characteristics of Aircraft Hydraulic Fluids, WADC Tech Report 57-151, Oct. 1956.
Ibid, WADC Technical Report 57-151 Supp. 1, December 1957.
Ibid, Part II WADC Technical Report 57-151, March 1959, 29 pp.

29. Strasser, A., N. C. Waters, J. M. Kuchta, Ignition of Aircraft Fluids by Hot Surfaces under Dynamic Conditions, AFAPL-TR-71-86, BuMines PMSRC Report No. 4162, November 1971, 30 pp.

30. Jacobson, J., A. R. Cooper, and J. Nagy, Explosibility of Metal Powders, BuMines RI 6516, 1964, 25 pp.

31. Huggett, C. et al, The Effects of 100% Oxygen at Reduced Pressure on the Ignitability and Combustibility of Materials, USAF School of Aerospace Medicine, SAM-TR-65-78, 1965, 30 pp.

32. Huggett, E. et al, The Combustibility of Materials in Oxygen-Helium-Nitrogen Atmospheres, USAF School of Aerospace Medicine, SAM-TR-66-85, 1966, 15 pp.

33. Lawson, D. I. and D. Hird, Radiation from Burning Buildings, Fire Office Committee, London Fire Protection Assn., June 1953.

34. Grosse, A. V. and J. B. Conway, Combustion of Metals in Oxygen, IEC, Vol. 50, No. 4, April 1958, p. 663.

35. Scott, G. S., R. E. Kennedy and M. G. Zabetakis, Gas Explosions and Their Prevention, BuMines IC 7601, May 1951, 13 pp.

36. Kuchta, J. M., R. J. Cato, G. H. Martindill, and I. Spolan, Ignition and Fire Suppression in Aerospace Vehicles (BuMines PMSRC Report No. 4164), Air Force Aero Propulsion Laboratory, Tech Report AFAPL-TR-71-93, December 71, 38 pp.

37. Cousins, E. W., and P. E. Cotton, Design Closed Vessels to Withstand Internal Explosions, Chem Eng., August 1951, p. 133.

38. Sarkos, C. P., Titanium Fuselage Environmental Conditions in Post-Crash Fires, Federal Aviation Adm., Report No. FAA-RD-71-3, March 1971, 49 pp.

39. Geyer, G. B., Evaluation of Aircraft Ground Firefighting Agents and Techniques, Federal Aviation Adm., Report No. FAA-RD-71-57, February 1972, 188 pp.

40. Glasstone, S., The Effects of Nuclear Weapons, U. S. Atomic Energy Commission, April 1962, 720 pp.

REFERENCES (cont'd)

41. Weir, A. Jr.,and R. B. Morrison, Equilibrium Temperature and Composition Behind a Detonation Wave, Ind. and Eng. Chem, Vol. 46, 1954, p. 1056.

42. Kingery, C., and B. Pannill, Peak Overpressure vs Scaled Distance for TNT Surface Burst (Hemispherical Charges), BRL Memorandum Report 1518, Ballistic Research Lab., Aberdeen, Md., 1964, 22 pp.

43. Zabetakis, M. G., Safety with Cryogenic Fluids, Plenum Press, New York, N. Y., 1967, 156 pp.

44. Filler, W. S., J. M. Rossi, and H. R. J. Walsh, Barricade Effectiveness Evaluated from Records of Accidental Explosions, Armed Services Explosives Safety Board Work Group, Report AD 487554L, July 1966, 56 pp.

45. Burgess, D. S., J. N. Murphy, N. E. Hanna, and R. W. Van Dolah, Large-Scale Studies of Gas Detonations, BuMines RI 7196, Nov. 1968, 53 pp.

46. Day, W. C., Large Yield Explosive Charges and Effects, Thirteenth Annual Explosive Safety Seminar, Armed Services Explosives Safety Board, September 1971, p. 659.

47. High, W. G., Design and Scale Model Testing of a Cubicle to House Oxidation or High Pressure Equipment, Chem. & Ind., June 1967, p. 899.

48. Petes, J., Blast and Fragmentation Characteristics, Prevention of and Protection Against Accidental Explosion of Munitions, Fuels, and Other Hazardous Materials, Annals of the New York Academy of Sciences, Vol. 152, Article 1, October 1968, p. 283.

49. Richmond, D. R. and C. S. White, Biological Effects of Blast and Shock, DASA-1777 Lovelace Foundation, April 1966, p. 54.

50. Field, C., The Study of Missiles Resulting from Accidental Explosions, A Manual for Investigators, Safety and Fire Protection Bulletin No. 10, U. S. Atomic Energy Division, Washington, D.C., March 1966, 61 pp.

51. Simmonds, W. A., and P. A. Cubbage, Symposium on Chemical Process Hazards, Inst. Chem. Engrs, 1960, p. 69.

52. Guide to the Use of Flame Arrestors and Explosion Reliefs, Ministry of Labour, New Series No. 34, H. M. Stationery Office, 423 Oxford St., London WI, August 1965, 55 pp.

REFERENCES (cont'd)

53. Kuchta, J. M., and D. S. Burgess, Effectiveness of Halogenated Agents Against Gaseous Explosions and Propellant Fires, Symposium on an Appraisal of Halogenated Fire Extinguishing Agents, Nat'l Academy of Sciences, Washington, D.C., April 1972, p. 257.

54. National Fire Protection Association, Standard on Halogenated Extinguishing Agent Systems, Halon 1211, NFPA No. 12B, 1972, 45 pp.

55. National Fire Protection Association, Standard on Halogenated Extinguishing Agent Systems, Halon 1301, NFPA No. 12 A, 1971, 70 pp.

56. Cato, R. J., Martindill, G. H., and J. M. Kuchta, Ignition and Fire Suppression in Aerospace Vehicles (Phase II) (BuMines PMSRC Report No. 4178), Air Force Aero Propulsion Laboratory, Tech. Report AFAPL-TR-72-96, December 1972, 22 pp.

57. Grumer, J., and D. Burgess, Experiments in Extinguishing Liquid Fuel Flames with High Expansion Foams, BuMines RI 6068, 1962, 10 pp.

58. Rasbash, D. J., The Extinction of Fires by Water Sprays, Fire Res. Abs. and Rev., Vol 4, 1962, p. 28.

59. ________, Investigation of 21 Chemicals with Respect to Explosion-Proof Electrical Equipment, Underwriters Laboratories, File USNC-48, October 1972.

60. Stack, C., and D. C. Woodhead, Correlation of Ignitabilities of Gases and Vapours by Break Spark and a Flange Gap, Proc. Inst. Elect. Engr. Vol 113, No. 2, 1966, p. 297.

61. Kuchta, J. M., R. J. Cato, I. Spolan, and W. Gilbert, Evaluation of Flame Arrestor Materials for Aircraft Fuel Systems, Air Force Aero Propulsion Laboratory Technical Report AFAPL-TR-67-148, February 1968, 30 pp.

62. Rossini, F. D., et al, Selected Values of Properties of Hydrocarbons, NBS Circular C 461, 1947, 483 pp.

63. Schnidman, L., Gaseous Fuels, 2nd Edition, American Gas Assn., New York, N.Y., 1954, 453 pp.

64. Maxwell, J. B., Data Book on Hydrocarbons, Second Ed., D. Van Nostrand Co., Inc., New York, N.Y., 1951, 259 pp.

65. Chemical Engineers Handbook, Third Edition, McGraw Hill Book Co., Mew York, N.Y., 1950.

REFERENCES (cont'd)

66. Standard Handbook for Mechanical Engineers, Seventh Edition, McGraw Hill Book Co., New York, N.Y., 1967.

67. Lawrence Radiation Laboratory, University of California, Properties of Chemical Explosives, AEC Contract No. W-7405-eng-48, Report UCRL-14592, 16 December 1965, 75 pp.

68. Botteri, B. P., R. E. Cretcher, and W. R. Kane, Aircraft Applications of Halogenated Hydrocarbon Fire Extinguishing Agents, Symposium on an Appraisal of Halogenated Fire Extinguishing Agents, Nat'l. Academy of Sciences, Washington D.C., April 1972, p. 215.

69. Marcy, J. F., E. B. Nicholas, and J. E. Demaree, Flammability and Smoke Characteristics of Aircraft Interior Materials, Federal Aviation Agency, Tech. Report ADS-3, Jan. 1964, 59 pp.

Appendix A. - Tables of Properties

Table 1-A. Standard Air Atmosphere[a]

Altitude ft	Temperature °F	Pressure psia	Density lb/ft^3
0	59	14.696	0.0765
1,000	55.4	14.175	0.0743
2,000	51.9	13.664	.0721
3,000	48.3	13.168	.0700
4,000	44.7	12.692	.0679
5,000	41.2	12.225	.0659
6,000	37.6	11.778	.0640
7,000	34.0	11.341	.0620
8,000	30.5	10.914	.0601
9,000	26.9	10.501	.0583
10,000	23.3	10.108	.0565
15,000	5.5	8.291	.0481
20,000	-12.3	6.753	.0408
25,000	-30.2	5.452	.0343
30,000	-48.0	4.362	.0286
35,000	-65.8	3.458	.0237
40,000	-67.0	2.721	.0187
45,000	"	2.141	.0147
50,000	"	1.690	.0116
55,000	"	1.331	.0091
60,000	"	1.046	.0072

[a] Data from reference 9; comparable to ICAO standard atmosphere.

Table 2-A. Properties of Air and Components of Air

Substance	Mol. wt.	Density (32°F) lbs/ft^3	Specific Gravity (Air = 1)	Specific Heat (70°F) Btu/lb-°F
Air	28.90	0.0766	1.000	0.240
Carbon dioxide	44.01	0.1170	1.528	0.200
Oxygen	32.00	0.0846	1.105	0.219
Nitrogen	28.02	0.0744	0.972	0.248
Water Vapor	18.02	0.0476	0.622	0.445

Major Components of Dry Air Atmosphere (Volume %)

Nitrogen - 78.084
Oxygen - 20.946
Argon - 0.934
Carbon dioxide - 0.033

Table 3-A. Properties of Hydrocarbons and Miscellaneous Combustibles[a/]

Combustible	Mol. Wt.	Specific Gravity (Air=1)	Boiling Point °F	Vapor Press.(70°F) psia	Heat Capacity C_p (~70°F) Btu/lb-°F		Net Heat of Combustion Btu/lb	$C_{st.}$ in air Vol. %	Flash Point °F	AIT in air °F	Flamm. Limits in Air LL Vol.%	UL Vol.%
Methane	16.04	0.55	-259	---	0.529(g)	---	21,500	9.48	Gas	1,000	5.0	15.0
Ethane	30.07	1.04	-128	560	0.414 "	0.78 (1)	20,420	5.65	Gas	959	3.0	12.4
Propane	44.09	1.52	- 44	124.	0.393 "	0.58 "	19,930	4.02	Gas	871	2.1	9.5
n-Butane	58.12	2.01	31	33.	0.402 "	0.58 "	19,670	3.12	Gas	761	1.8	8.4
n-Pentane	72.15	2.49	97	8.4	0.402 "	---	19,500	2.55	<- 40	496	1.4	7.8
n-Hexane	86.17	2.98	156	2.5	0.403 "	0.60 "	19,240	2.16	- 7	433	1.2	7.4
n-Octane	114.22	3.94	258	0.2	0.404 "	0.58 "	19,100	1.65	56	428	0.95	6.5
iso-Octane	114.22	---	211	0.80	0.404 "	---	19,080	---	10	779	1.1	6.0
n-Decane	142.28	4.91	345	0.03	0.405 "	~0.5 "	19,020	1.33	115	406	0.75	5.6
Ethylene	28.05	0.97	487	882	0.366(g)	---	20,290	6.53	Gas	840	2.7	36
Propylene	42.08	1.45	- 53	151	0.358 "	0.57 (1)	19,690	4.45	Gas	856	2.4	11
Acetylene	26.04	0.9	-118	645	0.399 "	---	20,740	7.72	Gas	580	2.5	100
Cyclohexane	84.16	2.91	179	1.55	0.304(g)	---	18,680	2.27	- 4	473	1.3	7.8
Benzene	78.11	2.69	176	1.5	0.245 "	0.406(1)	17,270	2.72	12	1,040	1.3	7.9
Toluene	92.13	3.18	231	0.45	0.264 "	0.421 "	17,450	2.27	40	896	1.2	7.1
o-Xylene	106.16	3.67	292	0.1	0.295 "	0.411 "	17,610	1.96	90	887	1.1	6.4
Naphtha	---	2.5	95-140	---	---	---	---	---	< 0	550	1.1	5.9
Turpentine	---	---	300	---	---	0.411 "	---	---	95	488	0.8	---
Methyl alcohol	32.04	1.11	147	1.85	---	0.600(1)	8,580	12.25	52	725	6.7	36
Ethyl alcohol	46.07	1.59	173	0.85	---	0.581 "	11,550	6.53	55	689	3.3	19
Propyl alcohol	60.09	2.07	207	0.3	---	0.586 "	13,190	4.45	77	824	2.2	14
Ethylene glycol	62.07	---	387	0.0	---	0.573 "	7,340	---	232	752	3.2	---
Propylene glycol	76.09	---	270	---	---	---	9,350	---	210	700	2.6	12.5
Methylether	46.07	1.59	- 11	---	---	---	12,340	6.53	---	662	3.4	27
Ethylether	74.12	2.56	95	8.7	---	0.547(1)	14,560	3.37	- 49	356	1.9	36
Acetone	58.08	2.01	0	3.6	---	0.528 "	12,280	4.97	0	869	2.6	13
Methylethylketone	72.10	2.49	21		---	0.549 "	13,490	3.67	21	960	1.9	10
Methyl acetate	74.08	2.56	14	3.3	---	0.468 "	8,700	5.65	14	935	3.2	16
Ethyl acetate	86.10	3.04	24	1.45	---	0.459 "	10,300	4.02	24	800	2.2	11
Carbon monoxide	28.0	0.97	-313	---	0.248(g)	---	4,340	29.50	Gas	1,128	12.5	74
Hydrogen	2.02	0.07	-423	---	3.412 "	---	51,600	29.53	Gas	752	4.0	75
Ammonia	17.08	0.59	- 28	129	1.10 "	---	8,000	21.83	Gas	1,204	15	28

a/ References 7, 8, 62, 63, 64.

Table 4-A. Properties of Aviation Fuels[a]

Fuel	Av. Mol. Wt.	Sp. Gr. (Water = 1)	Boiling Pt.		Reid Vapor Press.(100°F) psi	Net Heat of Combustion Btu/lb	C_{st}[b] in air Vol. %	Flash point °F	AIT in air °F	Flamm. Limits in Air	
			10% °F	90% °F						LL Vol.%	UL Vol.%
JP-1	151	0.81	350	410	<0.1	18,480	1.3	115	440	---	---
JP-3	112	0.76	160	440	6.0	18,710	(2.5)	--	460	1.4	7.9
JP-4	125	0.78	210	390	2.6	18,710	(2.4)	0	445	1.3	8.0
JP-5	169	0.83	380	460	<0.1	18,440	1.1	150	435	0.6	4.5
JP-6	147	0.84	350	500	0.1	18,620	(1.3)	100	450	0.7	4.8
JP-8	164	0.8	370	460	<0.1	18,400	---	115	435	---	---
Jet A	---	0.8	370	480	<0.3	18,590	---	105-140	435	Similar to JP-5	
Jet B	---	0.8	230	390	2.4	18,780	---	0-20	450	Similar to JP-4	
Gasoline 100/130	---	0.7	140	240	7.0	19,000	(2.4)	-45	825	1.3	7.1
Kerosene	---	0.8	380	490	<0.1	18,600	(1.3)	125	480	0.7	4.8

[a] References 7, 8, 10, 11, 12, and 16.

[b] Values in parenthesis, calculated by equation 14.

Table 5-A. Properties of Lubricants and Hydraulic Fluids[a]

Fluid	Specific Gravity (water=1)	Flash Pt. °F	AIT, in Air °F
MIL-H-5606 (mineral oil)	∿0.9	195	437
MIL 2190 (mineral oil)	0.86	450	665
Harmony 44 (mineral oil)	0.88	460	680
Mobil DTE-103 (mineral oil)	0.92	390	702
Houghto-Safe 271 (water glycol)	1.045	---	767
Ucon 50 HB-260 (polyalkylene glycol)	---	455	743
Pydraul 150 (phosphate ester)	1.125	380	975
Cellubube 220 (phosphate ester)	1.145	455	1038
Skydrol (phosphate ester)	---	360	>1300
Houghto-Safe 1055 (triaryl phosphate ester)	1.145	505	1020
Pydraul AC (phosphate ester - chlorinated)	1.36	450	1148
MIL-7808 (sebacate-adipate diester)	---	437	728
MIL-9236 B (trimethylolpropane ester)	---	430	738
MLO-54-581 (diester)	---	435	734
MLO-56-610 (dodecyltridecyl silane)	---	535	750
MLO-54-540 (silicate ester)	---	325	703
MLO-54-856 (silicate ester)	---	315	716
Oronite 8200 (silicate ester)	---	385	716
Versilube F-44 (silicone)	1.045	550	900
Dow Corning 400 (polymethyl siloxane)	---	255	610
Dow Corning 500 (polymethyl siloxane)	---	470	900
MLO-53-446 (chlorinated silicone)	---	580	786
Pydraul A-200 (chlorinated hydrocarbon)	---	350	1200
Arochlor 1248 (tetrachlorodiphenyl)	1.41	380	1185
OS-124 (polyphenyl ether)	1.20	550	1112
MCS-293 (aromatic ether)	1.19	428	914
SAE No. 10 Lube oil	<1	340	720
SAE No. 60 Lube oil	<1	480	770
Olive oil	0.91	437	650
Soybean oil	0.925	540	833
Linseed oil	0.9	432	650

a/ Reference 18.

Table 6-A. Properties of Combustible Metals[a]

Metal	At. wt.	Specific Gravity (Water=1)	Melting Point °F	Heat of Combustion Btu/lb	Ignition Temperature, °F	
					In O_2 Slab or Sheet	In Air Dust Cloud
Aluminum	26.97	2.70	1220	13,400	---	1200
Brass	---	8.4 - 8.8	∿1600	---	---	---
Cadmium	112.41	---	610	1,000	1400	1070
Chromium	52.01	6.93	3430	4,750	---	1080
Copper	63.57	8.92	1980	1,070	---	1290
Iron	55.85	7.86	2795	2,000	1710	1620
Lead	207.21	11.34	620	460	1600	1310
Magnesium	24.32	1.74	1200	11,600	1160	1150
Molybdenum	95.95	10.20	4750	3,430	1380	1330
Nickel	58.69	8.90	2810	1,780	---	NI
Silver	107.88	10.50	1760	65	---	---
Stainless Steel	---	7.6 - 7.9	2600	2,000	1710	NI
Tin	118.70	7.31	450	2,160	1590	1170
Titanium	47.90	4.50	3100	6,820	1600	630
Tungsten	183.92	19.30	6100	1,970	---	1350
Zinc	65.38	7.14	785	2,300	1650	1260

[a] References 30, 34, and 65.

Table 7-A. Mechanical Properties of Metals and Alloys[a]

Substance	Form	Tensile Strength kpsi	Yield Point kpsi
Aluminum	Rolled	13-24	5-21
Aluminum alloy, 51ST	---	48	40
Aluminum alloy, 17ST	---	56	34
Aluminum copper alloys	Cast	19-23	12-16
Aluminum bronze	Cast bar	70-80	32-35
Aluminum brass	Annealed tube	52-100	15-76
Brass, red	Sheet	40-83	14-58
Copper	Annealed	32	5
Copper	Hand Drawn	68	60
Duraloy A	Cast	50	40
Duraloy B	Cast	90	55
Hastelloy A	Cast	69-77	42-45
Hastelloy A	Rolled, annealed	110-120	47-52
Inconel 600	Cold drawn	95-150	70-125
Inconel 600	Hot rolled	85-120	35-90
Iron	Cast	18-60	8-40
Magnesium alloys	---	21-45	11-30
Monel metal (70% Ni)	---	100	50
Nickel	Cold drawn	65-115	40-90
Nickel	Hot rolled	55-80	20-30
Nickel-clad steel	Plates	55	30
Steel, stainless 304	Annealed bar, plate	80-95	35-45
Steel, stainless 321	Annealed sheet	80-90	35-45
Timken steel, 16-13-3	Annealed	≥80	≥30
Titanium (99%)	Annealed bar	95	80

[a] References 65 and 66.

Table 8-A. Radiant Ignition Energies and Flame Spread Rates of Combustible Solids[a]

Material	Ignition Energy[b] Btu/ft^2 1 Atm air	Flame Spread Rate in/sec Downward Burning	
		1 atm air	1/3 atm O_2
Aluminized Mylar	---	0.20	1.95
Asbestos tape	221	NB	0.08
Cotton shirt fabric	48	0.10	1.50
Cellulose acetate sheet	---	0.012	0.28
Foam cushion	---	0.19	12.4
Food packet, plastic	---	0.33	0.55
Masking tape	83	0.17	1.82
Natural rubber	---	0.01	0.61
Neoprene rubber	NI	NB	0.32
Nylon 101	NI	NB	0.19
Paint, 3 M velvet	37	NB	0.15
Paint, Capon	111	NB	0.38
Paper	118	0.08	0.90
Polyethylene	---	0.014	0.25
Polystyrene	---	0.032	0.80
Plexiglas	---	0.005	0.35
Plastic wire coating	74	NB	0.84
Polyvinyl chloride	NI	NB	0.10
Tygon tubing	---	0.18	0.50
Wood	92	0.025	0.35
		45° Upward Burning	
Cotton sheeting	---	0.8	1.3
Natural rubber sheeting	---	NB	$\sim$0.7
Paper drapes	---	2.0	$\sim$3.3
Plexiglas sheet	---	0.2	---
White pine strips	---	0.2	---

---

[a] References 24, 31, and 32.

[b] Radiant flux source of 13.2 cal/cm^2-sec (48.7 Btu/ft^2-sec).

Table 9-A. Self-Ignition Temperature of Solids[a]

Material	Type of Specimen	°F
WOODS AND FIBROUS MATERIALS		
Short-leaf pine	Shavings	442
Long-leaf pine	Shavings	446
Douglas fir	Shavings	500
Spruce	Shavings	502
White pine	Shavings	507
Paper, newsprint	Cuts	446
Paper, filter	Cuts	450
Cotton, absorbent	Roll	511
Cotton, batting	Roll	446
Cotton, sheeting	Roll	464
Woolen blanket	Roll	401
Viscose rayon (parachute)	Roll	536
Nylon (parachute)	Roll	887
Silk (parachute)	Roll	1058
Wood fiberboards	Piece	421 to 444
Cane fiberboard	Piece	464
SYNTHETIC RUBBER		
GR-S (R-60) black	Coagulum	590
GR-S (R-60) black	Buffings	374
GR-S, black	Coagulum	563
GR-S, black	Buffings	320
GR-S, Indulin	Crumb	824
METALS		
Aluminum paint flakes	Fine powder	959
Tin	Fine powder	842
Tin	Coarse powder	1094
Magnesium	Fine powder	883
Magnesium	Coarse powder	950
Magnesium ribbon	Cuts	1004
Magnesium, cast	Piece	1144
Magnesium-Al-Zn-Mn alloys (Mg 89 percent or more)	Piece	860 to 1256
Zinc	Fine powder	1202
MISCELLANEOUS		
Nitrocellulose film	Roll	279
Matches (strike anywhere)	Heads	325
Carbon spot	Dust	366
Crude pine gum	Powder	581
Shellac	Scales	810
Paint film, oxidized linseed oil-varnish.	Powder	864

---

[a] Reference 8; values refer to lowest temperatures at which exothermic reaction (oxidation) may self-accelerate to ignition under isothermal heating conditions.

Table 10-A. Temperature Limits of Selected Materials[a/]

Material	Characteristic	Temperature Range, °F
Glass	Softening	1400-1600
Paraffin	Melting	130
Polystyrene	Distortion	210
Plastic vinyl chloride	Distortion	185
Nylon	Distortion	300-360
Methyl methacrylate	Distortion	210
Neoprene	Blistering	500
Silicone rubber	Blistering	700
Silver solder	Melting	1165-1450
Aircraft points	Blistering	800-850

a/ References 5 and 13.

Table 11-A. Properties of Explosives[a]

Explosive	Molecular Weight	Nominal Density lb/ft^3	Heat of[b] Detonation Btu/lb	Detonation[b] Velocity ft/sec	Detonation[b] Pressure atm.
Primary High Explosives					
Lead azide, PbN_6	291.3	300	661	16,990	---
Lead Styphnate, $PbC_6HN_3O_8$	450.3	194	823	17,060	---
Mercury fulminate, $C_2N_2O_2Hg$	284.6	295	769	16,400	---
Secondary High Explosives					
Baratol, 24% TNT + 76% Ba $(NO_3)_2$	---	162	1010	15,970	139
Comp B, 36% TNT + 63% RDX	---	107	2755	26,210	292
LX-04-1, 85% HMX + 15% Viton A	---	116	2555	27,750	356
Nitrocellulose, guncotton, ≥13.35% N	274.1	99	2270	23,940	208
Nitroglycerine, propanetriol trinitrate	227.1	99	2860	25,260	250
Nitromethane	61.0	71	3490	20,730	139
PETN, pentaerythritol tetranitrate	316.2	110	2970	27,220	302
Pentolite, 50% TNT + 50% PETN	---	104	2430	24,500	246
RDX, trinitrotriazacyclohexane	222.1	114	2915	28,340	335
Tetryl, trinitrophenylmethylnitramine	287.0	107	2735	25,750	248
TNT, trinitrotoluene	227.1	102	2520	22,730	218

a/ Reference 67.

b/ Calculated or observed values; heats of detonation refer to gross or maximum values with water formed as liquid.

Table 12-A. Properties of Halogenated Hydrocarbon Fire Extinguishants[a]

Chemical Name	Halon No.	Molecular Wt.	Freezing Point, °F	Boiling Point, °F	Critical Temp., °F	Density (Liq) @70°F, lbs/gal	Storage Thermal Stability, °F
Carbon Tetrachloride	1040	154	-9	170	341	13.2	400
Methyl Bromide	1001	95	-135	38	381	14.4	---
Bromochloromethane	1011	129	-125	153	567	16.1	250
Dibromodifluoromethane	1202	210	-223	73	390	19.0	350
Bromotrifluoromethane	1301	149	-282	-72	154	13.1	>500
1, 2 Dibromotetrafluoroethane	2402	260	-167	117	418	18.0	>500
Bromochlorodifluoromethane	1211	165	-257	25	309	15.3	400

---

[a] Reference 68.

Appendix B. - Table of Conversion Factors

Table 1-B. Listing of Conversion Factors by Physical Quantity[a]

To convert from	To	Multiply by
	Area	
Square inch	Square centimeter	6.452
Square inch	Square meter	6.452×10^{-4}
Square foot	Square meter	9.290×10^{-2}
Square yard	Square meter	0.836
	Density or Mass Capacity	
Ounce/cubic inch	Kilogram/cubic meter	1.730×10^{3}
Pound/cubic inch	Gram/cubic centimeter	27.680
Pound/cubic inch	Kilogram/cubic meter	2.768×10^{4}
Pound/cubic foot	Kilogram/cubic meter	16.018
Pound-mass/gallon	Kilogram/cubic meter	1.198×10^{2}
	Energy or Work	
British thermal unit, Btu[b]	Joule	1.055×10^{3}
British thermal unit, Btu[b]	Calorie, gram	252.16
Calorie, gram[b]	Joule	4.187
Erg	Joule	1.00×10^{-7}
Foot-pounds	Joule	1.356
Foot-poundal	Joule	4.214×10^{-2}
Watt-hour	Joule	3.60×10^{3}
Ton (nuclear equiv. of TNT)	Joule	4.20×10^{9}
	Energy/Area-Time	
Btu/square foot-second[c]	Watt/square meter	1.135×10^{4}
Btu/square foot-hour[c]	Watt/square meter	3.153
Calorie/square centimeter-minute[c]	Watt/square meter	6.973×10^{2}
	Flow	
Cubic foot/minute	Cubic meter/second	4.719×10^{-4}
Cubic foot/minute	Gallon/second	0.125
Cubic inch/minute	Cubic meter/second	2.732×10^{-7}

Table 1-B. Listing of Conversion Factors by Physical Quantity[a] (cont'd)

To convert from	To	Multiply by
	Force	
Dyne	Newton	1.00×10^{-5}
Kilogram	Newton	9.807
Pound	Newton	4.448
Pound	Poundal	32.174
	Heat	
Btu/sec-sq foot- °F/inch[b]	Watt/meter- °K	5.192×10^{2}
Btu/hr.-sq foot- °F/inch[b]	Watt/meter- °K	1.442×10^{-1}
Btu/hr.-sq foot- °F[b]	Watt/square meter- °K	5.678
Btu/square foot[b]	Joule/square meter	1.136×10^{4}
Btu/pound- °F[b]	Joule/kilogram- °K	4.187×10^{3}
Btu/pound[b]	Joule/kilogram	2.326×10^{3}
Calorie/gram- °C[b]	Joule/kilogram- °K	4.187×10^{3}
Calorie/gram[b]	Joule/kilogram	4.187×10^{3}
Calorie/square centimeter	Joule/square meter	4.183×10^{4}
	Length	
Foot	Meter	3.048×10^{-1}
Inch	Meter	2.540×10^{-2}
Micron	Meter	1.00×10^{-6}
Mile (statute	Meter	1.609×10^{3}
	Mass	
Ounce	Kilogram	28.35×10^{-3}
Pound	Kilogram	45.36×10^{-2}
Ton (Short)	Kilogram	9.072×10^{2}
	Power	
Btu/second[c]	Watt	1.054×10^{3}
Calorie/second[c]	Watt	4.184
Foot'pound/second	Watt	1.356
Horsepower	Watt	7.457×10^{2}
Horsepower	Foot-pound/second	5.50×10^{2}
	Pressure or Stress	
Atmosphere	Millimeter of Mercury (0 °C)	760
Atmosphere	Pound/square inch	14.696
Bar	Newton/square meter	1.00×10^{5}
Pound/square inch	Millimeter of Mercury (0 °C)	51.715
Pound/square inch	Newton/square meter	68.95×10^{2}
Pound/square foot	Newton/square meter	1.488

Table 1-B. Listing of Conversion Factors by Physical Quantity[a] (cont'd)

To convert from	To	Multiply by
	Velocity	
Foot/second	Meter/second	3.048×10^{-1}
Mile/hour (Statute)	Meter/second	4.470×10^{-1}
Mile/hour (Statute)	Foot/second	1.467
	Volume	
Cubic foot	Cubic meter	2.832×10^{-2}
Gallon (liquid)	Cubic meter	3.785×10^{-3}
Cubic inch	Cubic meter	1.639×10^{-5}
Liter	Cubic meter	1.00×10^{-3}

---

a/ Reference 70

b/ International Steam Table

c/ Thermochemical

Flame Prop. = Exp. Ratio × Burning Vel.

$$S_u^2 = R\left(\frac{\lambda}{c_p \rho}\right)\left(\frac{4}{m_i}\right)\left(\frac{T_f - T_0}{T_{ig} - T_0}\right)$$

$\uparrow$

Flame
Prop.

$\downarrow$

U = burning vel.

AFSC DH 1-6 System Safety.

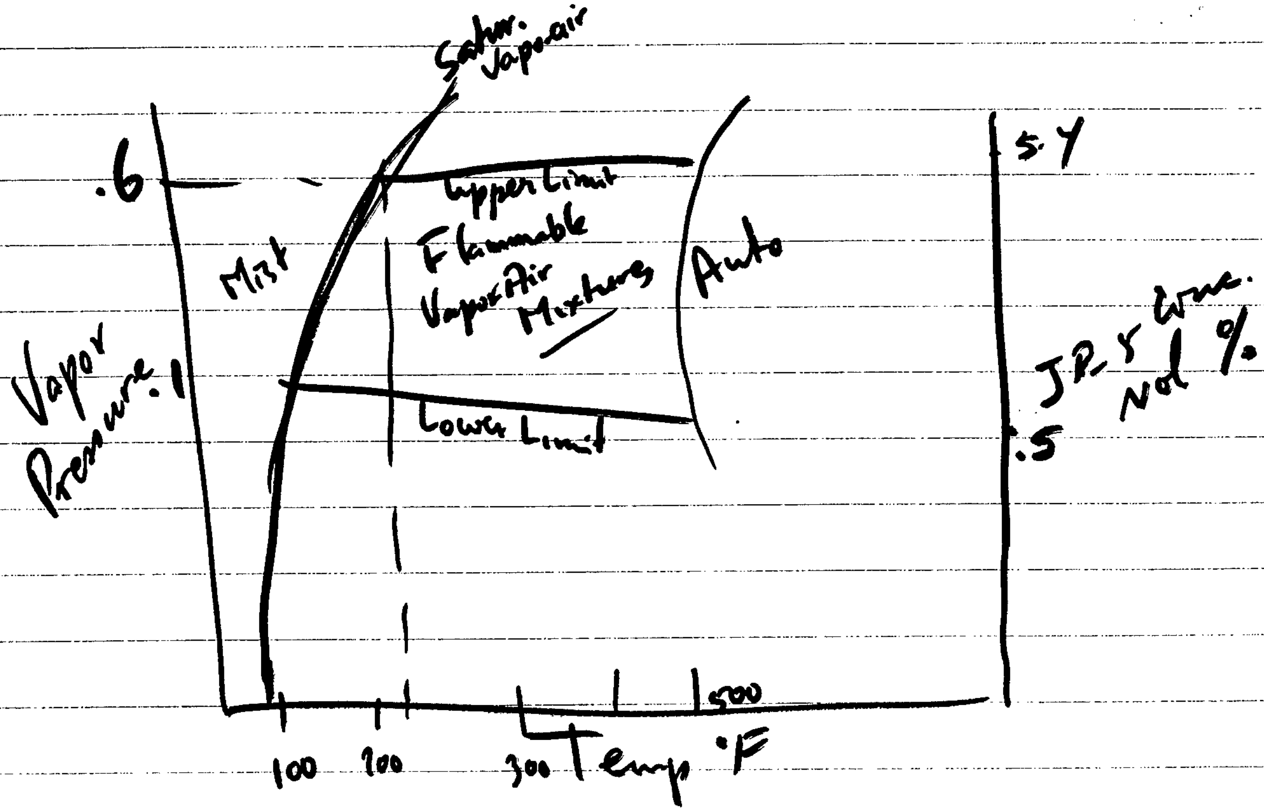
MIL STD 882 Hazard Analysis.

Concentration Limits of Flammability

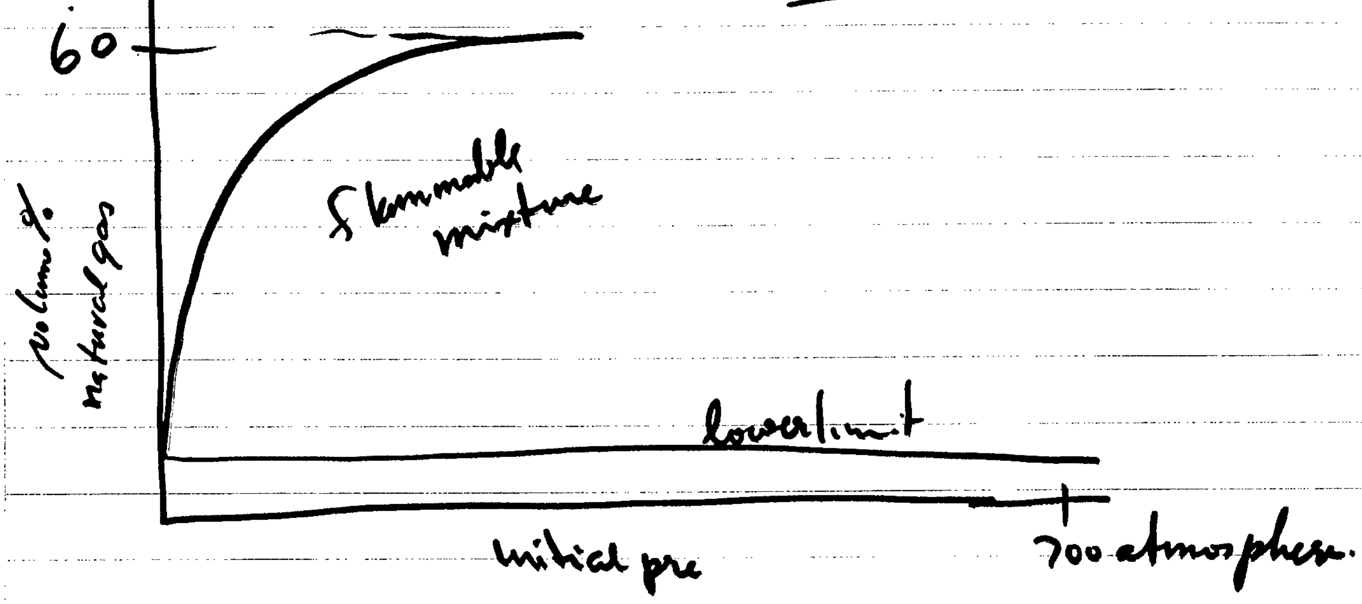
Char. of Flame Front.

Flame

1. Exothermal Reaction >10 K cal/mole.
2. Gaseous Products.
3. Flame ~~[illegible]~~ Temperature. >1500° K
4. Chemiluminescence.
5. Propagation Rate.
6. Pressure Rise in Confinement.



Flame Temp. ≈ $\underline{1300}$ °C



Inert

N_2
Exhaust Gas
H_2O
} ≈ min O_2 10%

CO_2

$CHCl_2F$
CCl_2F_2
CCl_3F
} min O_2 16%

AIR FORCE MANUALS/REGULATIONS/HANDBOOKS

AFM 127-1	Aircraft Accident Prevention and Investigation
AFM 127-2	USAF Accident/Incident Reporting
AFR 127-4	Investigation and Reporting US Air Force Accidents and Incidents
AFR 127-9	Life Sciences Investigation and Reporting of US Air Force Aircraft Combat Mishaps
AFM 127-100	Explosive Safety Manual
AFM 127-101	Industrial Safety Accident Prevention Handbook
AFM 127-200	Missile and Space System Mishaps Investigation
AFM 127-201	Missile and Safety Handbook

AFSC Design Handbook DH 1-6	System Safety
AFSC Design Handbook DH 2-3	Propulsion and Power
AFSC Design Handbook DH 2-7	System Survivability

DOCUMENTS CONTAINING FIRE SAFETY CRITERIA

AFSC DH 1-6	System Safety
AFSC DH 2-2	Crew Stations & Passenger Accommodations
AFSC DH 2-3	Propulsion & Power
MIL-STD-882	System Safety Program for Systems and Associated Subsystems and Equipment: Requirements for
MIL-I-83294	Installation Requirements, Aircraft Propulsion Systems, General Specification for
MIL-E-5007	Engines, Aircraft, Turbojet and Turbofan, General Specification for
MIL-F-38363	Fuel System, Aircraft, Design, Performance, Installation, Testing, and Data Requirements, General Specification for
MIL-H-5440	Hydraulic Systems, Aircraft, Types I and II, Design, Installation, and Data Requirements for
MIL-W-5088	Wiring, Aircraft, Installation of
MIL-F-7872	Fire and Overheat Warning Systems, Continuous, Aircraft: Test and Installation of
MIL-D-27729	Detecting Systems; Flame and Smoke, Aircraft and Aerospace Vehicles, General Performance, Installation and Test of
MIL-E-22285	Extinguishing System, Fire, Aircraft, High-Rate-Discharge Type, Installation and Test of

TABLE 3. - Lean Limit Mixture Heats of Combustion for Upward Propagation of Organic Fuels in Air

Fuel	$\frac{L_u}{100} \Delta H_c$ kcal (mole of mixture)$^{-1}$	Fuel	$\frac{L_u}{100} \Delta H_c$ kcal (mole of mixture)$^{-1}$
n-Butane	10.7	Methyl acetate	11.2
n-Pentane	11.0	Diethyl ketone	10.9
iso-Pentane	10.3	Diethyl ether	11.4
n-Decane	11.6	Ethyl amine	13.0
cyclo Hexane	11.8	t-Butyl amine	11.2
Benzene	9.8	Allyl alcohol	10.3
Diphenyl	10.1	i-Butyl alcohol	10.0
Naphthelene	10.5	Ethylene oxide	10.2
Butene-1	9.7	Pyridine	11.4
Styrene	11.1	Acetaldehyde	10.3
Xylene	11.4	Nitroethane	10.1

Average 10.8 ± .6

TABLE 4. - Correlation Between Lean Flammable Limits and Minimum Experimental Safe Gaps (MESG)

Fuel	Limit Equivalence ratio (Φ_L)	MESG (in)		NEC classification
		British	U.L.	
Diborane	0.12			
Carbon disulfide	.20	0.008	0.002	
Hydrogen		.004	.003	B
Hydrazine	.27			
Acetylene	.32	<.001	.003	A
Ethyl nitrite	.35	.038		
UDMH	.40		.018	C
Ethylene	.41	.028	.027	C
Ethylene oxide	.47	.026	.013	B
Propylene	.54		.035	D
Diethyl ether	.56	.033	.013	C
Propane	.58	.038	.037	D
n-Butane	.58	.042	.039	D
Benzene	.50	.034		D
p-Xylene	.58	.042	.048	D
Ammonia	.69	.133	.040	D
Trichlorethylene	.91			

Explosion Pressure Limits

Combustible	Vessel ID inch	Press. Limit psia
Propargyl Bromide	8	0.03
Chloroazide	2.5	0.04
Hydrazine	1	0.23
Ethyl Nitrate	-	<0.48
Propargyl Chloride	8	0.58
Monochloroacetylene	2	1.16
Ethylene Oxide	8	10.2
Acetylene	6	~13.0
Allene	8	32.7
Methylacetylene	4	58.0

where W is the charge weight and d_o is the scaled diameter for a unit weight of charge. If W is in pounds, d_o for a 1-lb TNT charge or equivalent will be about 1.5 or more, depending upon the nature of the surface and the depth to which the charge is buried. The depth of the crater is usually not more than about 1/4 the diameter. Figure 40, (Ref. 46) shows the predicted crater dimensions for explosions at various charge depths in dry soil with the dimensions scaled to 1-ton charges of TNT. Generally, surface explosions of deflagrating materials, e.g., smokeless gun powders, do not produce craters.

The damage by missiles or fragments from an explosion will depend upon their mass and velocity. Approximately 10 percent of the available chemical energy (strong confinement) or pressure energy (weak confinement) in a gaseous explosion may be assumed to be required for rupturing a vessel or tank (Ref. 47). Also, about 20 percent of the available energy can be taken as the kinetic energy of the fragments ($1/2\ m\ v^2$). Thus, if the mass (m) of a fragment and chemical energy (ΔH) of the explosive mixture are known, the fragment velocity (v) can be calculated. For cased explosive charges, more complicated expressions are necessary for calculating the fragment velocities. The depth of penetration into mild steel that can be produced with small metal missiles ($\lesssim$ 1 oz) at various velocities is shown in figure 41 (Ref. 48). Note that any of the missiles with a striking velocity of 2000 ft/sec could penetrate steel vessel walls of at least 0.15 inch thickness; this velocity is in the same range as that obtained from firing a 30-caliber weapon (e.g. 2-3000 ft/sec). The human damage levels that could result from head or total body impacts (tertiary effects) at various velocities are indicated in figure 42 (Ref. 49); this figure also describes blast-induced translational velocities for a nylon sphere as a function of time. It should be noted that the threshold impact velocity for a skull fracture is slightly over 10 ft/sec, as compared to about 30 ft/sec for the lethal level with a 100 percent probability. The "safe" threshold of 10 ft/sec for head impacts is also comparable to the "safe" limit reported for total body impacts and for head impacts produced by a 10 lb blast fragment (secondary effect); the kinetic energy of such a fragment would be equal to about 16 ft-lbs.

The initial velocity (v_o) of an explosion fragment can be estimated from its distance from the explosion site, i.e., its range (R). The maximum range is obtained when the trajectory angle (α) of the missile is 45°:

$$R = \frac{v_o^2 \sin 2\alpha}{g} \qquad (50)$$

where g is the gravitational constant (32 ft/sec^2). One can also estimate the striking velocity (v_s) if V_o, R, and the drag coefficient (K_D) for the object are known:

$$v_s = v_o\ e^{-kR} \qquad (51)$$

Here, the constant $k = K_D\ A/m\rho$, where ρ is air density, and A (area) and m (mass) refer to the fragment. Further discussion on this topic is given in reference 50.