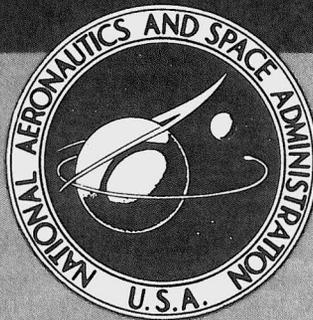


SPACE-CABIN ATMOSPHERES

Part II—Fire and Blast Hazards

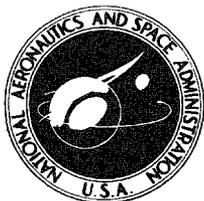


SPACE-CABIN ATMOSPHERES

Part II—Fire and Blast Hazards

A literature review by
Emanuel M. Roth, M.D.

Prepared under contract for NASA by
Lovelace Foundation for Medical Education
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Foreword

THIS REPORT IS PART II OF A STUDY ON *Space-Cabin Atmospheres*, conducted under sponsorship of the Directorate, Space Medicine, Office of Manned Space Flight, National Aeronautics and Space Administration. Future parts of this report will be: Part III, "Physiological Factors of Inert Gases," and Part IV, "One- versus Multiple-Gas Systems." Part I, "Oxygen Toxicity," was originally published as NASA TN D-2008, dated August 1963, and will be republished as NASA SP-47.

This document provides a readily available summary of the open literature in the field. It is intended primarily for biomedical scientists and design engineers.

The manuscript was reviewed and evaluated by leaders in the scientific community as well as by the NASA staff. As is generally true among scientists, there was varied opinion about the author's interpretation of the data compiled. There was nonetheless complete satisfaction with the level and scope of scholarly research that went into the preparation of the document. Thus, for scientist and engineer alike it is anticipated that this study will become a basic building block upon which research and development within the space community may proceed.

GEORGE M. KNAUF, M.D.
Acting Director, Space Medicine
Office of Manned Space Flight

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Introduction

THE RAPID EVOLUTION OF AIRCRAFT and, lately, space vehicles has brought with it the ever-increasing difficulty of designing for prevention of fires and explosions. The present-day sealed cabin with its limited work space, unusual atmospheric constituents, and lack of flexibility in emergency situations has brought new and ill-defined hazards into the picture.

In the past, numerous data have been compiled on the fire and explosion characteristics of all things combustible. Unfortunately, much of the material is not pertinent to the actual operational problems in space. The confusion and controversy arising from attempts to evaluate the space-cabin fire problem appear to stem from past failure to compile the scattered data and to expose it to critical review and selection. In the compilation that follows, an attempt has been made to review the best available data that was deemed actually pertinent to the present problem. The effects of unusual atmospheres have been emphasized, but, as will soon be evident, other physical parameters also play a major role in determining the nature of the problem.

Chapter 1 contains a discussion of pertinent definitions and theory. This is detailed only to the point of anticipating some of the problems of interpretation that may arise in other chapters of the report. Included in this chapter is speculation on the impact of unusual environmental conditions such as aerodynamic heating, reduced gravitational acceleration, and low ambient pressures. Chapter 2 covers flammable fabrics and carbonaceous solids; Chapter 3, specific fire hazards involving flammable liquids, vapors, and gases; and Chapter 4, electrical fires. Chapter 5 covers the fire, blast, and flash hazards from meteoroid penetration; and Chapter 6, the problems of fire prevention and extinguishment in space cabins. Chapter 7 reviews the factors of fire and blast hazards in selection of a space-cabin atmosphere.

Definition and Theory

IN DEFINING THE WORD "FIRE," we are starting our discussion in a hazardous but necessary way. A *fire* is usually thought of as a rapid decomposition of matter by oxidation such that heat is dissipated and gases emitted. The process is usually defined to include a visible flame. The definition of flame is more difficult. *Flames* (or deflagration processes) are the products of strongly exothermic free-radical reactions between gases and vapors resulting in hot combustion products and accompanied by light emission.^{89, 133}

The terms "detonation" and "explosion" are widely misused. Both have been used to describe violent reactions such as those accompanied by loud noise or even a shock wave, or those causing severe damage. For the purposes of this report, an *explosion* will be defined as a condition of chemical reaction in which self-acceleration of rate leads to rapid pressure rise. Two kinds of explosion are commonly distinguished. One is called a branched chain explosion, of which the hydrogen-oxygen reaction discussed on pages 18 and 19 is an example. The other is a thermal explosion. In this the material reacts exothermally to produce heat at a faster rate than heat is lost by conduction, convection, and radiation. Because of the generally exponential dependence of rate of reaction on temperature, in such a situation the rate of chemical reaction increases rapidly. The result is a disruptive pressure rise.

A *detonation* is specifically an exothermic reaction which takes place in a high-pressure hydrodynamic wave moving at supersonic velocity with respect to the unreacted material.⁶⁹ *Flames* (or deflagration processes), on the other hand, travel at subsonic velocity with respect to the unreacted material. Further, except

for transients during the building or decay periods, the velocity of propagation is a constant and is more closely defined by the fluid thermodynamic variables than by the chemical variables in the system.

Now that we have generally defined our terms, let us proceed to an analysis of those physicochemical factors which define the actual fire or detonation hazard in any system.

During the past few years there has been considerable progress in development of flame theory. Most of the theoretical approaches to gas-phase theory have been generated by Hirschfelder and his coworkers in the United States,^{56, 108} Spalding in England,^{209, 210} and Lovachev in the U.S.S.R.^{137, 138} A critical review of the theory of deflagration in homogeneous gas mixtures prior to 1952 may be found in an excellent paper by Evans.⁷³ Major contributions to the development of the theory of condensed-phase deflagration have been made in the past several years. The most pertinent appear to be the studies of Spalding²⁰⁸ on burning of solid and liquid propellants, Wise and Agoston²⁴¹ and Williams²⁴⁰ on the burning of liquid droplets, Nachbar and Williams¹⁶³ on the analysis of linear pyrolysis, and Andersen et al.⁴ on combustion of composite solid propellants. The theories of condensed-phase detonations owe much of their current sophistication to the pioneering efforts of Wood and Kirkwood^{124, 245} and Eyring and his coworkers.⁷⁴ A recent contribution to the theory of gas-phase detonation has been the work of D. R. White.²³⁶ A comprehensive review of detonation theory has been presented by Evans.⁶⁹ Finally, initiation phenomena (ignition) have received modern theoretical treatment by Bowden and his coworkers.^{20, 21}

In the past, most theories of flame propagation, flammability limits, quenching diameters, and detonation parameters were greatly oversimplified. Specific flame systems are often dependent on a single limiting physicochemical parameter. Because of this fact, attempts to formulate flame theory on the basis of heat transfer alone, diffusion of active species alone, or chemical kinetics alone had some success. It was obvious, however, that a unified approach required that all parameters be taken into account. Background factors such as chemical rate constants, diffusion rates, and radiation constants became part of the increasing complexity of mathematical solutions to the problem. In spite of the sophistication of recent treatments, an overall analysis of the parameters in any one flame system has yet to be attained.

One can hardly expect analysis of a problem such as "fire hazard" to be amenable to anything but an order-of-magnitude approach. Attempts have been made to define fire hazards on a basis other than pure intuition. An excellent review of this approach has been presented by Van Dolah et al.,²²⁰ of the Bureau of Mines, U.S. Department of the Interior. Much of the material presented in this chapter is taken from this review; figures 1, 2, 3, 5, and 6 are Van Dolah's adaptation of figures from Lewis and von Elbe.¹³³ The physicochemical variables will be stressed because they are so critical in defining a hazardous condition. Apparent in this discussion will be the "threshold factors" which play such a major role in free-radical reactions of all types. The theoretical role of oxygen and inert gases as they affect each phase of the combustion process are also discussed. It will be apparent that a statement defining the hazardous nature of any gaseous environment must include a very rigid definition of the entire system. Much of the confusion which appears to exist today arises from the basic neglect of these system variables. Recent interviews with "fire experts" suggest that many opinions regarding the problem of fire hazards in space have been given by individuals quite unfamiliar with the basic physics and chemistry of combustion. Their sweeping statements regarding "the hazard" have only served to confuse the

issue. Therefore, an attempt is made to cover each phase of the combustion picture: ignition, flame propagation, detonation, and flame extinguishment. The environmental variables presented by the total space-cabin conditions which modify these phases are then discussed. These discussions and their bibliographic notations are not meant to be comprehensive. They will point out only the major factors pertinent to the problem at hand.

IGNITION

Ignition, or the initiation of a combustion process, must be defined in an operational way. One judges whether ignition has occurred only by setting the physical criteria of whether a deflagration or detonation process has indeed occurred. Grossly, the presence of a visible high-temperature flame may satisfy the judgment. Under confinement, flames may produce rises in pressure. Thus, changes in temperature, radiation, and pressure are usually the criteria used to judge ignition.

The initiating source is obviously critical in defining ignition. In general, sources may be categorized as follows:

- (a) Electrical—electrostatic or induction (break) sparks
- (b) Hot surfaces—frictional or impact sparks; heated walls, surfaces, or wires; heating by high shear rates; and plastic deformation of sharp points
- (c) Heated gases—hot gas jets (pilot flame); adiabatic compression; shock waves and metallic vapor from meteoroid penetrations
- (d) Hypergolic ignition

In space cabins the first three types of ignition are the most probable. As we shall see, any combustible mixture will respond to the effects of ambient pressure and mixture ratios quite differently under different ignition conditions.

In general, one must think in terms of localization of the source of energy in space and time. At one end of the spectrum are electrostatic sparks which may discharge across a gap of less than 1 mm in less than a microsecond. The high local temperature of such a source triggers the chemical reaction in a microscopic flame kernel and makes the energy of the source the key factor in initiation. Ignition depends only

on whether the kernel is large enough to develop a self-propagating flame. Quenching the kernel below the temperature required for self-propagation will effectively arrest the flame. Miners' safety lamps and quenching flanges on explosion-proof motors make use of this flame-arrestor principle. At the other end of the time-space spectrum is the heating of a gaseous mixture within a closed container. Here much energy is supplied *in toto* but only the specific temperature of the system determines ignition. The spontaneous ignition temperature may be defined as that temperature at which the rate of exothermic chemical heating of the system exceeds the rate of heat loss from the system. Another parameter to be considered is the phenomenon of ignition delay. A finite time of exposure to any heat source is required for initiating ignition. For example, a methane-air mixture with a spontaneous ignition temperature of 1,000° F may be safely exposed to an impinging jet of gases at 2,000° F if the contact time between source and combustible material is short enough. Each ignition source is reviewed in greater detail in the following paragraphs to illustrate how time, space, and components of the combustible system control ignition.

Electrical Sparks

The structure and dynamics of sparks have been studied thoroughly by many groups from different points of view. Internal-combustion engineers, fire-safety engineers, and explosive experts, to name a few, have wrestled with this problem. After World War II, Lewis, von Elbe, and their coworkers introduced a new approach to the problem.^{15, 16, 132, 133} These workers shifted from the focus on capacitance and inductance in spark circuits to the spark energy available at the point source. Some of the physicochemical factors controlling the effectiveness of any spark energy in initiating combustion will now be reviewed. Only general concepts will be discussed except where potential space-cabin considerations are involved. This material has been taken from the review by Van Dolah et al.²²⁰ of the Lewis and von Elbe studies. It shows how difficult it is to actually define a spark-induced fire hazard

in quantitative terms, especially in as complex a system as a space cabin. Figure 1 illustrates the dependence of critical spark energy on the electrode separation or length of spark gap.

Shorter gap lengths require greater critical energies for ignition because the propagating flame kernel has to reach a critical size to initiate combustion, and the electrodes themselves may act as quenching agents. There is, as expected, an optimum gap length for minimum-energy ignition.

Figure 2 indicates how this minimum ignition energy, in turn, depends on the fuel-air ratio for any given combustible mixture. As the mixture approaches limits of flammability, the energy required for ignition approaches infinity.

Figure 3 shows how the molecular weight of a homologous series of hydrocarbons determines the minimum spark energy required for ignition of any given stoichiometric ratio of fuel to air. In general, the greater the molecular weight, the more the minimum ignition energy shifts to the higher stoichiometric fraction of hydrocarbon. It is believed that in this type of ignition the relative diffusivity of fuels in air controls the initial aerodynamic factors in propagation of the flame kernel and that this factor is more important than the actual chemical reactivity of the materials.

The factors presented in figure 4 are most pertinent to the space-cabin problem. These graphs show how the oxygen content of the system affects the minimum spark energy for the ignition of propane. It is evident that at any given percentage of oxygen in an oxygen-

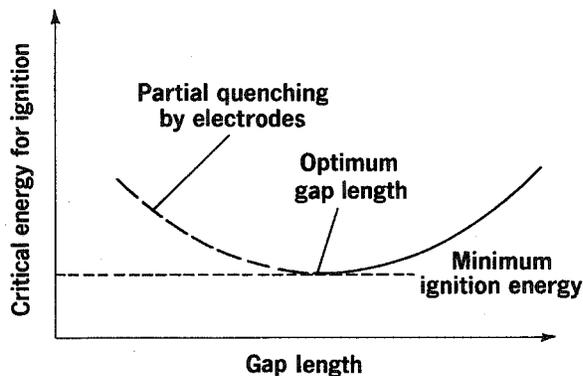


FIGURE 1.—Minimum ignition energies at various lengths of spark gap. (AFTER VAN DOLAH ET AL.²²⁰)

nitrogen mixture, halving the total pressure will increase the minimum energy by a factor of about 5. It is also evident that increasing the percentage of oxygen at any total pressure will not only decrease the minimum spark energy, but also extend the limits of flammability to a much wider range. For example, in going from 21 percent oxygen to 100 percent oxygen, the minimum required spark energy decreases by 3 orders of magnitude. The total range of flammability increases from about 2–10 percent propane in a mixture with air to 2–55 percent propane in a mixture with 100 percent oxygen. These curves are referred to again in the discussion of the selection of space-cabin atmospheres (Chapter 6).

The generation of an electrostatic spark within a space-cabin system is always a danger. An

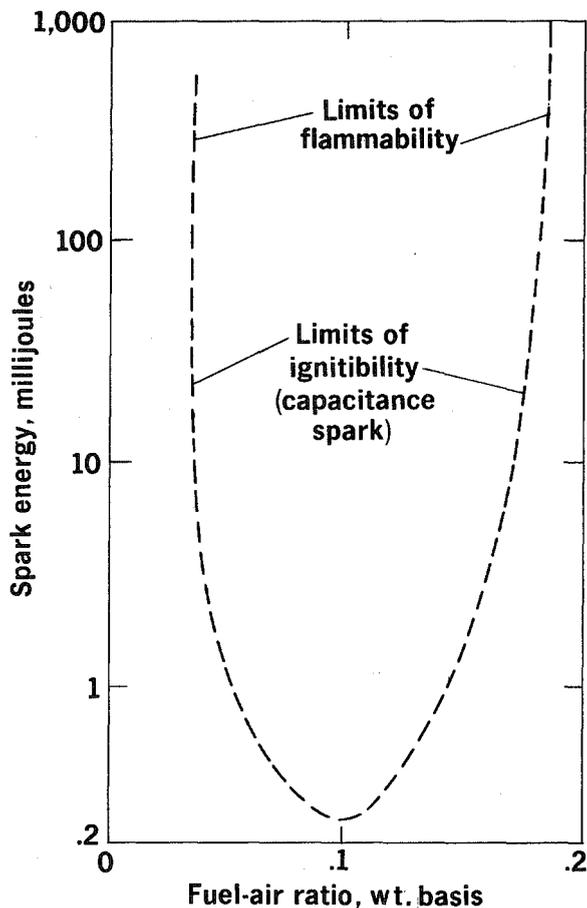


FIGURE 2.—Ignitibility curve for butane-air mixtures at 1 atmosphere and 78° F. (AFTER VAN DOLAH ET AL.²²⁰)

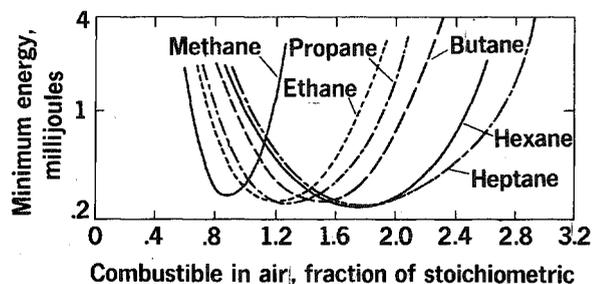


FIGURE 3.—Effects of molecular weight of fuel on stoichiometric ratio for easiest ignitibility at pressure of 1 atmosphere. (AFTER VAN DOLAH ET AL.²²⁰)

average-sized man with a capacitance of 300 μf , charged to 10,000 volts, could conceivably initiate a discharge of energy ($CV^2/2$) equal to 15 millijoules. How dangerous is this spark discharge? Figure 5 is a compilation of all the measurements made by the Lewis and von Elbe group on hydrocarbon mixtures that contained from 21 percent to 100 percent oxygen at initial pressures from 0.1 to 2.0 atmospheres. It would appear from this compilation that almost any of the flammable mixtures studied can be spark-ignited by commonly occurring electrostatic discharges.

The “excess enthalpy theory” of spark ignition of von Elbe and his coworkers has recently been opened to question by several groups.^{245, 256} However, the general concepts outlined above are still valid.

The general problem of protection against electrostatic spark discharges is not limited to the problem of dissipation of energy but includes as well the control of generation and accumulation processes. The problem as encountered in hospital operating rooms has been studied by Guest et al.⁹⁴ and will not be reviewed here except to mention the use of electrically conducting materials in the breathing apparatus, sheets, uniforms, shoes, and floors. Additional dissipation is attained by maintaining the atmospheric humidity at a high level. The general problem of protection against electrostatic hazards has been adequately studied by the American Petroleum Institute.¹⁷³

A recent study by Litchfield¹³⁵ at the Bureau of Mines suggests that the characteristics of electrostatic spark ignition are encountered in

other ignition processes, especially break sparks, heated fine wires, and converging shock waves. This should be kept in mind during consideration of other ignition sources.

When an electrical switch is opened or when a current-carrying wire is broken mechanically, an arc may jump between the separating conductors. Ignition of the insulation or combustible gas mixtures may then occur. Since most of the energy is converted into heat while the conductors are close together, the parameters for ignition resemble those for short-gap electrostatic sparks. Because of the quenching effects of short spark gaps (see the curve of fig. 1), it appears that the spark energy for ignition by break sparks would be higher than the corresponding minimum energies described in

figures 2 to 5. In general, the millijoule range rather than fractional millijoule range is required for ignition. Most data⁹³ are given as maximum safe current in wires. The variable heat sinks provided by the wire and inductance factors in the system prevent as rigorous a treatment of break sparks as that available for electrostatic sparks.

Hot Surfaces

Small wires, especially if the heating current occurs as a brief pulse, can be treated as local sources of energy release similar to electric sparks. The results of Jones¹²¹ cover the short-duration hot-wire effects on condensed-phase ignitions. In practical fire-hazard problems, fine-wire heating usually occurs not in micro-

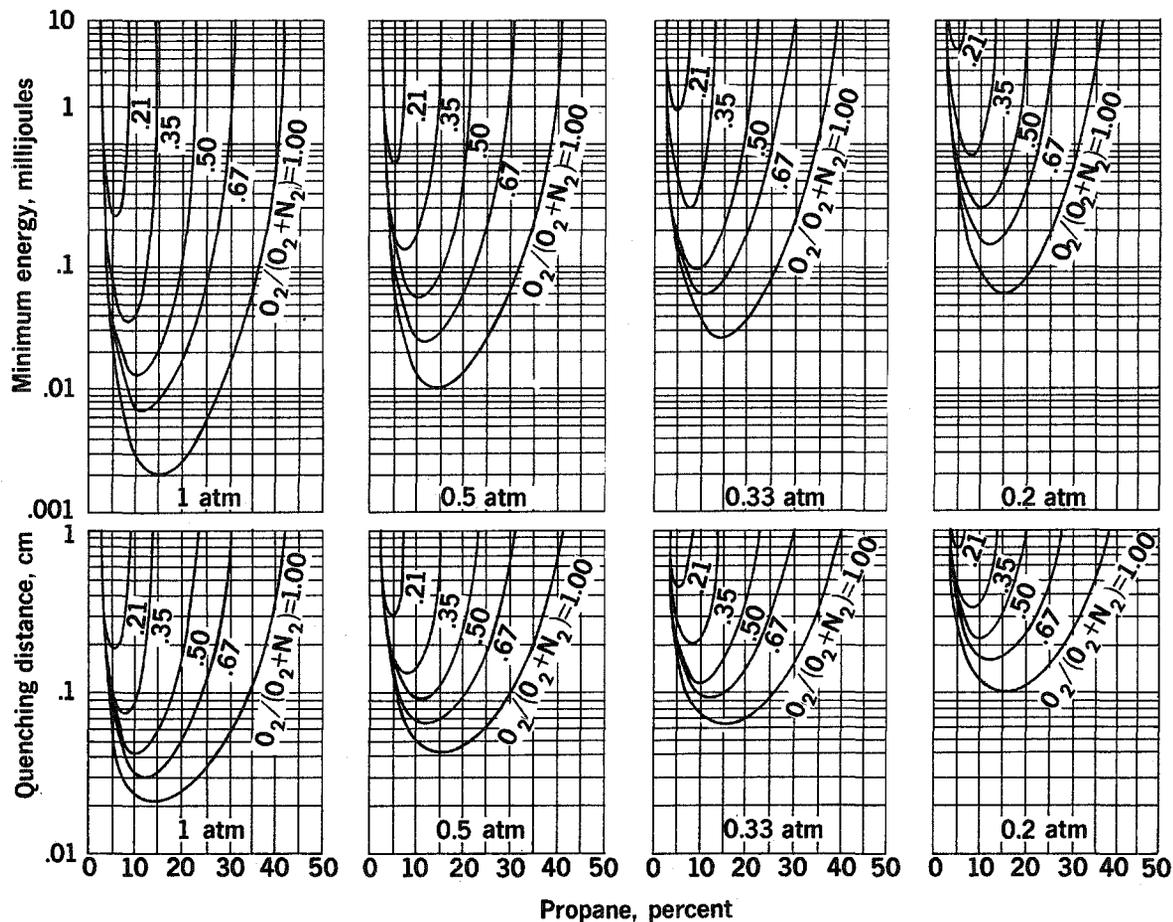


FIGURE 4.—Minimum spark ignition energies and quenching distances between flanged electrodes for mixtures of propane, oxygen, and nitrogen. (AFTER LEWIS AND VON ELBE.¹³³)

seconds, but in multisecond pulses. The ignition system is therefore similar to one involving larger hot surfaces.

In general, the temperature required to ignite a large volume of combustible gases decreases with increase in wire diameter, as illustrated by the typical curve in figure 6. Gravitational factors begin to play a role in this ignition picture. Large heated wires set up convection currents which limit the contact time between

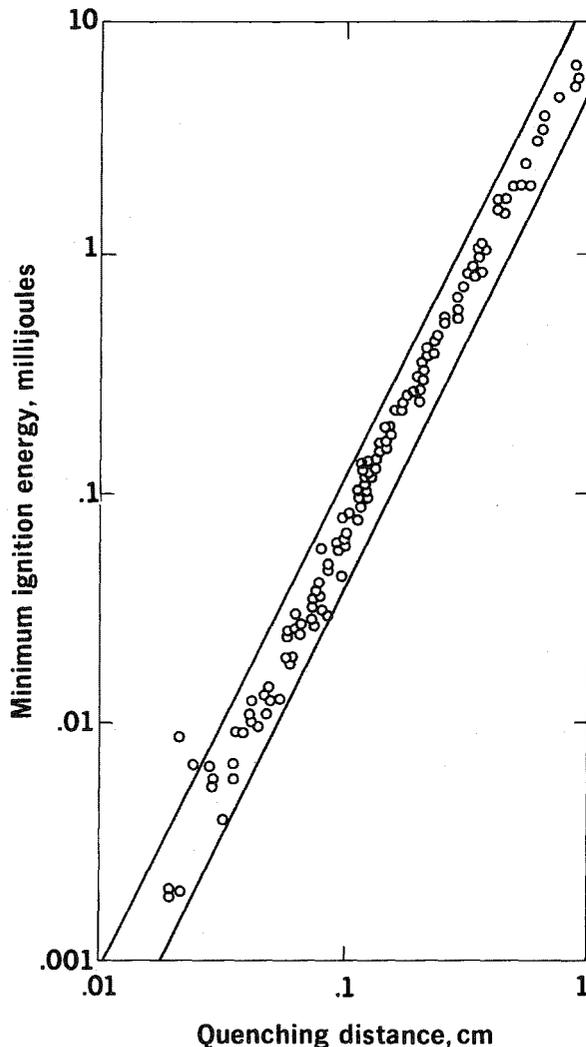


FIGURE 5.—Relationship between minimum ignition energy and optimum electrode separation (quenching distance) for hydrocarbon mixtures containing 21 to 100 percent oxygen at initial pressures from 0.1 to 2.0 atmospheres. (AFTER VAN DOLAH ET AL.²²⁰)

the heated surface and the small adjacent volume of combustible gas. Increasing the diameter of the wire prolongs the contact time and thus decreases the surface temperature required for ignition. Reduction of the gravitational field decreases convective cooling and simulates an increase in diameter. More will be said of this in the discussion of space environment effects. Surrounding the gas mixture with a hot surface also simulates the factors invoked for increase in wire diameter.²⁵⁰

An interesting offshoot of hot-surface ignition is the case of the ignition of combustible mixtures by incandescent carbon wear particles. The carbon brushes of electrical motors are the most usual sources of these hot particles, though other mechanical friction systems involving carbon structures can be at fault.

It has been demonstrated that flash temperatures of high spots or asperities on surfaces in sliding contact can be 900° to 1,800° F (500° to 1,000° C) above the bulk temperatures of the sliding materials.²² Wear particles from asperities may achieve incandescent temperatures and, in an oxygen-containing atmosphere, can burn.¹⁸ In particular, the wear of carbon is accelerated by operation at high altitude¹⁵³ and by an electric potential across the sliding interface. All these conditions may be experienced in the operation of an electrically driven vane-type fuel pump such as is used in flight vehicles. Buckley et al.³⁰ studied these pumps in propane-air mixtures. Even when the electrical parts of the pumps were adequately insulated, friction from carbon vanes sliding against metal disks could initiate combustion in propane-air mixtures. Altitudes of 38,000 feet (150 mm Hg) accelerated the wear of vanes and increased the carbon particle sizes. However, electric potential and current as low as 106 volts and 3 amperes at 400° F across the vane-dish interface were required for incandescence of particles and for ignition of the propane-air mixtures. Electric potentials alone without wear produced no ignition. These potentials are much lower than the 10,000-volt potentials seen in similar operational static conditions. The high electrical resistance of anodized aluminum surfaces and of lubricant films in machines will allow static buildup, especially when the rotating shafts are

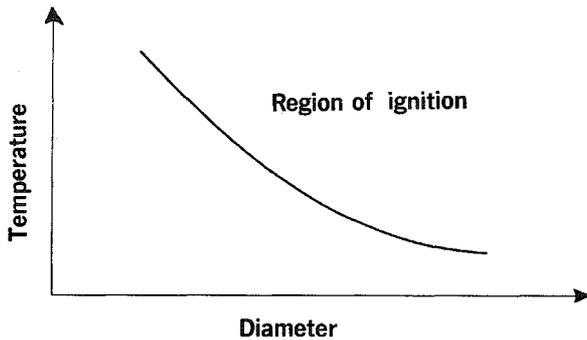


FIGURE 6.—Effect of wire diameter on ignition temperature of a flammable mixture. (AFTER VAN DOLAH ET AL.²²⁰)

floating free in their bearings. Zero gravity would augment this condition. It thus appears that under appropriate conditions, even well-lubricated and shielded rotating systems can create unexpected ignition hazards.

The problem of surface hot spots produced by high shear rates in metal and by plastic deformation of sharp points has not been studied adequately.⁶³

The hot-surface ignition temperature is reduced by modifying the oxidizing components of the atmosphere. At any fixed total pressure, increasing the percentage of oxygen, chlorine, fluorine, and so forth, in the mixture will usually reduce the hot-surface ignition temperature.

In general, the ignition temperatures of most flammable mixtures tend to decrease with increase in total pressure of the system. Some high-energy fuels show a reverse trend in the response to ambient pressure. Concrete examples of this oxygen and pressure effect are presented in other sections of this report.

Hot Gases in Absence of Surfaces

Pilot Flames and Hot Gas Jets. While these are not the most probable sources of space-cabin fires, they are possible hazards. The penetration of a meteorite into a cabin, especially in an oxygen atmosphere, will be accompanied by a jet of vaporized metal as well as by a compression wave. This is discussed in Chapter 5.

Wolfhard and Burgess²⁴⁴ have shown that pilot flames, if sufficiently small, may be treated

as point sources in the manner of electrostatic sparks. In general, however, pilot flames act like extended sources and the critical factor is the temperature of their combustion products. The ignition problem really converts itself to one of flame propagation.

Ignition by streams of hot gases is a subject well developed in connection with the hazards of flammable atmospheres in coal mines and in the design of jet engines where control of flames is determined by recirculation of combustion products.^{154, 223} The interplay of chemical kinetics and contact times is too complex for adequate discussion in this report. For most gas mixtures, the short contact times in jets require that the ignition temperature be much higher than for the corresponding mixture in the hot-surface ignition situation.

Adiabatic Compression. The classical ignition problem of diesel engines finds its counterpart in space-cabin situations. The water hammer effect, the operation of certain gear pumps, and the rapid operation of valves can lead to ignition by adiabatic compression. The classic example is the explosion of oil or carbonaceous washers in the reducing valves of oxygen cylinders which are "cracked" too rapidly. As long as the rate of heat loss is low enough to allow ignition temperatures to be maintained through periods exceeding the ignition delay, a successful ignition is possible. This problem is quite serious in the extracabin control of monopropellants. Slow valving and careful "oxygen discipline"^{10, 63, 203} should eliminate the adiabatic compression problem within cabin equipment.²⁰³ The possibility of ignition of external lubricants in gear trains and other moving parts needs to be considered, especially in high-oxygen environments.

Shock-Wave Compression. Adiabatic compression at a rate approximating that of the molecular velocity at a specified temperature and pressure is referred to as *shock-wave compression*. It may be assumed that when a shock wave is caused to converge, a local critical source of energy is formed. In the ignition process, this energy must be dissipated in a small volume of the combustible mixture. This condition reverts back to the electrostatic spark problem.⁷⁶ The problem of plane

shock waves reduces itself to the case of adiabatic compression.¹¹ Table 1 indicates the temperature ranges to be expected from different compression ratios.

From the temperatures in table 1 and the specific gaseous ignition temperatures discussed in subsequent sections, it is apparent that pressure ratios of less than 10 will not ignite many fuel-air mixtures. Fuel-oxygen mixtures, however, will be ignited by relatively weak shocks.^{62, 200}

Hypergolic Ignition

The term "hypergolic ignition" is reserved for spontaneous ignition upon mixing of a bipropellant mixture at ambient temperature. Though control jets in spacecraft may employ hypergolic mixtures, it is doubtful that any will be found inside a cabin. However, one can imagine a situation in future missions where self-maneuvering units employing hypergolic propellants may be filled and serviced inside space cabins. The surrounding atmosphere and physical parameters may well determine the actual hazard involved. There is a major extracabin hazard with hypergolic chemicals. Ignition by accidental mixing adjacent to cabins (meteorite penetration of storage tanks) may, of course, effect damage to the cabin.

Unfortunately, each hypergolic mixture has its own hazard parameters and most work has been done in the specific condition of small-scale rocket engines. It will suffice to mention here two studies on the accidental mixing of hypergolic materials at launch sites. A Rocketdyne program at Edwards Air Force Base is evaluating the blast potential,¹⁸² and the Bureau of Mines is studying the role of inerting agents required to prevent ignition in both the liquid and gaseous phases.²²⁰

Most of the initiation phenomena described above were for gas-phase reactions. In recent years a considerable body of theory on the ignition of solid surfaces has been developed. Since most of these studies are related to explosives and propellants which can sustain flames in the absence of an oxidant atmosphere, only a brief review of the basic principles involved will be presented. The earlier work in

TABLE 1.—*Compressed-Gas Temperatures at Various Compression Ratios* [AFTER VAN DOLAH ET AL.²²⁰]

| Compression ratio | Temp. of compressed gas, °R | |
|-------------------|-----------------------------|-----------------------|
| | Shock wave | Adiabatic compression |
| 2----- | 604 | 594 |
| 5----- | 866 | 766 |
| 10----- | 1, 270 | 927 |
| 50----- | 4, 070 | 1, 430 |
| 100----- | 6, 950 | 1, 710 |
| 1,000----- | 34, 400 | 3, 075 |
| 2,000----- | 52, 000 | 3, 715 |

the field of ignition of explosives has been covered by Bowden and his coworkers.^{19, 20, 21} Recent studies have led to two schools of thought. One holds that ignition (initiation of deflagration wave) occurs only when thermal ignition of the solid occurs at the surface. The studies of Hicks and his coworkers^{80, 107} and of Altman and Grant³ have tended to support this point of view. Contrary opinion, however, suggests that ignition occurs when gases are formed from the solid surface and ignite to establish a flame.^{121, 140, 180}

It may well be that specific combinations of solid-phase and gas-phase reactions are initiating factors for each solid in question. Evans⁶⁸ will shortly publish a report reviewing the controversy. Application of mechanisms of propellant ignition to the ignition of carbonaceous and other solids of all types remains unclear at this point. Were gas-phase initiation to be the general rule, one would expect the inert gases in the atmosphere to play a significant role in the phenomena.

FLAME PROPAGATION

Once a flammable mixture is ignited, the resultant flame will either propagate through the mixture or be extinguished. The speed of flame propagation is greatly influenced by oxygen, inert-gas, and ambient-pressure parameters, as well as by the ignition source and physical environment. Much of the concrete

data to be presented in other sections will cover these parameters. In order to idealize the propagation picture, the two major systems which determine the propagation of flames in a combustible-oxidant mixture are discussed next: premixed or homogeneous systems, and unmixed or heterogeneous systems. The combustion of solids is a subcategory of the latter system.

Homogeneous Systems

A flammable homogeneous system is one whose composition lies between the compositional limits of flammability of the combustible vapor at a specified temperature and pressure. For example, the butane-air system of figure 2 has a lower (lean) limit of flammability at a fuel-air ratio of 0.04 and an upper (rich) limit at about 0.18. Figure 3 shows how the limits of flammability of a homologous series of hydrocarbons in air will vary. When the temperature of a mixture is increased, the flammable range widens. An electric spark or any local heat source may produce a local flame in a mixture outside of the flammability limits, but the flame will not propagate through the mixture. By maintaining the source in the nonflammable mixture, one can gradually oxidize all of the fuel component without a flame process.

Condensation of fuel components may well change the flammability of a mixture. As the temperature of a flammable mixture is decreased, the range of flammability narrows. As the temperature is lowered the percentage of fuel in the mixture decreases if the vapor pressure of the fuel is at the saturation point for that temperature. Further decreases in temperature will decrease the concentration of fuel in the vapor phase until the lower (lean) limit of flammability is reached. Figure 7 indicates that the intersection of the lower-limit curve and the vapor-pressure curve occurs in a temperature region known as the *flash point* of the combustible liquid.

The effect of ambient pressure on a combustible mixture is somewhat more complicated. A decrease in ambient pressure produces little effect on the limits of flammability until the *low pressure limit* is reached. This limit is critically determined by the nature of oxidant and com-

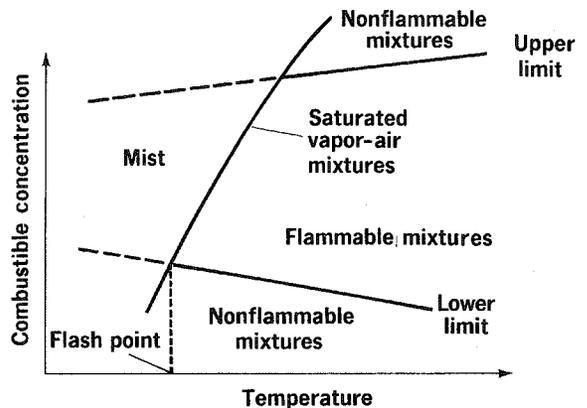


FIGURE 7.—Effects of temperature on limits of flammability of a combustible vapor in air. (AFTER VAN DOLAH ET AL.²²⁰)

combustible and the size, geometry, and attitude of the confining vessel. Failure of propagation of flame through a pipe is a good test of the low-pressure effect. Figure 8 shows, in an idealized way, how the quenching effect of a cylindrical pipe wall can become critical as the low-pressure limit is reached.

As has been mentioned, the lower the pressure, the greater the energy requirement for ignition. Flames have been shown to propagate through tubes at ambient pressures as low as 0.01 psia, but the energy requirements for ignition and the tube diameters must be quite

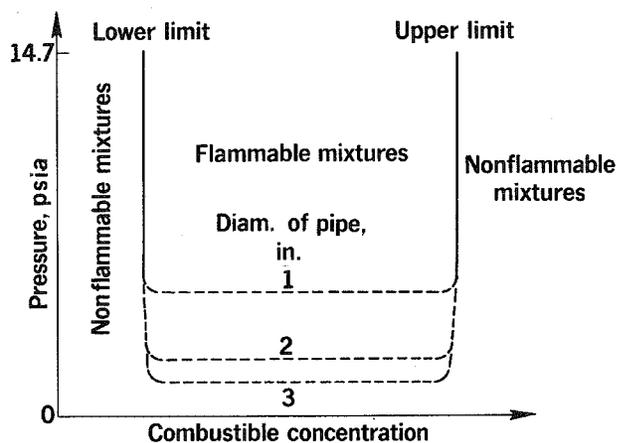


FIGURE 8.—Effects of pressure and concentration on limits of flammability and quenching diameter of a combustible vapor in air. (AFTER VAN DOLAH ET AL.²²⁰)

large. The homogeneous system is fine for discussion of principles. Most fire hazards, however, involve heterogeneous systems.

Heterogeneous Systems

A single-state system may be heterogeneous by virtue of concentration gradients and is invariably formed when a combustible vapor is leaked into an oxidant such as air.

A multistate heterogeneous system is formed when a liquid or solid fuel is injected into an oxidant medium. The sudden disruption of a hydraulic line would represent a practical case of this type which is discussed in Chapter 3. A rigid analysis of flame propagation in single-state and multistate systems is quite beyond the needs of the present discussion. Only a qualitative representation of the two conditions will be given.

When a vapor is injected into an oxidant, concentration gradients are set up which span the spectrum of mixtures above, below, and within the flammable-concentration limits. The flammable zone may ignite and propagate a flame until either mixing or depletion of fuel reduces the concentration below the lower (lean) limits.

When a liquid or a flammable solid is injected into an oxidant medium, a vapor-mist-oxidant system can be formed if temperatures are below the flash point ("Mist" area of fig. 7). Flammable sprays can be produced over a wide range of temperatures, both above and below the flash point. The introduction of an ignition source into an ignitable spray or mist will tend to vaporize the fuel droplets or solid fuel particles locally and, thus, form flammable mixtures similar to the single-state type. These behave like the vapor injected into oxidant. In the case of complex mixtures of liquid or solid fuels, fractionation may occur prior to burning. The fuels may carbonize, pyrolyze, and yield combustible gases and vapors quite unlike the original liquid or solid fuel. In such a system the geometry of the container, type of ignition source, and physical state of the spray or mist are critical in description of flame propagation.

It is obvious that ignition in heterogeneous liquid-gaseous systems is much more difficult

to study than ignition in homogeneous gaseous systems. A variety of experimental methods and techniques have been employed in the study of spontaneous ignition of liquid fuels. There are the CFR octane-number-rating engine, well-instrumented engines with single-cylinder motors in which single combustion cycles can be isolated, and special devices such as the rapid-compression machines and constant-volume bombs which restrict themselves to the development of a fraction of a combustion cycle. There are also various combustion containers under both static and flow conditions in which the variables affecting ignition may be isolated more individually and in which the chemistry of the ignition and combustion processes may be studied more closely. All these methods provide valuable information which can be used in the interpretations of ignition behavior. It is noteworthy that the same particular phenomena associated with ignition and combustion are often apparent in one form or another in the results obtained with the various methods. It appears worthwhile to review some of the variables involved in the determination of ignition phenomena in condensed-phase hydrocarbon systems.

There are at least two generalized mechanisms for the oxidative reactions that lead to ignition of hydrocarbons. In the low-temperature mechanism, which predominates up to temperatures of 350° to 400° C, the reactions proceed through free-radical chain-branching processes involving the formation and decomposition of peroxides and hydroperoxides. The high-temperature mechanism, which predominates above 350° to 400° C, depends at least partially on pyrolysis prior to and during oxidation.

Early studies of spontaneous-ignition temperatures of fuels were reported by Townend and his coworkers.^{147, 217} More recent data by Johnson et al.,¹²⁰ of the Naval Research Laboratory, point up many of the hazards in interpreting ignition points of fuels and the effects of oxygen and inert gases on the phenomenon. The apparatus used in the latter studies consisted of a stainless-steel block containing an ignition chamber of about 21 ml capacity with an opening at the top and two gas outlets near the bottom. The chamber had a small de-

pression in the bottom designed to hold a shallow stainless-steel crucible which could be replaced easily and which served as a receptacle for the fuel. The block was heated in an electric furnace to a high temperature and one drop of fuel was added to the crucible. The reaction which followed was then observed and recorded. Since it was easier to change the temperature than the oxygen concentration, the procedure was repeated at progressively lower temperatures until the ignition pattern for a given oxygen level was established. The oxygen-nitrogen concentration was then changed and the process repeated until a delineation of the ignition zones could be obtained. The recorded temperatures were those of the block, although for many studies a thermocouple was suspended in the chamber itself to record gas-temperature changes.

Figure 9 shows the ignition curve of *n*-octane in oxygen with nitrogen as diluent. The area of positive ignition (visible and/or audible combustion) lies above and to the right of the ignition curve. In the area labeled "Cool flames" a definite but much weaker type of reaction or ignition occurs which can be seen only in the dark or observed by means of thermocouple response. To the left is the area of nonignition in which oxidative reactions still proceed but too slowly to culminate in ignition.

Johnson et al. interpret this model curve as follows:

The self-ignition point (SIP), is the lowest temperature at which a drop of fuel will ignite when pure oxygen is being supplied. It is a readily reproducible value characteristic of the fuel in a given ignition chamber. For many substances this temperature remains nearly constant for oxygen concentrations down to 50 percent and below. The ignition curve reverses itself at lower oxygen levels to give an inflection point at M. As yet no good explanation can be given for this particular feature of the ignition curve, but since it appears in a variety of fuels and pure hydrocarbons it is very likely a reflection of a fundamental part of the ignition process. There does appear to be a relationship between the height of B and ease of ignition. . . . As the temperature is raised past B, reactivity again increases to a maximum value at N. This region represents the greatest reactivity of the fuel to oxidation by the low temperature mechanism. As the temperature is increased further, this apparent reactivity decreases probably due to the increased thermal instability of certain heat-sensitive intermediates. Accordingly, more

oxygen is required to furnish the necessary supply of these intermediates so that positive ignition may occur. At higher temperatures, OP, the high temperature mechanism becomes effective so that again less oxygen is required for positive ignition.

It is evident that the amount of oxygen required for the formation of cool flames is very small in that cool flames are observed even when pure nitrogen is fed into the chamber. Under these conditions the only oxygen available is that which enters the chamber from the air above by back diffusion or convection.

Similar curves were obtained from many different hydrocarbons and specific differences were interpreted in the light of molecular structures. The ignition lags for each system were also studied to get a firmer basis for the molecular mechanisms involved. The ignition lag, or time delay, is the time elapsing between addition of sample and ignition. Figure 10 is a portion of the curve of figure 9 showing these lags as a family of curves.

The exponential increase in lag with decreasing temperature seen in figure 10 is typical of the results obtained for all fuels and hydrocarbons studied at all oxygen concentrations. It is of interest that there is a smooth continuity to the ignition lags as they change with temperature, regardless of the type of ignition occurring. Furthermore, it is evident in figure 10 that although the ignition lags are very dependent on temperature, they are scarcely affected by changes in oxygen concentration. Also, as has been observed by other investigators under special conditions, a cool flame (or

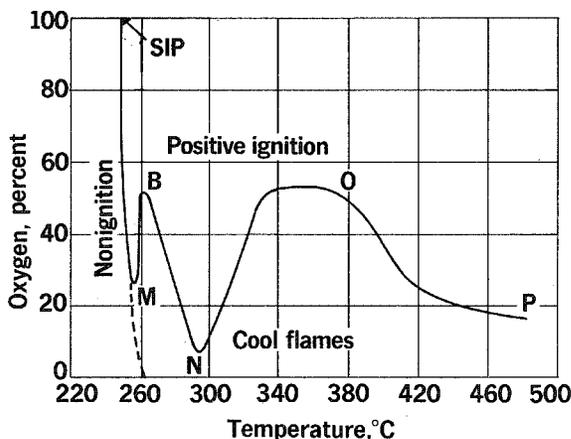


FIGURE 9.—Ignition curve for *n*-octane.
(AFTER JOHNSON ET AL.¹²⁰)

some related phenomenon) immediately precedes positive ignition. Although this two-stage process may occur generally, the cool flame usually was not observed because of the shortness of the time interval and the masking effect of the much more violent positive ignition.

All the above phenomena were interpreted along the following lines:

Peroxides and hydroperoxides are among the first oxidation products formed. These then decompose or react to initiate branched-chain reactions. Neither cool flame nor positive ignition can occur if the rate of quenching of these chains is greater than their rate of initiation and propagation. In view of the relatively long time lags before ignition, when contrasted to the short duration of the ignition itself, it appears that there is a gradual increase in concentration of intermediate oxidation products up to a critical value. When this is reached, then either cool flame and/or positive ignition ensues immediately.

Under a given set of conditions the net increase in rate of formation of these intermediates must be greater for easily ignitable substances than for less easily ignitable ones, or else the critical concentration is much lower.

The ignition curves show that positive ignition can occur under conditions of higher temperature and lower oxygen partial pressure for a more difficultly ignitable . . . substance than for a more easily ignitable . . . substance. This would imply that although the necessary intermediates are formed with more difficulty for the former type, nevertheless they must be more stable thermally. If peroxides are involved in these intermediates this is in keeping with their known thermal stability properties—namely, that primary peroxides are very unstable, whereas secondary and tertiary peroxides are increasingly more stable. . . .

In the low temperature mechanism zone the pre-ignition oxidative reactions for a given substance are independent of the type of ignition that follows.

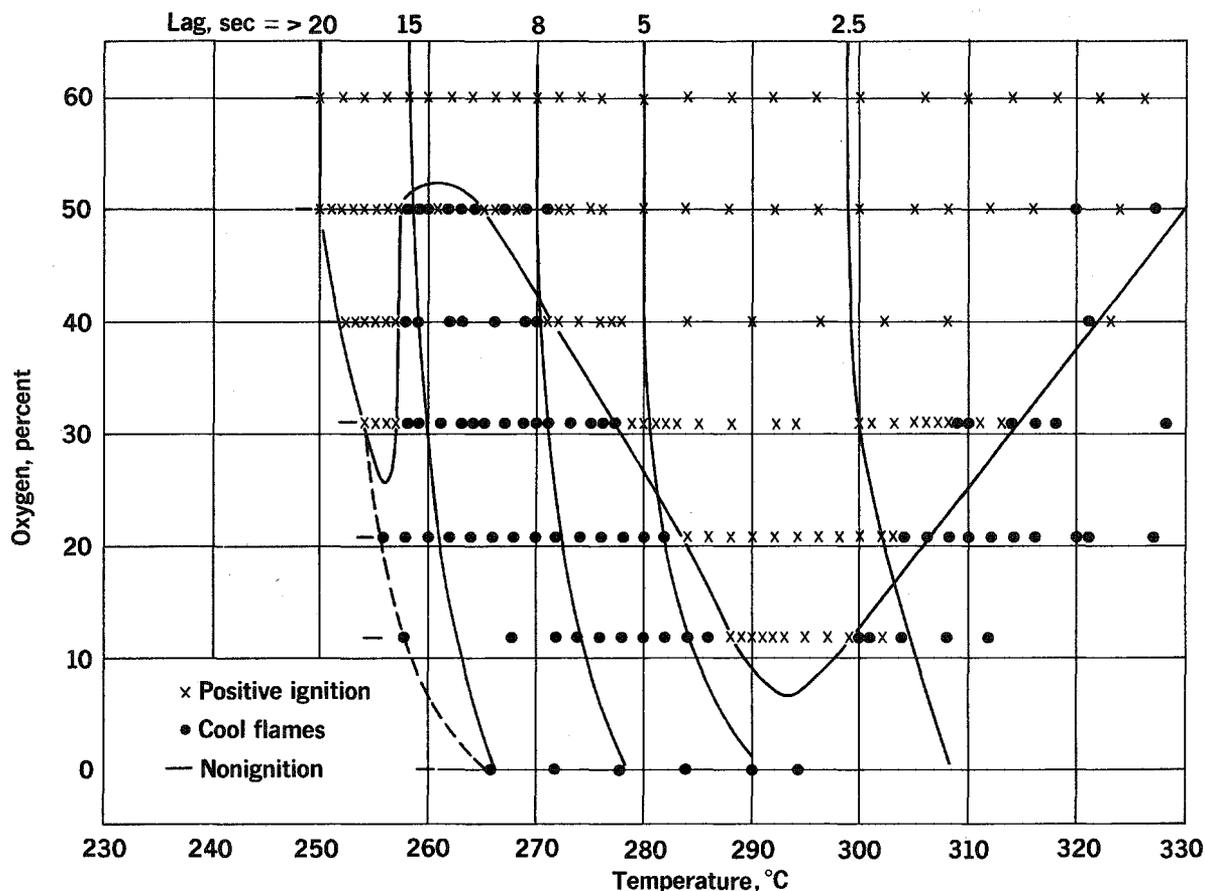


FIGURE 10.—Portion of ignition curve for *n*-octane with ignition lags shown as a family of curves. (AFTER JOHNSON ET AL.¹²⁰)

whether positive or cool flame. These preignition reactions are constantly yielding intermediates, which for want of a better name, will be labeled X. These compounds, X, are continually being lost by chemical reaction, degradation, and physical removal. The formation of X requires relatively little oxygen, but the rate is very dependent on temperature. If the temperature is high enough, then the rate of formation of X will be greater than the loss of X, and eventually a critical concentration is reached and ignition occurs. This explains why a minimum temperature is necessary for ignition of a particular substance in a given apparatus; the almost perpendicular boundary between nonignition and both types of ignition; and the very rapid continuous decrease in ignition lags with increasing temperature regardless of the type of ignition.

A second concept is that there are certain heat sensitive reactants, Y, part of which are dependent on the cool flame reaction, that are necessary intermediates for the reactions which result in positive ignition. In addition, these must attain a critical concentration before positive ignition can occur. This implies that the first reactions in ignition are the cool flame ones which, if they yield Y above the critical concentration, immediately will become positive ignition; otherwise, if the rate of destruction of Y is greater than its generation, the ignition remains a cool flame. These ignition reactions are generally very fast compared to the preignition reactions, but the border line case exists where under certain conditions the cool flame can be observed immediately preceding positive ignition. Two-stage combustion may well be another manifestation of this same phenomenon. The sharpness of the boundaries between positive ignitions and cool flames in the ignition curves shows that attainment of the critical concentration of Y at a particular temperature is very dependent on the availability of oxygen. This is quite in contrast to the formation of intermediates, X. However, the formation of Y is also somewhat dependent on temperature since less oxygen is required at the point of greatest reactivity (N in fig. 9). The rise in the positive ignition curve at temperatures above N in fig. 9 implies that the reactants, Y, may well be peroxidic in nature . . . their temperature instability coefficient being greater than the coefficient of formation so that the composite gives the inflection at N.

It is of interest that these generalizations have some support from observation of temperature changes of the gases in chambers following addition of a drop of fuel. Under conditions of longer ignition lags, the gas temperature dropped several degrees because of the cooling effect of evaporation. The temperature then rose slowly to slightly above block temperature owing to the small amount of heat liberated by the preignition reactions (the formation of com-

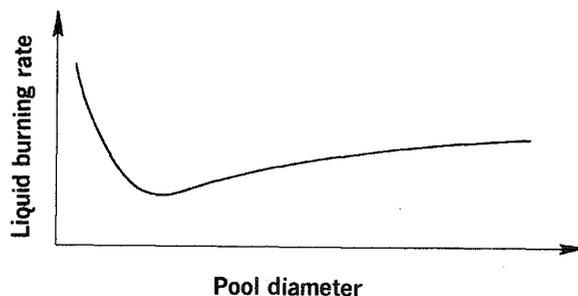


FIGURE 11.—*Burning rate of a liquid fuel from a pool.* (AFTER VAN DOLAH ET AL.²²⁰)

pounds X mentioned previously). At the moment of ignition, either positive or cool flame, there was a very sudden temperature rise or “kick” due to the large amount of heat liberated (the time at which X reached the critical concentration).

These complex phenomena are probably important in explaining the anomalous effects of oxygen environments in the ignition of hydrocarbon systems to be discussed in Chapter 3, under “Liquids and Vapors.” Prediction of the degree of fire hazard in accidental situations of this type in space cabins is quite beyond the present state of the art. The best one can do is get an intuitive feel for the degree of hazard, and try to choose the least hazardous liquid hydrocarbon systems.

Diffusion flames are special cases of flame propagation in heterogeneous systems. They are flames whose rates are controlled by diffusive mixing processes. In engine applications, diffusion flames are controlled by the rate at which fuel and oxidant are brought together.⁸⁸ In a consideration of hazardous conditions, the burning of a pool of flammable liquid is the typical example of a diffusion flame process. Spillage of flammable materials on launch pads or within space cabins presents such a hazard.

When burning occurs above a pool, the rate of burning can be increased by heating the liquid or increasing the concentration of oxidant above the pool. The pool diameter in any fixed containing environment also determines the rate. For example, figure 11 demonstrates that linear liquid burning rate or pool regression rate is a complex function of diameter of the pool. At small pool diameters the burning rate is high

because of the addition of heat to the pool by the containing medium. The rate usually reaches a minimum value and then increases to a constant velocity. Zabetakis and Burgess²⁴⁹ have studied these pool phenomena and find that this constant velocity (in inches per minute) is 0.03 times the net heat of combustion divided by the sensible heat of vaporization. Container geometry determines the approach to this burning rate at infinite pool size.

DETONATION

The detonation process has already been defined at the beginning of this chapter. The theory of detonation has been reviewed quite thoroughly in recent years (refs. 52, 69, 92, 117, 133, 136, 148, 215, and 220). The physics of detonations will not be discussed here except for a brief review of the factors in a space cabin which may seriously alter the detonation process.

In discussing detonation both gaseous and condensed systems must be considered. In gaseous systems, initiation of detonations requires amounts of energy several orders of magnitude greater than those required to initiate deflagrations. For electrical initiation there are required at least 10's to 100's of joules. In some systems, however, lower levels of energy are sufficient. Evans and Ablow⁷⁰ report that in a mixture of 67 percent hydrogen and 33 percent oxygen a detonation wave was initiated with an electric spark of 540 millijoules' energy, the wave being formed 1 to 2 feet from the spark in 2- to 4-inch-diameter tubes. Under the proper conditions, detonation of several tenths of a gram of primer explosive is enough to initiate a major detonation process in a large system. A typical accidental detonation in gaseous systems occurs in pipes or tubing where a deflagration initiated by a low-energy source increases the energy in the system sufficiently to propagate a detonation. In such a system, the following sequence of events may occur: (a) The pressure waves from the deflagration continuously catch up with previous wave fronts, until a shock wave occurs; (b) the shock wave increases in strength

until it is capable of initiating, after an induction period, a detonation reaction; and (c) the reactions behind the shock-wave front become continuous and a detonation wave is propagated.

In condensed liquid or solid systems the same initiation processes are potentially available. Electric sparks, explosive primers, or transitions from deflagration to detonation are possible initiating events. The initiation of detonation by intense shock waves of any origin is a constant problem complicating the handling of many monopropellant systems such as solid-fuel rockets. Evans,⁶⁸ for example, reports that a rapid deflagration or explosion of certain liquid monopropellants can be accomplished by a succession of sparks of millijoule energy. Presumably vapor is being formed during the first sparks, and this is ignited by a later spark.

The detonation processes themselves fall into two classes: high-velocity (high-order or hydrodynamic) detonations and low-velocity detonations. In most condensed liquid or solid systems high-velocity detonations usually involve pressures of about 10^6 atmospheres, require high shock pressures for initiation, and, as will be discussed subsequently, have smaller critical diameters for propagation. In some systems, a shock magnitude of only 10^3 atmospheres is required to initiate these high-order detonations. This has been demonstrated with granular ammonium perchlorate⁷² and granular PETN^{72, 195} in an uncompressed state. The low-velocity detonations, on the other hand, are initiated by weaker shocks, and they have lower pressures and larger critical diameters than the typical hydrodynamic detonation. These low-velocity detonations resemble deflagrations such as are seen with black powder. In liquids, the process appears to be quasi-steady-state with a net velocity approximately equal to that of sound. The details of these low-velocity detonations are still under study.^{95, 196, 216}

As in the case of deflagrations, there are critical environmental limits for detonations. The concentration limits are usually narrower than the corresponding flammability limits. A typical example is the hydrogen-oxygen system where the lower limit for flammability is 4 percent, and for detonation, 16 percent.

In the case of flames, environmental limits are conveniently determined as quenching distances. With lesser distances (tube diameters or plate separation), the flame is quenched by extraction of heat. Contrariwise, below the critical diameter for detonation, the rate of energy loss through expansion of the product gases is too great for the wave to continue to propagate. Critical diameters are one indication of the relative sensitivity to detonation, and have been employed for this purpose. Since the rate of energy release is important, less energetic or slower reacting systems will have larger critical diameters. Typically, critical diameters may vary from 0.02 inch or less for nitrogen tetroxide-hydrocarbon systems to over 1 inch for insensitive mixtures. An increase in lateral confinement produced by heavy-walled tubing will naturally reduce the absolute value of this critical diameter. Low-velocity reactions, being apparently less energetic, appear to have larger critical diameters. A recent paper by Evans⁶⁹ discusses the relation between failure diameter and shock sensitivity for high-order detonations of homogeneous condensed materials, and the relation of both to chemical kinetics of thermal decomposition.

Subcritical-diameter tubing is commonly employed for *detonation traps*, devices that prevent a detonation initiated in one part of a system from propagating to another. One use of such a device is to isolate a monopropellant tank on a test stand from an experimental motor. For systems exhibiting the low-velocity reaction, traps consisting of 270° or 360° loops of larger tubing may be adequate. The suggestion has been made that such traps operate by the initiation of a low-velocity reaction at the point of intersection. This reaction breaks the liquid column but is in itself incapable of propagation, since the tubing diameter is below the critical diameter for propagation of the low-velocity reaction.

It is important to remember that an oxygen-enriched atmosphere reduces the time scale of combustion phenomena, so that fire hazards become explosion hazards, and deflagrations become detonations. It is fortunate that the number of accidental situations capable of

forming detonations in space cabins are quite few. The presence of propellant refilling stations for "self-maneuvering" personal propulsion systems would probably create the greatest hazard. Hydrogen or other combustibles required for the function of fuel cells or fuel-cell oxygen detectors and hydrogen from overcharged batteries are other possible sources of difficulty. A major detonation danger, of course, involves the shock sensitivity of oxygen (liquid or gaseous) in contact with organic materials, or compounds like hydrazine in contact with rusty surfaces.^{10, 97} Proper discipline should avoid intracabin hazards from these sources.^{10, 62, 63, 175}

The reviews of Van Dolah²²⁰ and of the Office of the Director of Defense Research and Engineering⁹⁷ cover adequately the quantitative detonation hazards of most rocket fuels in use and projected for future missions. Because this subject area is primarily of concern in extracabin design, it will not be pursued further in this report. The role of inert gases in detonation processes is discussed in the last section of this chapter and the physical characteristics of typical fuels and oxidizers are presented in Chapter 7.

FLAME EXTINGUISHMENT

The problem of flame extinguishment in sealed cabin systems is mostly related to the toxicological dangers involved. The entire problem of flame extinguishing agents has been reviewed adequately by Friedman and Levy.⁸¹ The mechanism of extinguishment is dependent on the oxidant system since the many chemical extinguishing agents (alkyl halides) interfere with the free-radical flame reactions. Container geometry, heats of reaction, and many other factors determine the optimum approach to extinguishment.

Physical methods of flame control consist of (a) isolation of combustible from oxidant (blanketing or diluting), (b) removal of heat (cooling), (c) disturbance of flame zone, and (d) blockage of radiation. Specific problems created by each of these physical approaches and by the many chemical methods in space cabins are reviewed in Chapter 7.

ENVIRONMENTAL FACTORS IN SPACE-CABIN FIRE HAZARDS

In this section, factors in space cabins which contribute immediately to the fire hazard are briefly reviewed in light of the theory discussed above. The problem of meteoroid penetration is discussed in Chapter 5.

Temperature

Local hot spots resulting from electrical equipment, frictional sites, and adiabatic compression procedures all increase the fire hazard. Autoignition tendencies, reaction rates, limits of flammability, flame speeds, and extinguishment problems are all affected by hot spots within the cabin.

Pressure

Since pressure affects reaction rates, the limits of flammability, flame speeds, and autoignition tendency are affected by cabin pressures. An increase in ambient pressure usually widens the flammable range and decreases the temperature required for autoignition in most systems except in the case of some of the high-energy fuels.²²⁰ In the latter instance, the vapor pressure of the liquid appears critical. Since vapor pressure is dependent on temperature, a decrease in ambient pressure results in a decrease in flash point even though limits of flammability are not affected by this small pressure change. Accordingly, mixtures with flash points above room temperature at 1 atmosphere may form flammable mixtures when pressures are reduced. This factor will be invoked in the discussion of plate ignition temperatures in Chapter 3. The tendency of electrical contacts to arc is increased by low extracabin pressures. Rapid deterioration of plastic insulation may occur from the excess heat evolved and cause malfunctions.¹⁶⁸ Reduced pressure within the cabin itself can increase arcing of electrical contacts. More will be said about pressure effects on burning solids in Chapters 2 and 4.

Velocity

The velocity of gases in the area of a possible ignition site affects the mixing, ignition, and extinguishment parameters of the flame process.

In general, more energy is required to ignite flowing mixtures than static ones; and conversely, moving heat sources require higher temperatures than static ones to ignite static gas mixtures. The air-conditioning system, therefore, plays a role in the fire hazard.

Gravitational Fields

The role of gravitational fields is indeed a complicated one in the total fire hazard. There appear to be four phases to the problem: (1) the preparation of combustible mixtures where liquid and gaseous combustibles are involved, (2) the ignition process, (3) flame propagation, and (4) flame extinguishment.

The effect of gravity on the preparation of flammable mixtures depends on the properties of the flammable material and the nature of the spill or leak. In the absence of both gravity and forced convection, the spread of flammable vapor or gas would be entirely by diffusion. A spill on a surface in the presence of gravity would result in gravity's "holding" the liquid pool to the surface. Vapors move away from the surface and mix with the ambient gas. A vapor heavier than the ambient gas would tend to cling to the surface and probably be spread less under full gravity than under reduced gravity conditions.¹⁸⁶ This spreading factor can be calculated for any system of liquid and ambient gas.

There would appear to be one other mixing problem. If a spill or leak imparts even a small momentum to the fluid, the motion of the fluid through the atmosphere of a space cabin under zero gravity conditions would be such that a more random distribution of flammable sources would be expected. The actual motion of such fluid particles may even set up a forced convection by entrainment in zero gravity states and promote the mixing and combustion process. A quantitative analysis of forced convection by "particle movement" still remains to be made.

The ignition process in zero gravity states is an interesting problem. Gas mixtures that would ordinarily not be ignited by a small heated object because convective flow past the hot spot limits contact time with the gas may now be susceptible to ignition. This factor is

rather difficult to evaluate from theoretical considerations and requires empirical study.

The principal experimental combustion studies have, of course, been made under normal gravitational conditions. The theoretical studies, on the other hand, have usually neglected gravitational effects. The reasonable agreement between the two suggests, at first glance, that gravity plays a minor role in the combustion process. In the empirical equations which have been developed to include natural convection effects, gravity appears as a term raised to a fractional exponent. Spalding,²⁰⁷ for example, uses the following equation to describe the data obtained from the burning of single drops of liquid fuel in air:

$$\frac{\dot{m}dc}{k} = 45B^{3/4} \frac{(gd^3)^{1/4}}{\alpha^2}$$

where

- \dot{m} vaporization rate per unit surface area
- d sphere diameter
- c specific heat
- k thermal conductivity
- B transfer number, a function of fuel properties
- g acceleration due to gravity
- α thermal diffusivity

The equation is purely empirical and the obvious conclusion cannot be drawn that the burning rate is zero when g is set equal to zero. An equation of the form

$$\dot{m}_g = \dot{m}_0 [1 + f(g)]$$

would probably be more nearly correct, where the subscript g refers to gravity conditions and o to the zero gravity case.¹³⁶ The function $f(g)$ would probably be relatively small compared with unity. Irrespective of its magnitude, however, the burning rate would unquestionably be less in the absence of convective effects.

Let us consider a liquid or solid diffusion flame, a flame which could result from the burning of a pool of liquid or a piece of solid material. Gravity would be expected to increase the burning rate above that at zero gravity by increasing heat and mass transfer through the addition of natural convection to the diffusion process. Product gases that

normally rise and are convected away from the flame zone would tend to distribute uniformly about the burning zone and impede the flow of oxidant, with resultant extinguishment. Experiments performed with burning candles in "freely falling" sealed containers showed flame extinguishment much before that which occurred in static control tests.⁸¹ Kumagai and Isoda¹²⁹ recently demonstrated that the flame around a freely falling droplet of fuel was spherical when observed 0.1 to 0.4 second after ignition. The conclusions of this study of the combustion of single drops under various accelerations from zero gravity to normal gravity conditions are:

(a) The dimensions of the flame boundary and the hot-air zone become higher and narrower as the acceleration increases, because natural convection becomes stronger.

(b) Burning rates increase as acceleration increases. Burning rates can be expressed in the form

$$D_o^2 - D^2 = kt$$

where

- D drop diameter at time t
- D_o initial drop diameter
- k evaporation constant

The value of k roughly doubles in going from a zero gravity condition to the normal value for g .

It has been known for some time that convective effects influence flammability limits. The limits are almost always narrower; that is, the flammable range of mixture ratios is narrower for downward propagation than for upward propagation. The most marked difference occurs on the rich side and is attributed to the inability of rich "cool" flames to move in the absence of convection in the direction of propagation. It is postulated that convection serves to preheat the unburned mixtures just ahead of the flame, thus increasing the ease of flame propagation. These hypotheses also suggest that flame vigor would be less under zero gravity conditions than under normal gravity conditions. It would appear that changes in the gravitational field should not affect flame propagation through premixed combustible-

oxidant systems. Actually, in the absence of a gravitational field, one would expect the flammable range to be narrowed, approaching the limits of flammability seen with horizontal propagation of flame. For example, Van Dolah et al.²²⁰ have reported that in horizontal propagation, the flammable range of hydrogen in air would be 6.5 to 71 percent instead of 4 to 75 percent and the flammable range of ammonia would be 18 to 25.5 percent instead of 17 to 26.5 percent (by volume). These are rather small changes but illustrate the principle involved.

On the other side of the ledger, Wolfhard²⁴³ has pointed out that combustion involves the formation and expansion of gases. Unless a burning object is spherical, this would mean a preferential movement of gas in some direction. This movement could well supply oxygen to the flame. Also, the absence of convection currents may reduce heat loss from the flame front and prolong combustion events. Wolfhard feels that very small *g* loads from attitude control may be much worse than 1*g*.

The problem of zero gravity in fire extinguishing is also of interest. The many agents of solid, vaporous, or gaseous nature currently in use would probably not "settle down" over a fire area but would scatter in random fashion throughout a cabin. However, fighting "overhead" fires would probably be easier with these agents in zero gravity conditions. In view of the "scattering tendency" augmented by reduced gravity conditions, it may be well to review the problems of propulsion of many of these agents in the direction of the fire. More will be said of fire extinguishment in Chapter 7.

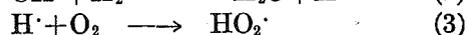
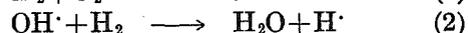
On the basis of this very cursory examination of the problem of burning under zero gravity conditions, it appears that, in general, combustion processes may be less severe than under normal gravity conditions. The overall effects may be small, however, and the only safe conclusion is that the same general precautions would be required with respect to fire hazards as are usually taken under normal gravity conditions.

Oxidants and Inert Diluents

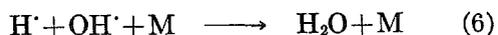
The empirical effects of oxidants and inert diluents in combustion problems pertinent to

space cabins are covered completely in Chapters 2, 3, 4, and 5. At this point only the theoretical aspects of the oxidant-diluent problem will be considered. The review of Friedman and Levy⁸¹ outlines the voluminous literature on this subject.

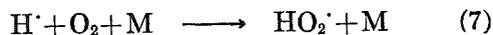
Insight into the oxidant-diluent problem may be attained by reviewing the basic theory of hydrogen-oxygen and hydrogen-air combustion reactions.^{192, 193} In such reactions, free radicals react in a chain process, creating more than one free radical for each one used up. Consequently, the rate of reaction increases exponentially with time and an explosion potential is created. The most likely elementary reactions at the flame front are:



Reactions (2), (4), and (5) cause chain branching. Reaction (5) is actually endothermic and is, therefore, the slowest. Flame is thought to be propagated by diffusion of hydrogen atoms into the unreacted gas, followed by reaction (5) to start a new chain. Because of their greater stability and diffusibility, the hydrogen atoms and not the other radicals are thought to be the actual propagating agents. In the "downstream" part of the flame, final reaction products are formed by three-body reactions such as:



The third body, M, carries off part of the energy liberated by combination of the radicals. It can either help to stop a chain reaction, as in (6), or reduce the reaction rate by aiding the formation of more stable free radicals such as



The greater the complexity of M, which can be any other molecule or radical, the greater its

specific heat and the more effective it is as an "energy trap."

Nitrogen or any other inert diluent may serve as M . It can affect the reaction in several ways, the most obvious being as an energy attenuator for chain termination or retardation (reactions (6) and (7)). The diluent helps maintain thermal equilibrium among the reacting molecules and can act as a third body in recombination reactions. In general, the flame temperature is reduced, as is the probability of detonation, by the presence of nitrogen or other inert gases.

It is obvious that the role of inert compounds in the explosion process is quite complex. The so-called "wall effect" contributed by the containing medium is an example of inerting surface reactions which exert a fine control over the chain process. The dividing line between explosive and nonexplosive conditions is a function of gas composition and of the size and material of the container. The temperature-pressure relationship of such a system has fascinated physical chemists for many years.⁹ Figure 12 represents these relationships. It is clear that for some temperatures (500° C) there is no explosion at low pressures. At intermediate pressures there is an explosion potential. At higher pressures, explosions are again not possible; and at the highest pressures, explosions can once again occur. The pressures at which transitions occur are called the first, second, and third explosive limits. Different inerting agents (M) or inhibitors will raise the first and third pressure limits and lower the second pressure limit. If enough free radicals react with chain-terminating compounds in the gaseous phase or on the wall, the exponential rise in free radicals required for explosion will not occur.

Pressure determines the explosion limits in a complex way. As was mentioned above, the hydrogen atoms are the ones most likely to diffuse to the wall. As long as more than one-half of these atoms hit the wall before reacting with other reactive gaseous components, no exponential rise in free radicals occurs. As soon as pressure rises, more hydrogen atoms collide with gaseous reactants prior to hitting the wall and explosions can occur, setting the

first limit. At higher pressures, reaction (7) is favored because it is a three-body reaction. Since $\text{HO}_2\cdot$ is more stable (less reactive) than $\text{H}\cdot$, these hydroperoxo radicals can travel farther without reacting with active gaseous components. This allows the wall effect to take over and sets the second limit. The third limit is reached when there are enough $\text{HO}_2\cdot$ radicals present so that more than half will react or decompose before reaching the wall, allowing explosion to occur. The diffusive as well as thermal gas properties appear to affect the responses to the hydrogen-oxygen system.

This complex picture gives one only a general feel for the "inerting" problem. Theoretical

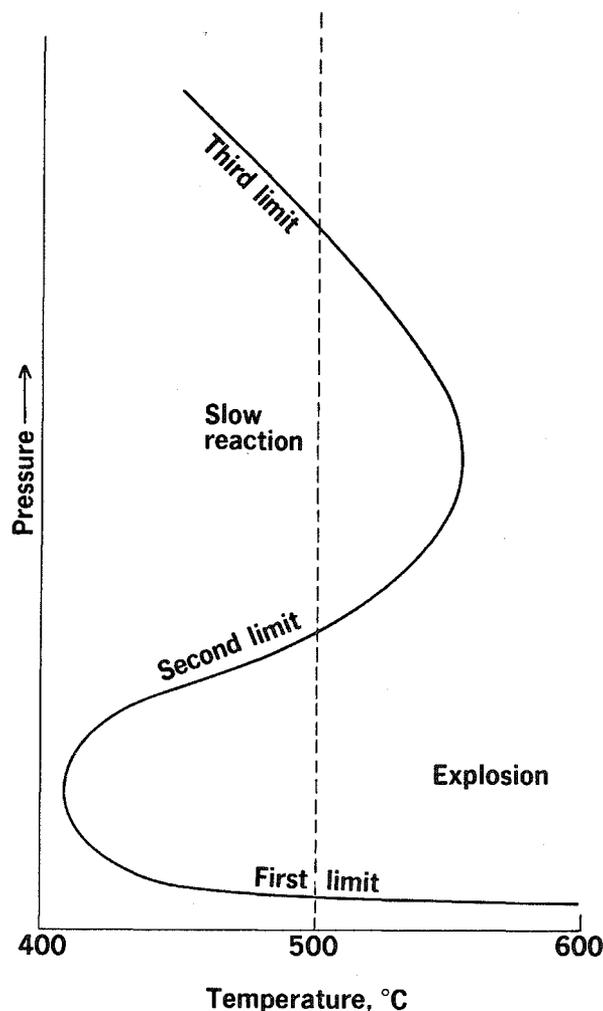


FIGURE 12.—Explosion limits of hydrogen-oxygen. (AFTER SKINNER.²⁰³)

analyses of hydrocarbon systems have more severe complexities,^{81 203} but appear to follow the general "rules of the game." It must be remembered that quenching and thermal conductivity are not the only physical variables involved in inert-gas effects. The diffusion of atoms in and out of the flame zone is also important. Most of the detailed work on the complex inert-gas effects has been carried out in hydrocarbon gas-oxygen mixtures. It may be worthwhile to review several models of burning velocity in an attempt to analyze the role of the inert-gas components in the process.

The relative validity of thermal and diffusion theories in modeling burning phenomena has been a matter of long-standing controversy. Ever since the pure thermal (heat conduction) theory of Mallard and LeChatelier was set forth in 1883, refinements of this theory have been numerous. Recent conflicts appear to center between the current thermal approach expressed by the Semenov-Zeldovich-Frank-Kamenetsky equation and the pure diffusion approach of the Tanford-Pease equation. The former may be written:²⁸

$$u_f = \frac{RT_o}{P} \sqrt{\frac{2\lambda_f}{X_f \bar{C}_p} \int_0^{T_f} \omega dT \over T_f - T_o}$$

where

- u_f burning velocity
- R gas constant
- P pressure
- T absolute temperature
- X_f mole fraction of combustible in the unburned gas
- λ_f thermal conductivity at the flame temperature
- \bar{C}_p mean molar heat capacity
- ω chemical reaction rates
- o initial
- f final

This version assumes that thermal and mass diffusivities are equal and neglects the change in the number of moles of gas across the flame.

The theory of Tanford and Pease²¹⁴ assumes that the rate of flame propagation is controlled by the diffusion of atoms and radicals from the burned gas and the rate at which these active

species react with the unburned fuels. The Tanford-Pease equation is as follows:

$$u_f = \left(\sum_i \frac{k_i C P_i D_i}{Q} \right)^{1/2}$$

where

- u_f burning velocity
- C concentration of fuel in molecules/cc (a mean value over the combustion zone)
- P_i partial pressure of the i th active species at the flame front
- D_i the diffusion coefficient into the unburned gas for the i th active species
- Q mole fraction of potential combustion product
- k_i rate constant for the reaction of the i th active species with the fuel

The active particles considered are hydrogen and oxygen atoms, and hydroxyl radicals. Clingman et al.⁴³ compared the burning velocities of methane in varying mixtures of oxygen and the inert gases nitrogen, argon, and helium. The inert gas-oxygen ratios were kept at 80:20. In proceeding from nitrogen to argon mixtures,

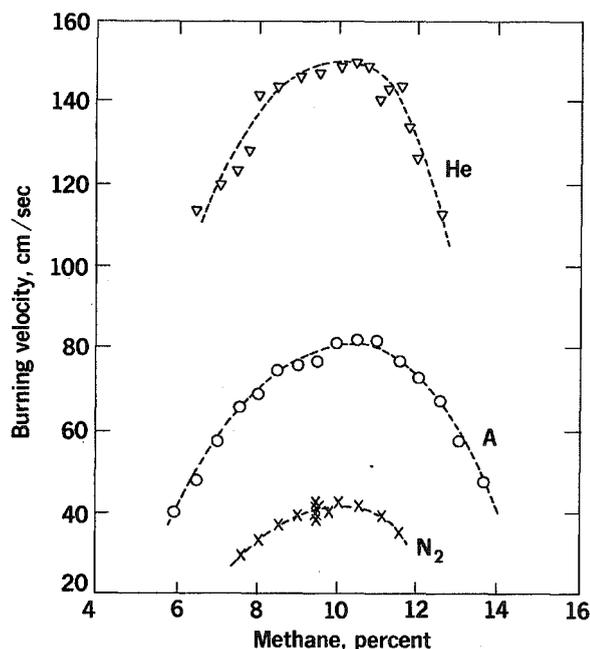


FIGURE 13.—Burning velocities of methane in oxygen with various inert diluents. (AFTER CLINGMAN AND PEASE.⁴⁴)

the flame temperature and, consequently, the concentration of active particles increases while thermal conductivity and diffusion coefficients are little affected. On the other hand, on going from argon to helium, the flame temperature and equilibrium concentrations of the burned gas will be the same, but diffusion coefficients and thermal conductivity are markedly altered. The results of these early experiments favored the diffusion theory of Tanford and Pease.

Using an improved technique, however, these investigators found that the ratio of burning velocity in argon to that in helium was 1:1.86, which is quite close to the 1:1.95 ratio predicted for the square root of the high-temperature conductivity ratios.⁴⁴ Figure 13 illustrates the effect of different inert gases on the burning velocities of various percentages of methane in oxygen.

A thermal theory rather than an active-particle diffusion theory also seems to explain the effect of inert diluents on flame quenching.¹⁷² Further, simple thermal considerations relate the pressure dependencies of various flame properties.²⁸ Finally, the numerical calculations of Giddings and Herschfelder⁹⁰ suggest to Brokaw²⁸ that the pure Tanford-Pease model is essentially inadequate for explaining burning velocities.

The complex relationship between thermal and diffusion factors in inert-gas interaction has also been emphasized by Mellish and Linnett¹⁵⁸ in the theoretical analysis of the effect of inert gases on limits of flammability, spark ignition, and wall quenching effects. The relative importance of thermal conductivity and diffusion varies with the changing physical parameters of the experimental conditions.¹⁵⁸ Quenching distances appear to be more dependent on the thermal conductivity of the gases than on

TABLE 2.—*Summary of Effects of Inert Gases on Flame Propagation* [AFTER MELLISH AND LINNETT¹⁵⁸]

| | |
|--|---|
| In reducing burning velocities .. | CO ₂ > N ₂ > A > He |
| In decreasing composition range for flammability: | |
| Wide tubes | CO ₂ > N ₂ > He > A |
| 2.2 cm diam..... | CO ₂ > He > N ₂ > A |
| 1.6 cm diam..... | He > CO ₂ > N ₂ > A |
| In increasing minimum spark-ignition pressure: | |
| (H ₂ +O ₂), low pressure..... | He > A > N ₂ > CO ₂ |
| (H ₂ +O ₂), high pressure..... | CO ₂ > N ₂ > A |
| (H ₂ +N ₂ O), low pressure..... | He > CO ₂ > N ₂ > A |
| In increasing minimum spark-ignition energy: | |
| (H ₂ +O ₂), atm. pressure..... | He > CO ₂ > N ₂ > A |
| (CH ₄ +O ₂), atm. pressure..... | He > N ₂ > A |
| In increasing quenching distance: | |
| (H ₂ +O ₂)..... | CO ₂ > He > N ₂ > A |
| (CH ₄ +O ₂)..... | He > N ₂ > A |

diffusion factors. Table 2 is a qualitative summary of the effects of different inert gases on flame phenomena.

It would appear that in dealing with the complex systems presented by space-cabin environments, only an empirical approach is possible. This fact should be kept in mind when considering the experimental results of Chapters 2 to 6.

Irradiation

Certain fuels, hydraulic fluids, and lubricants tend to break down when irradiated and produce materials with lower flash points (refs. 17, 75, 144, 149, 157, and 176). The space radiation hazard may, therefore, contribute to the fire hazard, though for present-day mission profiles and shielding parameters, the effect on internal cabin lubrication systems should be negligible.

Effects of Atmospheric Environment on Flammability of Fabrics and Carbonaceous Solids

IN THIS CHAPTER AND IN THE OTHERS TO FOLLOW, an attempt will be made to outline empirical studies which shed some light on the effects of internal atmospheric conditions on the fire hazard in space cabins. The results of these experiments will be interpreted, whenever possible, in light of the theoretical considerations outlined in Chapter 1.

EFFECTS OF OXYGEN ENRICHMENT AND DECREASED AMBIENT PRESSURE ON FLAMMABILITY OF PAPER AND FABRICS

Early quantitative studies of the effects of altitude, oxygen, and nitrogen on the burning rate of fabrics were performed in Germany by Clamann in 1939.³⁶ In these experiments, paper strips of uniform configuration and composition were used. Only the rate of burning and not the ignitibility was determined. Figure 14 is a plot of the results. It can be seen that as the total air pressure is reduced from sea level to 25,000 feet, the combustion time is increased from about 6.8 to 9.2 seconds. Reduction in oxygen partial pressure (p_{O_2}) is probably responsible for this. When the altitude is increased with constant oxygen partial pressure in air, there is a progressive decrease in combustion time. Clamann interpreted the altitude effect at constant partial pressure as being due to decreasing the amount of nitrogen diluent. He felt that nitrogen "absorbs heat in the flame zone and acts like an extinguisher."³⁷ In the discussion on oxidizers and diluents in Chapter 1 the mechanism of nitrogen retardation in hydrogen-oxygen reactions was

discussed. Clamann's hypothesis appears plausible in the light of the studies of inerting agents in gaseous systems. One can assume that the basic principles hold true in the burning of solids as well.

In an evaluation of the fire hazard for the Manhigh Projects, Simons and Archibald²⁰¹ studied the burning of paper strips and cloth in various oxygen-nitrogen environments. Figure 15 is a plot of their results with paper strips. The general patterns are the same as those reported by Clamann. An increase in

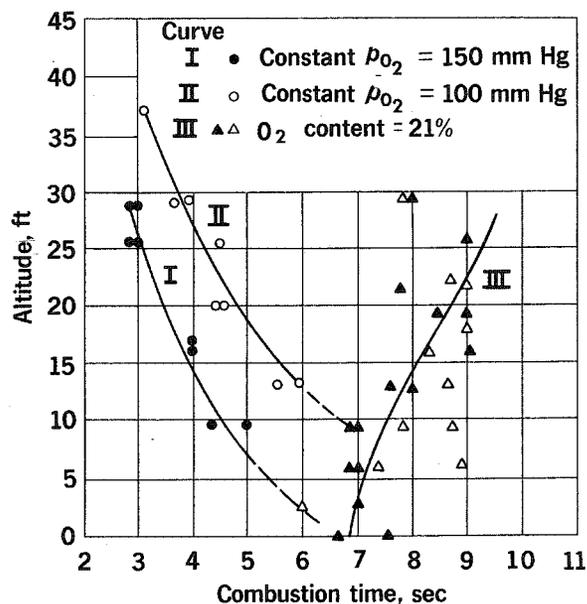


FIGURE 14.—*Flammability of paper strips.* (RE-PLOTTED FROM CLAMANN BY SIMONS AND ARCHIBALD.²⁰¹)

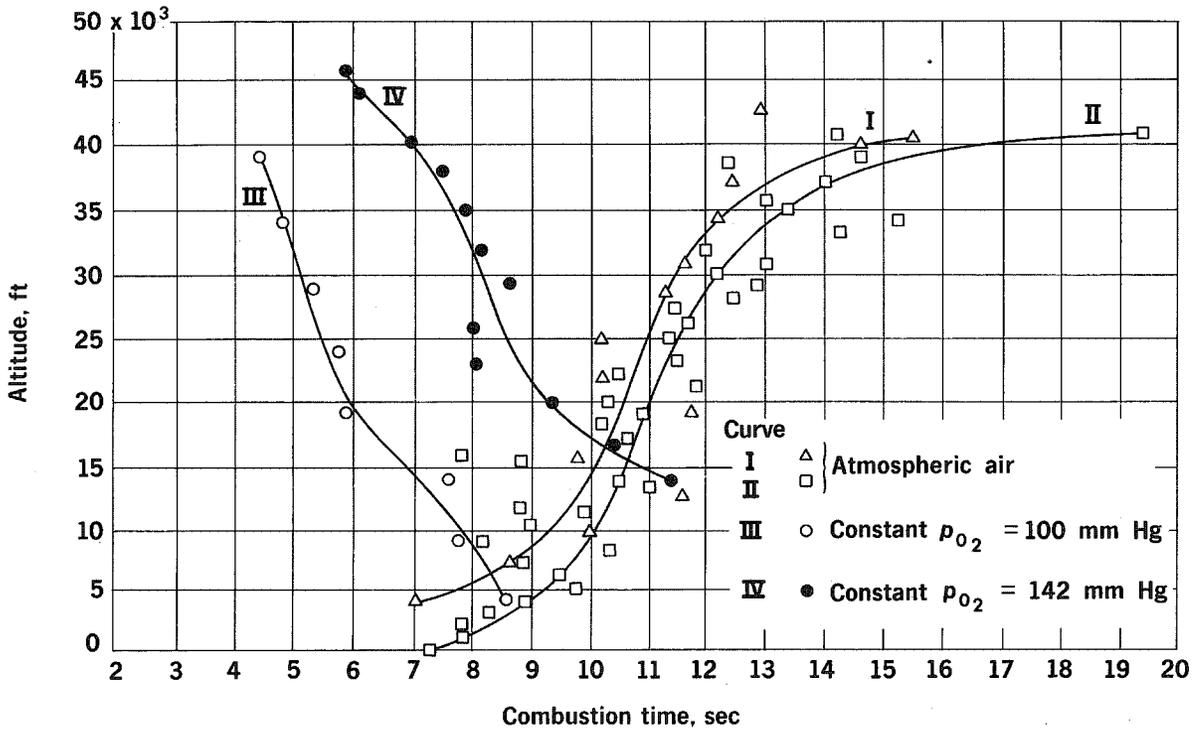


FIGURE 15.—*Flammability of paper strips.* (AFTER SIMONS AND ARCHIBALD.²⁰¹)

altitude to 40,000 feet in the atmospheric air environment prolonged combustion time along a sigmoid curve from 7 to about 17 seconds. At constant oxygen partial pressure, increasing the altitude decreased the combustion time.

Combustion of fabric from very light flying suits responded in the same general way. Figure 16 shows how decreasing the altitude in a 100-percent oxygen environment shortens the combustion time of fabric. There is, of course, no nitrogen effect under these conditions. The same fabrics at constant oxygen partial pressure in air show the nitrogen effect with a doubling of combustion rate in going from a pressure altitude of 8,000 feet to one of 38,000 feet. Simons and Archibald reported in this paper that analogous experiments with helium were being planned. Communications with both of these investigators revealed that no further studies have been performed by their respective laboratories.

Klein¹²⁵ has continued the study of fabric combustion in various gaseous environments.

For test material he used 2-inch squares of standard AATCC cotton (crockmeter squares) having thread counts of 96×100 per square inch and weighing 4.05 ounces per square yard. Squares were preheated in an oven at 150° F to insure constant moisture content and were ignited between two electrodes. Figures 17 to 19 are plots of the results.

Figure 17 indicates that as the proportion of oxygen in the atmosphere increases under any fixed nitrogen partial pressure, the burning time decreases. It also indicates that at any fixed partial pressure of oxygen the burning time increases with increasing nitrogen pressure. The curve at the extreme right (79 percent nitrogen) represents burning time in normal air mixtures at altitudes from sea level to 10,000 feet.

In figure 18, the ratio of burning rate at test conditions to burning rate at standard atmospheric conditions encountered in present aircraft (8,000-foot altitude) is plotted against total pressure. The three curves represent constant

oxygen partial pressures equivalent to air at 8,000 feet, 5,000 feet, and sea level. As the total pressure is reduced by lowering the nitrogen content, thus increasing the percentage of oxygen, the ratio of burning rates increases

considerably. The ratio of burning rates for pure oxygen at 10 in. Hg (250 mm Hg) is shown by a single point. This is the point for a cabin atmosphere of 100 percent oxygen at 5 psi and represents a burning rate 3.7 times that found

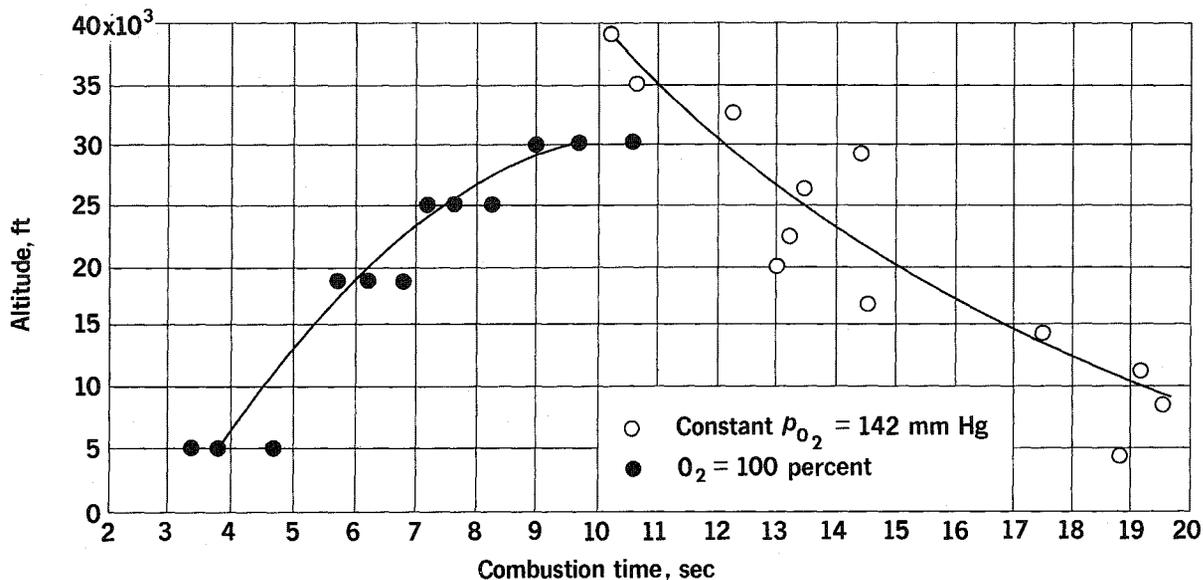


FIGURE 16.—Flammability of flight clothing. (REPLOTTED FROM SIMONS AND ARCHIBALD.²⁰¹)

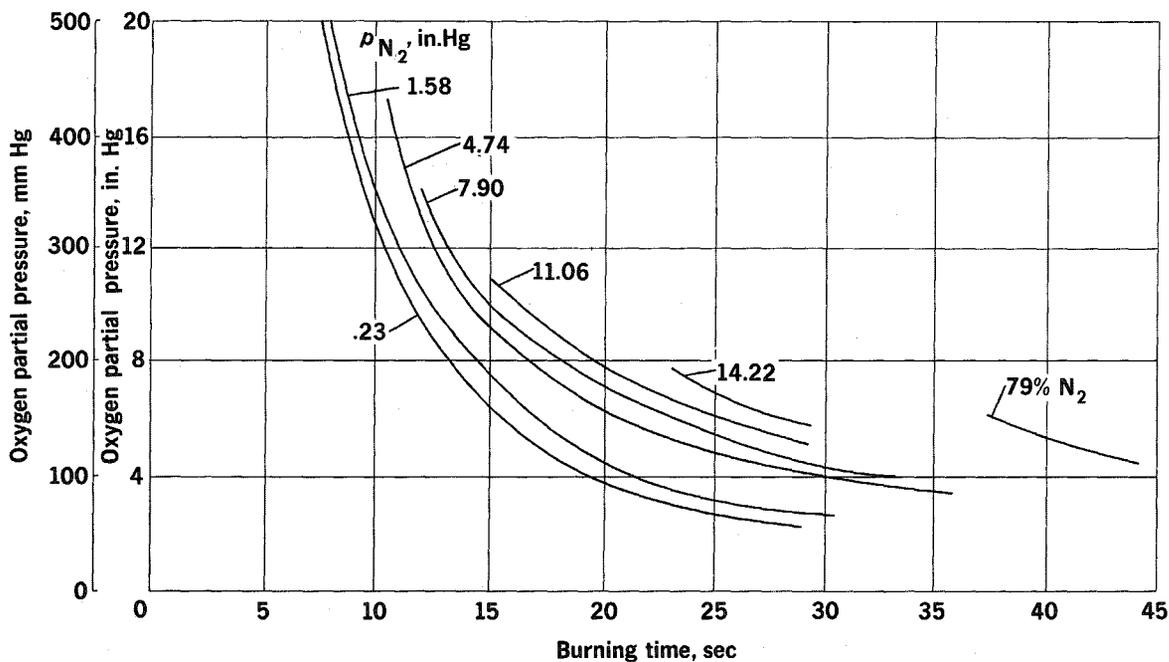


FIGURE 17.—Cotton fabric burning in oxygen-nitrogen. (AFTER KLEIN.¹²⁵)

in an air cabin at 8,000 feet. The dotted lines connect points of equal percentage of oxygen in the atmosphere. These lines indicate that the ratio of burning rates also increases when total pressure is increased while the percentage of oxygen is maintained constant. Within the range of oxygen partial pressures considered (8,000 feet to sea level) these lines are essentially straight.

EFFECTS OF A HELIUM ENVIRONMENT ON BURNING RATES OF FABRICS

Figure 19 indicates that helium-oxygen mixtures behave quantitatively quite like nitrogen-oxygen mixtures (fig. 17) in controlling burning times. It appears that helium offers no great advantage over nitrogen with respect to the fire hazard of burning fabrics. This is contrary to what was postulated by Simons and Archibald.²⁰¹ These investigators felt that because helium has a thermal conductivity 6 times as great as that of nitrogen, this gas would be a better "quenching agent." From the discussion of a model hydrogen-oxygen system in Chapter 1, it appears that the specific heat of a molecule as well as the thermal conductivity

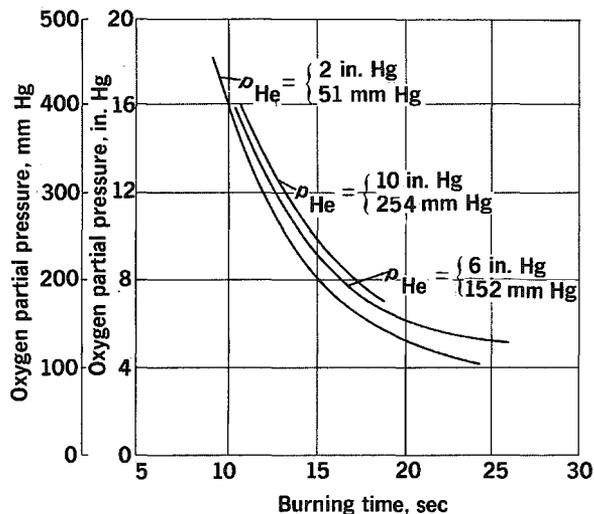


FIGURE 19.—Cotton fabric burning in oxygen-helium. (AFTER KLEIN.¹²⁵)

is a major factor in determining its "quenching" capacity. How would the specific heat factor fit the prediction of burning rates?

The molar specific heat of helium is 5 cal/mole and that of nitrogen is 7.2 cal/mole.¹⁰⁹ This would predict almost equal quenching capacity, all other factors being equal. From figures 17 and 19 it can be seen that at a partial pressure of oxygen of 8 in. Hg (200 mm Hg) and inert gas of 10 in. Hg (250 mm Hg), the burning time in helium is 17 seconds and that in nitrogen is 20 seconds. These are approximately the burning times one would predict from the molar specific-heat figures given above.

It is obvious, however, that diffusion and other factors play a role. These factors were presented in Chapter 1. The experiments on the methane-oxygen-inert gas system by Clingman et al.^{43, 44} illustrated these points. It would be expected that the fabric-oxygen-inert gas system would also include a diffusion factor and probably others as well. It may be merely fortuitous that in the latter system the relative burning rates in helium and nitrogen followed the predictions based on heat capacity alone.

RESISTANCE OF VARIOUS FABRICS TO BURNING IN HIGH-OXYGEN ENVIRONMENTS

Recent studies at the Fire Research Station at Boreham Wood, Hertfordshire, England,

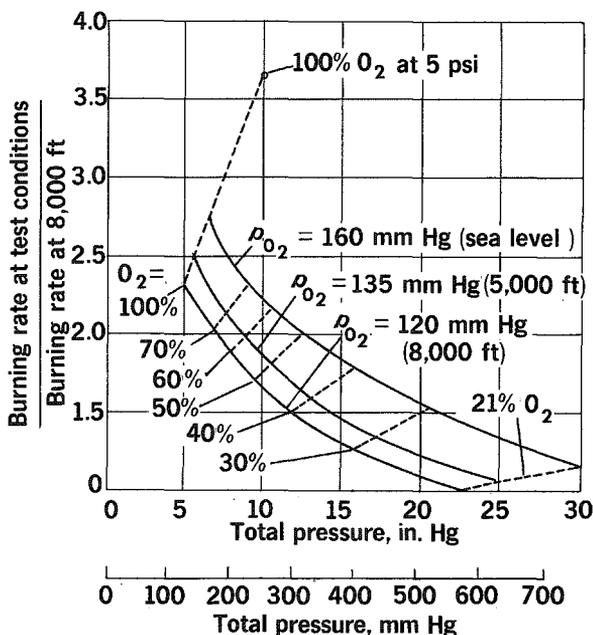


FIGURE 18.—Effects of atmospheric composition and pressure on burning of cotton fabric. (AFTER KLEIN.¹²⁵)

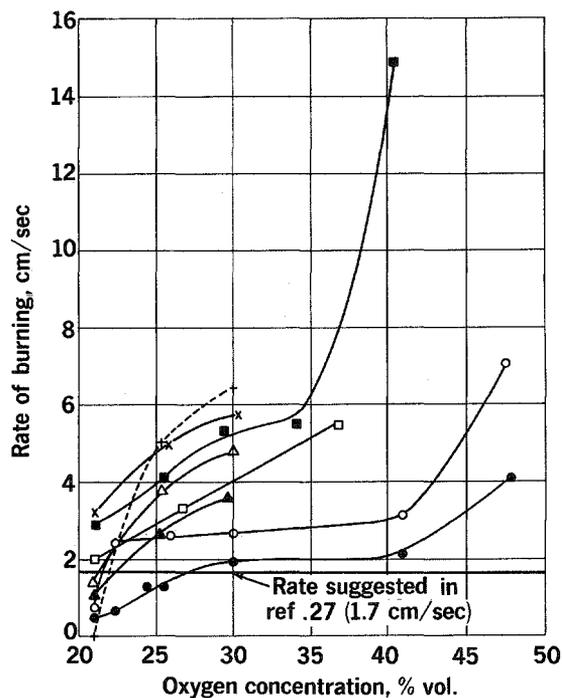
have evaluated the effect of oxygen-enriched atmospheres on the burning rate of many different fabrics under the influence of fire-retarding agents.⁴⁷ This is probably the most sophisticated study of this type yet performed. Table 3 indicates the specifications of the fabrics studied, and figure 20, the rates of burning (vertical flame speeds) under different volume percentages of oxygen in air at 1 atmosphere. The oxygen mixtures were admitted to the burning chamber at a flow rate giving linear speeds of 5 ft/min or 0.06 mi/hr. This rate was considered adequate for combustion, but too slow to give a "forced draft" effect. In air, woolen fabrics were difficult to ignite and the strips burned for only a short distance. Cotton fabrics were easily ignited, and burned more rapidly and usually to completion. A Terylene fabric melted and burning drops fell from the strips, but when it was blended with wool, the wool matrix supported the molten burning Terylene, and both were consumed. The flame speed of the mixture was comparable to that of a cotton drill. The P.V.C.-coated fabric and the retardant-treated green drill did not burn in air. The flame speeds were increased when oxygen was added to the atmosphere, and, as shown in figure 21, the residues of carbon and ash decreased steadily.

In the lower concentrations of oxygen it was noticed that, after ignition, a luminous flame ascended over the surface of the strip and was followed by a slower and less luminous flame. Combustion ceased when the upper flame was separated from the lower by more than 2 or 3 inches. In higher oxygen concentrations, the distance and distinction between the flames lessened and the ash became lighter in color. These changes were considered to indicate changes in the mode of burning, and may be responsible for the plateaus or inflections shown in figure 20 where flame speed is affected only slightly by the increases in oxygen content. Above an oxygen concentration of about 40 percent, the flame speeds increased rapidly with increase of concentration.

The flame speeds of the woolen fabrics were increased by only slight additions of oxygen, and the strips burned completely, although the flame speeds were very much lower than those

TABLE 3.—*Fabrics Used in Flammability Tests of Figures 20 and 21* [AFTER COLEMAN⁴⁷]

| Material | Weight | |
|---|-------------|-------------|
| | oz sq yd | gm sq cm |
| Blue melton wool cloth, waterproofed | 21. 8 | 0. 0738 |
| Blue wool serge cloth | 15. 7 | . 0517 |
| Wool-Terylene mixture, 45-55% | 7. 3 | . 0247 |
| Khaki cotton drill | 10. 4 | . 0343 |
| White unbleached cotton drill | 9. 6 | . 0327 |
| Green cotton drill | 7. 6 | . 0256 |
| Green cotton drill treated with flame retardant | 9. 1 | . 0309 |
| P.V.C.-coated cotton cloth | 16. 2 | . 0550 |



- Blue melton cloth
- x— Green cotton drill
- ▲ Khaki cotton drill
- White cotton drill after washing
- Blue uniform serge
- △— Green cotton drill with flame retardant
- +— Khaki cotton drill after washing
- Wool-Terylene mixture (45-55%)

FIGURE 20.—*Variation of burning rate with oxygen concentration.* (AFTER COLEMAN.⁴⁷)

of the cotton fabrics. P.V.C.-coated cloth burned in only 26 percent of oxygen, and the performance was similar to that of a wool fabric of comparable weight. The flame-retardant treatment given to the green drill was effective in air, but in 25.4 percent oxygen there was no significant difference between the treated and untreated fabric.

A British Standards Institution report²⁷ recommends that the flammability rating (in air) of fabrics should not be less than 150 seconds for a vertical flame traveling 100 inches, corresponding to a mean flame speed of 1.7 cm/sec. Figure 20 shows that with slight enrichment to 22.5 percent oxygen only the blue melton cloth would have satisfied this requirement, although it would have failed at 27.5 percent oxygen.

EFFECTS OF OXYGEN ENRICHMENT ON FLAMMABILITY OF FABRICS IMPREGNATED WITH FLAME RETARDANTS

It is evident that a comparatively slight addition of oxygen to the atmosphere would be sufficient to reduce considerably the protection afforded by fabrics of low flammability in air, and experiments were, therefore, made to determine the degree of protection provided by flame-retardant treatments. The material used was the white unbleached cotton drill, and strips were impregnated by soaking them in solutions of mixtures of boric acid with borax or phosphates. These mixtures, listed in table 4, have been suggested by previous workers.⁴⁷ The degree of impregnation of the retardant is expressed as a percentage of the original weight of the fabric. Thus, with 10 percent impregnation, 100 grams of fabric would weigh 110 grams after treatment. The results with the mixture of boric acid and borax (A) are plotted in figure 22. They show that the protection afforded by the white drill with 7 to 8 percent retardant approximates that of the blue wool serge; and with 10 percent retardant, approximates that of the heavy melton cloth.

The use of vertical flame speed as a criterion to assess the effects of oxygen concentration and type and weight of retardant required the production of replicate strips with closely controlled weight of deposit. This was difficult to achieve with the facilities available and ac-

TABLE 4.—*Flame Retardants Used for Impregnating White Cotton Drill* [AFTER COLEMAN⁴⁷]

| Retardant | Composition |
|-----------|--|
| A----- | { 30% boric acid (H_3BO_3) 70% borax ($Na_2B_4O_7 \cdot 10 H_2O$) |
| B----- | { 60% boric acid (H_3BO_3) 40% trisodium phosphate ($Na_3PO_4 \cdot 12 H_2O$) |
| C----- | { 60% boric acid (H_3BO_3) 40% disodium phosphate ($Na_2HPO_4 \cdot 12 H_2O$) |
| D----- | { 60% boric acid (H_3BO_3) 40% monosodium phosphate ($NaH_2PO_4 \cdot H_2O$) |
| E----- | { 60% boric acid (H_3BO_3) 40% monammonium phosphate ($(NH_4)_2H_2PO_4$) |

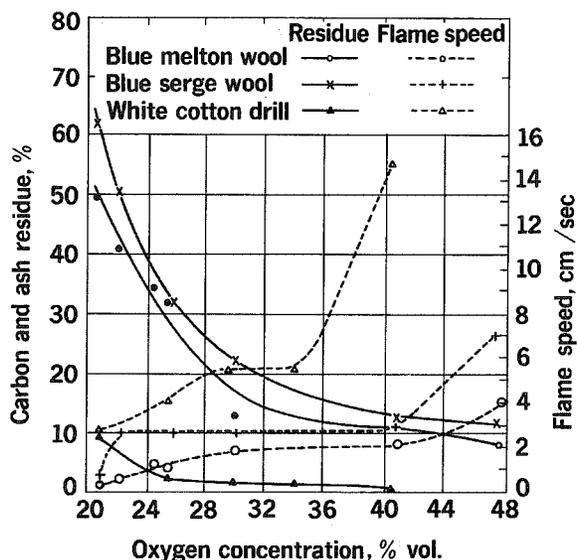


FIGURE 21.—*Variation of ash and flame speed with oxygen concentration.* (AFTER COLEMAN.⁴⁷)

cordingly other criteria, more convenient experimentally, were used in tests comparing the effects of different retardants. The criteria were: (a) the oxygen concentration above which the fabric burned, however much retardant had been added, and (b) the weight of retardant above which further additions had little effect.

The results of the tests to compare retardants are shown in figure 23. Strips with retardant concentrations and in oxygen concen-

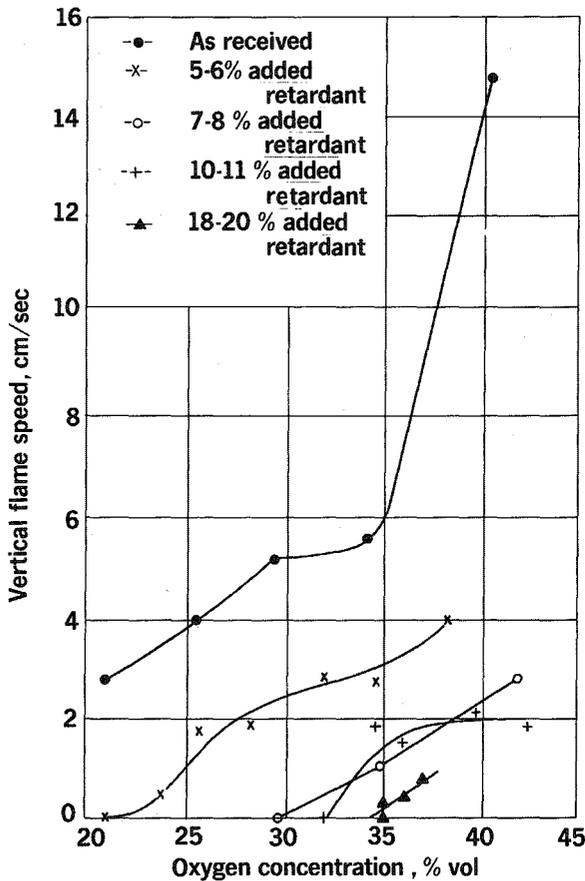


FIGURE 22.—Effect of oxygen enrichment on flame speed of white drill treated with mixture of 30 percent boric acid and 70 percent borax. (AFTER COLEMAN.⁴⁷)

trations shown on the left-hand sides of the curves did not burn, whereas those to the right burned. For each mixture there was a critical level of retardant concentration above which further additions did not materially increase the degree of protection, and there was also a critical level of oxygen concentration above which the fabrics burned whatever the weight of retardant. These critical values are given in table 5.

The boric acid-borax mixture was more effective than any of the others at lower concentrations of retardant and in higher oxygen concentrations. The optimum weight of this mixture was very close to the 10 percent recommended in many publications, and would afford protection in atmospheres containing up to about 32 percent of oxygen. The limits of

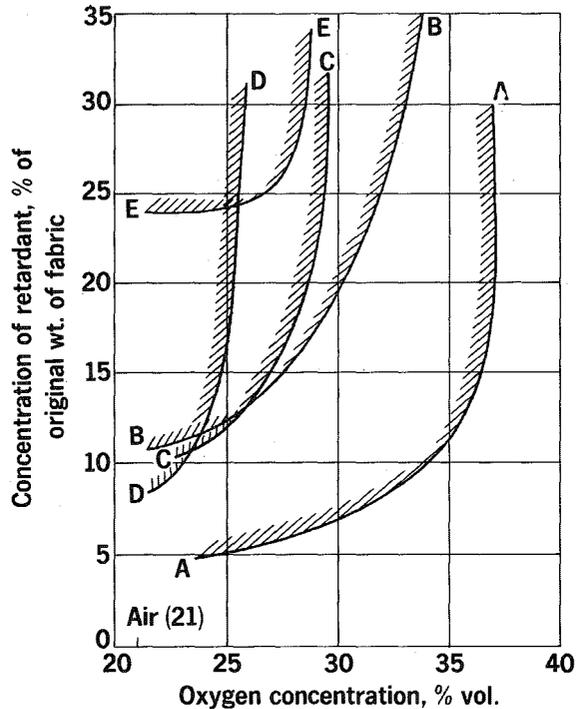


FIGURE 23.—Critical concentrations of retardant and oxygen at limits of flammability. (See table 4 for compositions.) The strips of impregnated fabric did not burn under conditions on shaded sides of curves. (AFTER COLEMAN.⁴⁷)

TABLE 5.—Limiting Values of Weight of Retardant and Oxygen Concentration [AFTER COLEMAN⁴⁷]

| Retardant* | Critical limiting values | |
|------------|--------------------------|------------------|
| | Oxygen, % vol. | Retardant, % wt. |
| A----- | 37 | 9 |
| B----- | 36 | 12 |
| C----- | 28 | 14 |
| D----- | 24 | 19 |
| E----- | 28 | 25 |

*See table 4 for compositions.

weight of deposit and oxygen concentration would be expected to vary with the weight of the fabric.

The results of these studies on fire retardants are of interest in view of the recent report of Helvey¹⁰³ in which materials to be used in his

TABLE 6.—*Preliminary Screening Tests of Materials for Possible Use in 100 Percent Oxygen Atmosphere* [AFTER HELVEY¹⁰³]

| Test | Description | Results | Remarks |
|------|--|---|---|
| 1 | Fiber-glass material coated white | Coating burned off completely | Fiber glass appeared brittle. |
| 2 | Fiber glass coated green | Coating burned off completely | Fiber glass appeared brittle. |
| 3 | Dynel cloth fabric | Burned completely | |
| 4 | Dynel, static free | Burned completely | |
| 5 | Dacron-rayon, static free | Burned completely | |
| 6 | 100% Dacron cloth fabric | Burned completely | |
| 7 | Scotch-Shield Type 75 (asbestos, aluminum coated). | Coating burned completely | Asbestos appeared brittle and tore readily. |
| 8 | Scotch-Shield Type 82 (flameproof rayon, aluminum coated). | Burned completely | |
| 9 | Nylon cloth fabric | Burned completely | |
| 10 | Pluton | Burned completely | |
| 11 | Army duck | Burned completely | |
| 12 | Goose down | Burned completely | Bright flame. |
| 13 | Foam rubber | Burned with bright flame | Filled bell jar with black oily smoke. |
| 14 | Epoxy foam | Burned almost completely | |
| 15 | Wool rug (Harlok) | Burned completely | Bright flame. |
| 16 | Wool rug, rubber coated | Burned completely | Bright flame. |
| 17 | Wash 'n Dri cloths, wet | Did not burn | |
| 18 | Wash 'n Dri cloths, dry | Burned completely | |
| 19 | Paperbound book with cover | Burned when flame applied; stopped when flame removed. | |
| 20 | Hardbound book (old paper) | Burned completely | |
| 21 | Insulated wire | Largely consumed | |
| 22 | Braided insulated wire | Insulation completely burned | |
| 23 | Plastic-insulated wire | Insulation almost completely burned. | |
| 24 | Aluminum-covered insulated wire | Insulation burned off with bright flame leaving aluminum wrapping intact. | |
| 25 | Asbestos-Dynel S/1445 | Dynel consumed; asbestos remained intact. | |
| 26 | Polyurethane foam | Completely burned | |
| 27 | Styrofoam (with combustion inhibitor). | Material ignited but did not support combustion. | |
| 28 | Paper towels | Burned completely | |
| 29 | Glass braided wire | Did not burn | |
| 30 | Mattress sample composite (urethane foam wrapped in aluminum foil and asbestos-Dynel). | Did not burn | |

chamber were subjected to ignition by high-voltage arcs in bell jars containing 100 percent oxygen at 1 atmosphere. Table 6 records the results of these screening tests.

It can be seen that most materials of carbonaceous nature exposed directly to the atmosphere burned completely in 100 percent oxygen. Even "flameproof" material such as Scotch-Shield Type 82 (test 8) burned com-

pletely in this environment. It is obvious that flameproofing materials need to be retested in high-oxygen environments.

The products of combustion of plastics under varying atmospheric conditions have not been adequately studied. The few pertinent reports that have been obtained concern burning of electrical insulation and are, therefore, discussed under electrical fires in Chapter 4.

Effects of Atmospheric Environment on Flammability of Gases, Liquids, and Vapors

GASES

IN SPACE CABINS, well-mixed gaseous combustion systems will rarely be involved in the fire hazard. Most of the combustion studies have been performed in such systems. It will be of value, however, to review some of the empirical data on the role of oxygen and inert-gas pressures on the combustion process in gaseous systems. One can derive an "order of magnitude feel" for the actual parameters involved in the space-cabin hazard. In Chapter 1 the theoretical aspects of the role of inert gases on the ignition and propagation of flame in gaseous systems were outlined. Figure 4 was presented as an example of the increase in minimum spark energy and decrease in limits of flammability which result upon the addition of nitrogen to oxygen-propane mixtures. In Chapter 1, also, a survey was made of the general effects of inert gases in reducing burning velocities, decreasing the range of flammability limits, increasing the minimum spark ignition pressure, increasing the minimum spark ignition energy, and increasing the quenching distance between electrodes in spark ignition. The experimental study of Clingman and Pease⁴⁴ was presented as an indication of the complexity of factors that control burning velocity in gaseous systems. Figure 13 indicated that in a 10-percent mixture of methane in different "airs" containing nitrogen, argon, and helium, the relative burning velocities were 0.28:1:1.86 (N₂:A:He). Clingman and Pease concluded that these ratios indicated that thermal con-

ductivity factors and not diffusion factors are most critical in determining burning velocity.

A few more studies will now be presented to indicate how the nature of the combustible gas controls the degree of the inert-gas effect.

Morgan and Kane¹⁶² studied the effects of varying concentrations of nitrogen, argon, and helium diluents on the flame speed and flame temperature of propane-, methane-, acetylene-, and hydrogen-oxygen combustion systems. Stoichiometric ratios of fuel to oxygen were used and all measurements were made at room temperature and pressure. The flame speed was determined by the "total" area method, in which the flame speed is equal to the area of the flame issuing from a nozzle divided by the volume rate of gas flow. At low concentrations of diluents, the high flame speeds and limitations of metering equipment prompted the use of burner nozzle exits of smaller diameter. The effects of nozzle changes are evident in the experimental curves of figure 24.

It can be seen in figure 24(a) that at a given volume percentage of diluent, the flame speed of the mixture containing nitrogen is lowest, that of the mixture with argon is somewhat higher, and that of the mixture containing helium is considerably higher than the others. Nozzle diameters affect the helium curve more than the curves of the other gases. The increase in flame speed at a helium concentration of 5 percent was reproducible. Figures 24(b) and 24(c) show that the variations of flame speed with the nature and concentration of the diluent

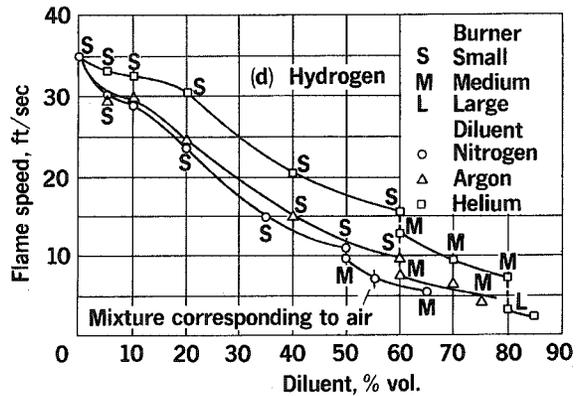
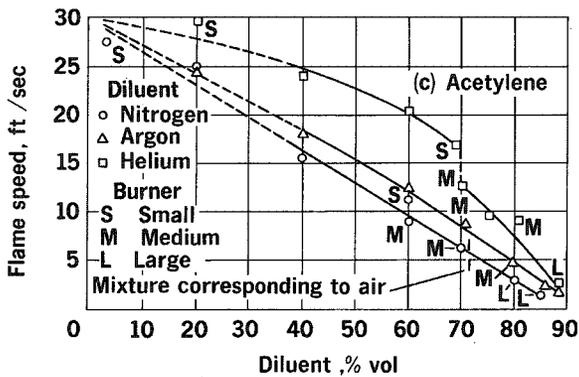
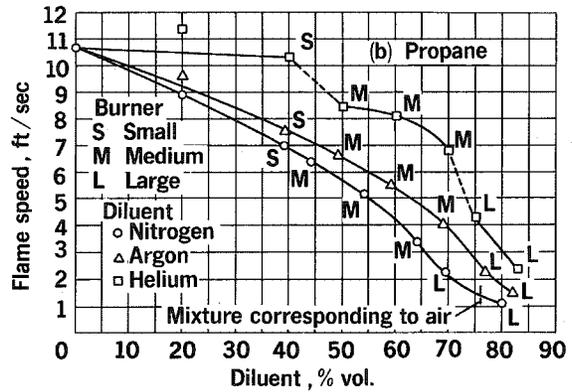
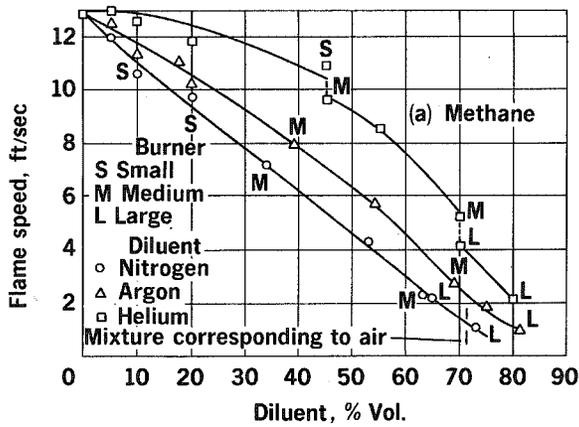


FIGURE 24.—Flame speed in varied inert diluents. (AFTER MORGAN AND KANE.¹⁰²)

for stoichiometric mixtures of oxygen with propane and acetylene are similar to those for methane. The "helium effect" at low diluent concentrations is also present. The curves in figure 24(c) are dashed below 40 percent diluent because ragged flame cones made measurements unreliable. Figure 24(d) shows the results for hydrogen. Measurement difficulties make the figures for low diluent concentrations relatively unreliable. The burner nozzle size is more critical than for the other fuels, even with nitrogen and argon as diluents. This may represent the effects of low density and high thermal conductivity of hydrogen and helium. The results of flame-temperature measurements of the several fuels and diluents may be seen in figure 25. The "sodium line reversal" temperatures of the burning mixtures containing helium and argon as diluents are about the same. Mixtures

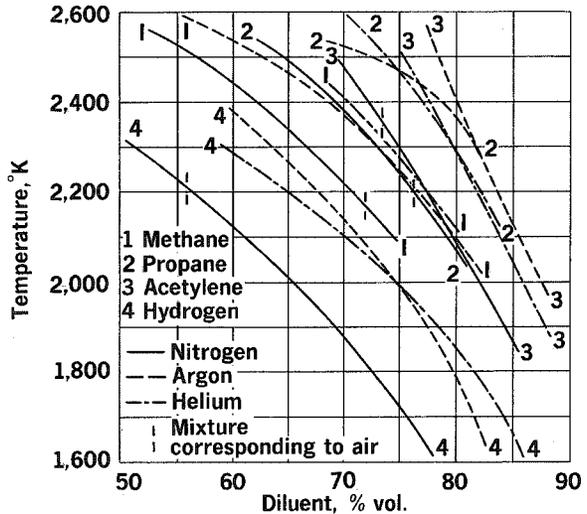


FIGURE 25.—Flame temperatures in varied inert diluents. (AFTER MORGAN AND KANE.¹⁰²)

TABLE 7.—Limits of Flammability of Fuel Gases in Mixtures of 21 Percent Oxygen and 79 Percent Inert Gas (Results Obtained by Egerton and Powling⁶⁴ and by Clusius and Gutschmidt⁴⁵) [AFTER MELLISH AND LINNETT¹⁵⁸]

| Ref. | Fuel gas and limit | Direction of propagation | Percent of fuel gas in mixture of oxygen and— | | | | |
|------|------------------------------|--------------------------|---|----------------|------|-------|------|
| | | | CO ₂ | N ₂ | He | Ne | A |
| 64 | CH ₄ , upper..... | Upward..... | 9.0 | 14.3 | 16.1 | ----- | 17.3 |
| 64 | CH ₄ , lower..... | Upward..... | 9.0 | 5.26 | 4.83 | ----- | 4.01 |
| 64 | H ₂ , upper..... | Upward..... | 69.8 | 74.6 | 75.7 | ----- | 76.4 |
| 64 | H ₂ , lower..... | Downward..... | 13.1 | 9.0 | 8.7 | ----- | 7.0 |
| 45 | H ₂ , lower..... | Downward..... | ----- | 9.60 | 8.07 | 7.07 | 7.10 |
| 45 | H ₂ , lower..... | Upward..... | ----- | 3.90 | 5.76 | 3.55 | 2.73 |
| 45 | D ₂ , lower..... | Downward..... | ----- | 11.0 | 8.36 | 7.72 | 7.72 |
| 45 | D ₂ , lower..... | Upward..... | ----- | 5.65 | 7.41 | 4.28 | 3.75 |

containing nitrogen had lower flame temperatures than those containing argon or helium.

From these figures it would appear that in terms of flame speed and temperature of combustion of gaseous mixtures, nitrogen is a safer diluent than helium for space-cabin use. The limits of flammability of gaseous fuels with diluents of carbon dioxide, nitrogen, helium, neon, and argon have been summarized by Mellish and Linnett¹⁵⁸ as seen in table 7. The upper and lower limits of flammability of the different fuel gases are recorded with the ratio of oxygen to inert gas at 21:79.

The extinguishing power of any inert gas is measured by its ability to raise the lower limit and depress the upper limit of flammability. As can be seen from table 7, there are no dramatic effects produced by any of these inert gases except for carbon dioxide. The relative effects of nitrogen, helium, and argon vary from fuel to fuel and with direction of propagation. As was discussed in Chapter 1, the complexities generated by the experimental variables make a clear-cut evaluation of the relative "safety" of the inert diluents most difficult for these gaseous combustion systems.

Table 8 outlines the effects of different inert gases in determining minimum spark energies and minimum quenching distances. The ratio of oxygen to inert gas was 21:79. It can be seen that in increasing minimum spark ignition energy, the order of effectiveness for hydrogen-

oxygen is helium>carbon dioxide>nitrogen>argon, and for methane-oxygen, helium>nitrogen>argon. Helium appears far more effective than nitrogen by a factor of almost 3 for both of these fuel systems. In increasing the quenching distance, the order of increasing effectiveness for hydrogen-oxygen is carbon dioxide>helium>nitrogen>argon, and for methane-oxygen, helium>nitrogen>argon. Helium is twice as effective as nitrogen in methane mixtures and only very slightly more effective than nitrogen in hydrogen mixtures.

A review of table 2 suggests that except for the reduction of burning velocity, and the narrowing of the range of flammability limits

TABLE 8.—Minimum Spark Ignition Energies (M.I.E.) and Minimum Quenching Distances (Q.D.) As Determined by Blanc, Guest, von Elbe and Lewis¹⁵ in Mixtures of 21 Percent Oxygen and 79 Percent Inert Gas [AFTER MELLISH AND LINNETT¹⁵⁸]

| Inert gas | Methane-oxygen | | Hydrogen-oxygen | |
|-----------------------|---------------------|----------|---------------------|----------|
| | M.I.E., millijoules | Q.D., cm | M.I.E., millijoules | Q.D., cm |
| CO ₂ | ----- | ----- | 0.038 | 0.086 |
| He..... | 1.08 | 0.39 | .043 | .070 |
| A..... | .06 | .1 | .015 | .058 |
| N ₂ | .42 | .21 | .019 | .063 |

in wide tubes, helium is more effective than nitrogen in the reduction of the fire potential. It is most difficult, however, to properly weight these factors in the overall evaluation of the fire risk in gaseous combustible systems. This problem is considered further in Chapter 7.

LIQUIDS AND VAPORS

Much of the recent work on the atmospheric effects on burning of liquids and vapors has been performed by the Naval Research Laboratory¹¹⁹ and by the Explosives Research Laboratory of the Bureau of Mines. The reviews of Van Dolah et al.,²²⁰ Kuchta et al.,^{127, 128} and Scott et al.¹⁹⁴ summarize much of the work on hydraulic fluids, aircraft fuels, and liquid rocket propellants. Several pertinent experiments of this group are worth mentioning at this time. The general trend of the data suggests that oxygen enrichment of air tends to increase the upper limit of flammability and decrease the minimum spontaneous ignition temperature of flammable liquids. Figure 26 demonstrates the effect of increased oxygen concentration in air on seven hydraulic fluids. Five of the fluids exhibit a decrease in spontaneous ignition temperature with increasing oxygen concentration; two show no change between 21 percent and 100 percent oxygen. Figure 27 indicates how little the oxygen partial pressure in mix-

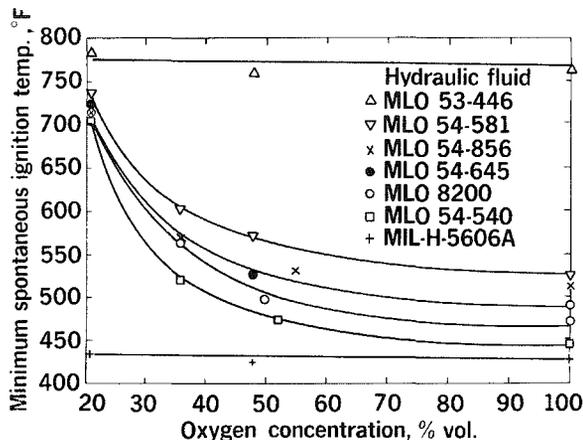


FIGURE 26.—Minimum spontaneous ignition temperatures of seven hydraulic fluids in oxygen-nitrogen atmospheres at 1 atmosphere pressure, in contact with Pyrex glass surface, as a function of oxygen concentration. (AFTER VAN DOLAH ET AL.²²⁰)

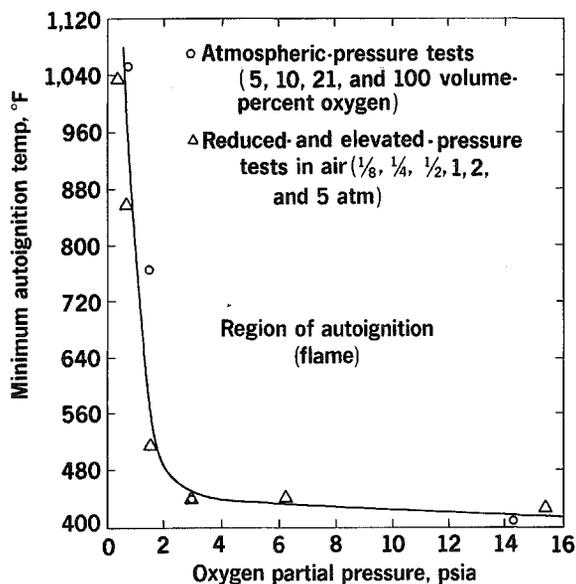


FIGURE 27.—Effect of oxygen partial pressure on the minimum autoignition temperatures of JP-6 fuel mixed with oxygen and nitrogen at various initial pressures. (AFTER KUCHTA ET AL.¹²⁷)

tures of JP-6 fuel with oxygen and nitrogen affects minimum autoignition temperatures in 20 percent to 100 percent oxygen (2.8 to 14.7 psia). Only at low oxygen partial pressures did autoignition temperatures appear affected. The effects of oxygen concentration on the ignition of JP-6 were comparable to the effects produced by varying the pressure.

The "quenching effect" of nitrogen on the ignition of liquid JP-6 fuel in this system is, therefore, quite unlike the "attenuation effect" of nitrogen in hydrogen-oxygen combustion and on the rate of burning of fabrics. The phase differences will be discussed below. The temperature of the flame, once ignited, does appear to be determined by the oxygen partial pressure in the 21 percent to 100 percent oxygen range. These JP-6 fuel data are not pertinent to the space-cabin problem in a direct way, but illustrate how variable the oxygen-diluent effects are with different hazard parameters and different molecular structures.

A much overlooked fire hazard is brought about by the "dieseling" of so-called "non-flammable" hydraulic and lubricating fluids.

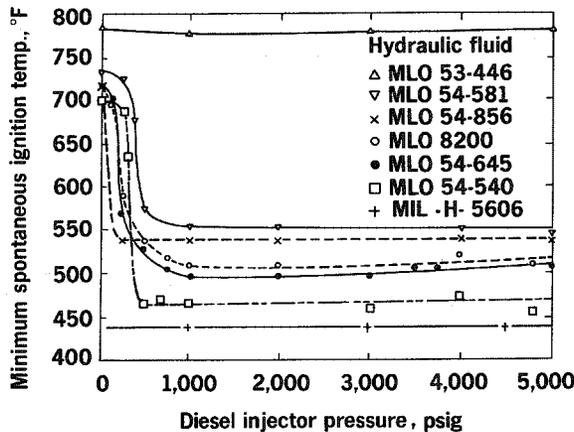


FIGURE 28.—Minimum spontaneous ignition temperatures of seven hydraulic fluids in air at 1 atmosphere pressure, in contact with Pyrex glass surface, as a function of diesel injector pressure. (AFTER VAN DOLAH ET AL.²²⁰)

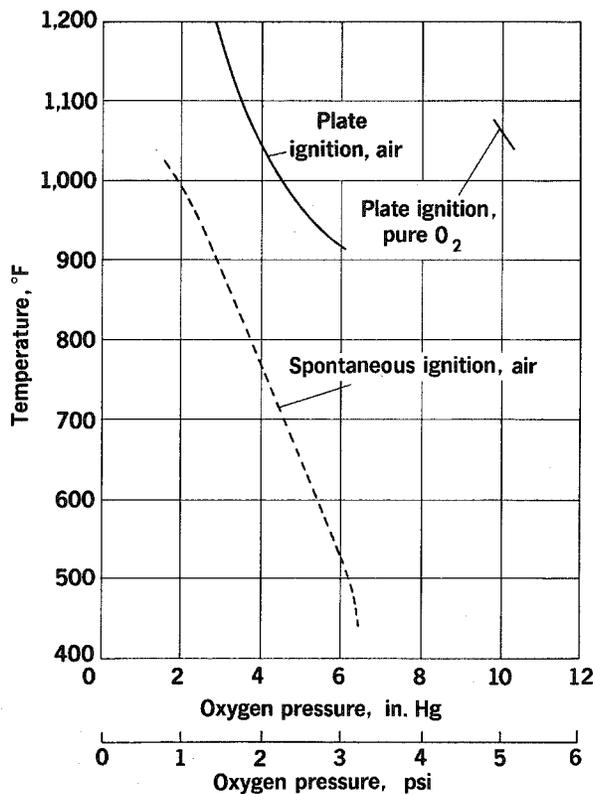


FIGURE 29.—Ignition temperatures for Mil-O-5606. (AFTER KLEIN.¹²⁶)

Dieseling is the increase of temperature by adiabatic compression and subsequent ignition of fuel. Mr. M. Braidech of the National Board of Fire Underwriters²⁵ reports that this dieseling phenomenon was probably responsible for the catapult room explosion of May 1954 which took 100 lives on the aircraft carrier *Bennington*. Dieselization apparently occurred in a large pressurized compressed-air accumulator filled with a mineral-oil hydraulic fluid. Pulses created by the "fill and draw" cycled operation with 1,500 psi peaks exploded the fluid, which had a 350° F flash point. Compression of the oil and air in the recharging gear pump of the apparatus was also suspected of contributing another point of dieselization to the system.

Braidech has also related that fine sprays of "certain high-flash-point hydraulic fluids" ejecting from a break in a high-pressure line will explode under oxygen pressures elevated above sea-level conditions. Detailed studies of this phenomenon have been published.²¹³ Braidech also mentioned that several explosions in Naval gun turrets were thought to be caused by spraying of hot lubricant materials in air atmospheres.

W. A. Zisman of the U.S. Naval Research Laboratory, Washington, D.C., may be contacted for more detailed information regarding these accidents and the entire explosive-mist problem. Petroleum companies now evaluate the safety of their hydraulic-fluid products by determining the minimal concentration of oxygen required to produce explosive mixtures with fine sprays of the material.²⁴² Data for many fluids are available.²¹³ Figure 28 illustrates the decrease in minimum spontaneous ignition temperature of hydraulic fluids as the fuel injection pressure increases.

Klein¹²⁵ has recently studied ignition of aircraft fluids under varying atmospheric conditions. He utilized the hot-surface technique which closely simulates the cabin fire-hazard condition. A stainless-steel plate 0.048 inch thick was placed in the test chamber to serve as the heated surface. When the desired atmospheric composition was attained, the plate temperature was raised to test level. A few drops of test fluid were dripped on the plate from a 17-gage needle suspended approximately 8

TABLE 9.—Comparative Ignition Temperatures of Aircraft Fluids [AFTER KLEIN¹²⁵]

| Chamber condition | Ignition temperature, °F, for fluid*— | | | | | | |
|------------------------------|---------------------------------------|-------|-------|-------|-------|-------|-------|
| | A | B | C | D | E | F | G |
| 850 ft alt..... | 910 | 970 | ----- | 895 | ----- | ----- | ----- |
| 5,000 ft alt..... | 950 | 1,010 | 1,015 | 935 | 955 | 1,095 | 990 |
| 10,000 ft alt..... | 1,010 | 1,065 | 1,025 | 985 | 975 | 1,115 | 1,050 |
| 15,000 ft alt..... | 1,100 | 1,100 | 1,045 | 1,040 | 1,000 | 1,130 | 1,090 |
| 20,000 ft alt..... | 1,200 | 1,120 | 1,090 | 1,090 | 1,025 | 1,145 | 1,125 |
| 25,000 ft alt..... | ----- | ----- | ----- | 1,140 | 1,045 | ----- | 1,145 |
| p_{O_2} = { 10 in. Hg..... | } 1,060 | 820 | 725 | 575 | 940 | 935 | 505 |
| { 5 psi..... | | | | | | | |
| p_{O_2} = { 8 in. Hg..... | } ----- | 920 | 975 | 790 | 980 | 975 | 550 |
| { 4 psi..... | | | | | | | |
| p_{O_2} = { 6 in. Hg..... | } ----- | 1,010 | 1,090 | 980 | 1,005 | 1,040 | 675 |
| { 3 psi..... | | | | | | | |
| p_{O_2} = { 4 in. Hg..... | } ----- | 1,080 | 1,185 | 1,125 | 1,030 | 1,135 | 1,020 |
| { 2 psi..... | | | | | | | |

*The fluids are identified as follows:

A—Hydraulic fluid, petroleum base, MIL-O-5606

B—Aviation fuel, JP-4

C—Lubricating oil, MIL-O-7808

D—Hydraulic fluid, Oronite, MLO-8200, 93.38% disiloxane, 4.6% silicone

E—Hydraulic fluid, methyltetrachlorophenyl, G.E. #81644

F—Hydraulic fluid, disiloxane-ester blend, MIL-H-8446A, 78.68% disiloxane, 4.3% silicone, 15% di(2-ethylhexyl)sebacate

G—Naphthenic mineral oil, MLO-7117

inches above the plate. Plate temperatures were recorded in degrees Fahrenheit and the minimum temperature required to ignite the fluid was determined within 5°. The lowest temperature that ignited the fluid was considered the ignition temperature. Fluids were tested under atmospheric conditions equivalent to 850 to 25,000 feet of altitude, and in pure oxygen at pressures of 4 to 10 in. Hg (2 to 5 psi). Test fluids, identified in table 9, included aviation fuel, lubricating oil, and several types of hydraulic fluids.

The data indicate that ignition temperatures of the several hydraulic fluids vary widely (table 9). Fluids E and F, which are high-temperature fluids, ignited at about the same temperatures as the standard fluid A. The data for some of these fluids, plotted in figures 29 to 33, show that the ignition temperature increases as the atmospheric pressure decreases, whether the atmosphere is pure oxygen or a

normal air mixture. Surprisingly enough, the ignition temperatures are generally higher in pure oxygen than in an oxygen-nitrogen atmosphere with an equivalent oxygen partial pressure. This appears to be the cause of much confusion regarding the hazard of oxygen in space cabins. These results and the results of studies of spontaneous ignition temperatures by other investigators²⁴⁸ have been quoted to us as indications that "high oxygen may affect burning rates, but does not affect ignition temperatures." The physical parameters of these tests must be understood in order to really evaluate the relative fire hazards which they represent. The results of spontaneous ignition temperatures and plate ignition temperatures for some of these fluids will be compared next.

The spontaneous ignition temperature for some of these fluids was previously measured by Zabetakis et al.²⁴⁸ at the Bureau of Mines. Curves for spontaneous ignition are included

in figures 29 to 32. The spontaneous ignition temperatures found by the Bureau of Mines are much lower than the plate ignition temperatures Klein recorded. This difference is not unreasonable and can be explained by the difference in test conditions. In Klein's tests, the fluid, simulating a dropping leak, was heated one drop at a time as the drops contacted the heated plate. In the Zabetakis studies, the fluid was heated in volume for the spontaneous ignition tests. Klein's drops boil as they contact the hot plate. This keeps the liquid and vapor temperature below that of the plate. The difference between the two ignition temperatures is a function of heat of vaporization of the fluid, vapor pressure of the fluid, and chamber pressure. In the studies of Zabetakis et al.,²⁴⁸ the atmospheric temperature approximates the plate temperature. When this condition exists, the heat of the atmosphere compensates for the heat of vaporization, and

heat lost by vaporization delays ignition only momentarily. The ignition temperature in this test, then, would be close to the spontaneous ignition temperature.

It must be realized that the ignition process in liquid hydrocarbon systems is quite complex. The discussion under "Heterogeneous Systems" in Chapter 1 suggests the crucial role of oxygen during the lag period and in the conversion of initial cool-flame phenomena to a full propagating system. It was pointed out that the temperature of the hot surface is critical in evaluating the effects of oxygen on the ignition system (figs. 9 and 10). The "lobes" exhibited by the ignition curves can cause serious errors in determinations and interpretations of spontaneous ignition temperature. For example, the spontaneous ignition temperature of n-octane ("hot ignition") in air (21 percent oxygen) is about 280° C for the apparatus used. A slight change in appara-

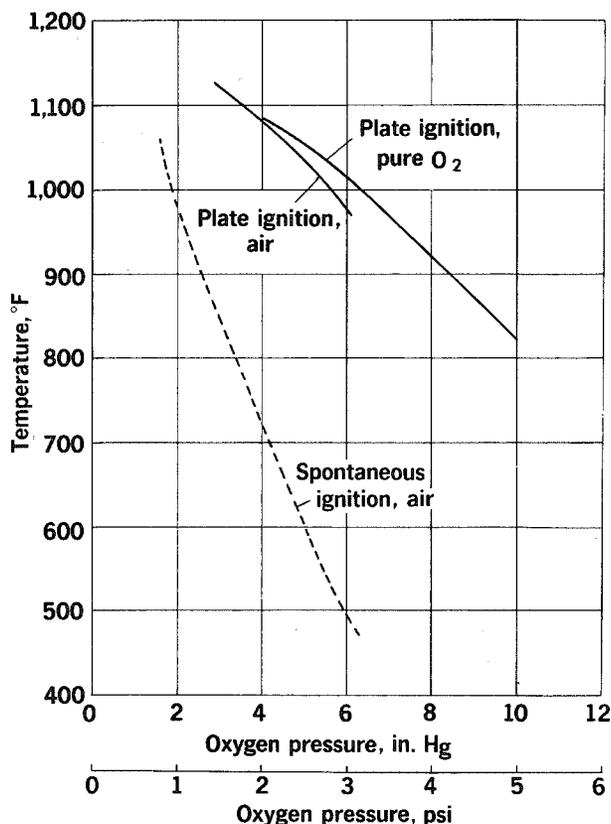


FIGURE 30.—Ignition temperatures for JP-4.
(AFTER KLEIN.¹²⁵)

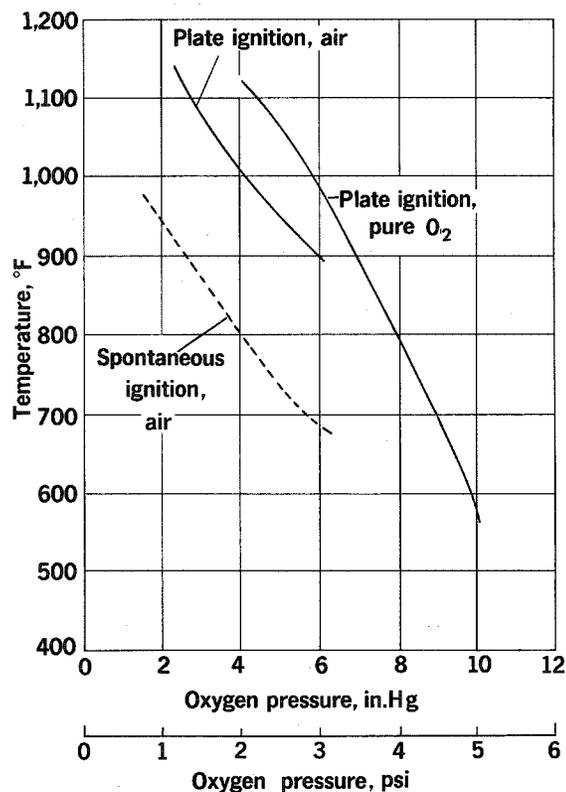


FIGURE 31.—Ignition temperatures for MLO-8200.
(AFTER KLEIN.¹²⁵)

tus, such as a larger chamber, would cause the ignition curve to shift downward and to the left, so that the 21 percent line would intersect the first lobe in the curve and yield a value which would be lower by 20° or more. In addition, at higher temperatures, "negative" ignition zones are observed. This is because cool-flame ignition is observable only in total darkness, not usually the condition in this type of determination. These factors introduce serious complications in the proper interpretation of spontaneous ignition temperature. For example, some of the spontaneous-ignition-temperature data of the Bureau of Mines were determined in a 200 ml flask by standard procedures and might not, therefore, be applicable to a space cabin. The effect of chamber geometry and other parameters as discussed by N. Setchkin¹⁹⁷ also points out the danger of using spontaneous-ignition-temperature data in evaluating fire hazards.

Why are the ignition temperatures in pure oxygen generally higher than those in an oxygen-nitrogen atmosphere with an equivalent oxygen partial pressure? There are several possible explanations. As the drops of fluid hit the hot test plate they vaporize. This vaporization removes heat from the surface of the fluid phase. The lower total pressure of the pure oxygen atmosphere promotes a more rapid rate of vaporization and heat removal for a given temperature. This vaporization can occur at temperatures below the ignition temperature of the vapor-oxygen layer over the surface of the fluid drop. It would appear that at a plate temperature that would cause ignition in the nitrogen-oxygen atmosphere, the liquid drop in the pure oxygen atmosphere can vaporize completely before the vapor-oxygen layer reaches ignition temperatures. This phenomenon would result in a measured plate ignition temperature which is higher in pure

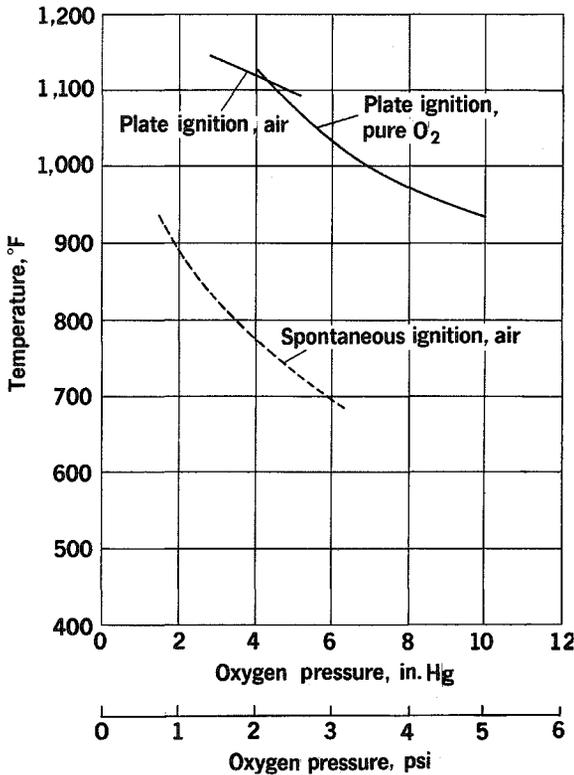


FIGURE 32.—Ignition temperatures for MIL-H-8446A. (AFTER KLEIN.¹²⁵)

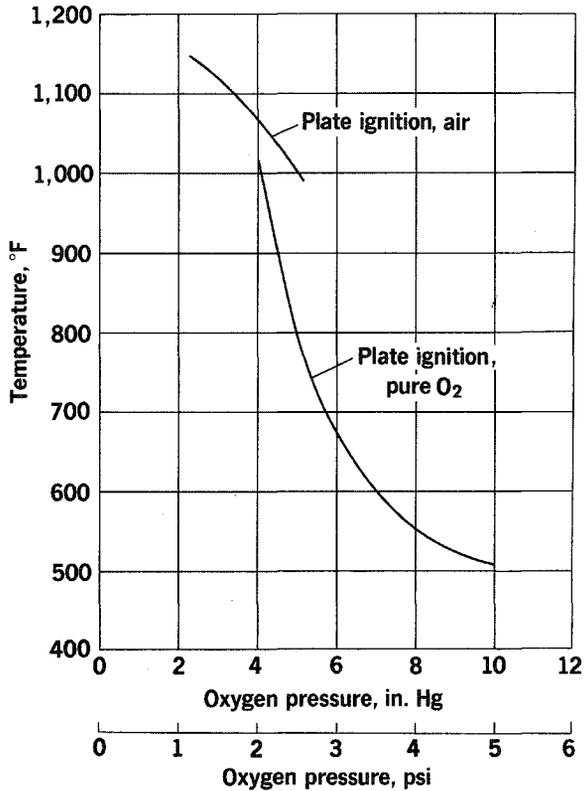


FIGURE 33.—Ignition temperatures for MLO-7117. (AFTER KLEIN.¹²⁵)

oxygen than in air at the same partial pressure of oxygen.

Another plausible explanation suggested by Brokaw²⁸ is based on the catalytic effect of surfaces in ignition phenomena.¹³⁸ In brief, the presence of pure oxygen predicts an enhanced catalytic oxidation on the surface of the plate. This may deplete the combustible near the surface, inert the combustion products, and result in an elevated ignition temperature. The complexities of the initial reactions in conversion of ignition phases to propagation phases¹²⁰ makes a more rigid analysis of the anomaly quite difficult.

Once burning is started in a pure oxygen atmosphere, however, it proceeds much more vigorously and at higher temperatures. Flames are blue-white in contrast to the orange and yellow flame in normal air.¹²⁵ Damage from fire in a pure oxygen atmosphere is greater and the conditions more dangerous than in an oxygen-nitrogen atmosphere, despite the somewhat higher ignition temperatures recorded in hot-plate tests.

In figures 29 to 33, there are marked differences from fluid to fluid in the shape and position of the curves representing spontaneous ignition temperature, plate ignition temperature in air, and plate ignition temperature in pure oxygen. The vapor pressure, flash points, and, ultimately, the molecular structure of each fluid determine the response to these atmospheric variables. Analysis of the fluid burning problem by study of only one or two fluids at several spot points on these curves has been performed in the past. It is obvious that thorough searches such as Klein and Zabetakis et al. have reported are required to get a valid picture of the situation. It is apparent that there is a wide choice of fluids and lubricants for space-cabin equipment. Those most favorable for the operation should be screened for maximum resistance to all combustion parameters under conditions of elevated oxygen partial pressure. It is also apparent that the use of minimum oxygen content with maximum inert-gas content would provide an optimum atmosphere insofar as reducing the total fire hazard from burning fluids is concerned.

Effects of Atmospheric Environment on Electrical Fire Hazards

IN GENERAL, the problem of electrical fires involves the ignition and flammability parameters relating to the metallic conductor as well as to the insulating materials. The recent study of Klein¹²⁵ has approached the problem by using three basic tests: (1) Determining the amount of current that causes wire to burn in various atmospheres, (2) measuring the effect of various atmospheres in propagating flame from a shorted wire to adjacent wires, and (3) measuring the effect of various atmospheres when extreme current is passed through wire.

EFFECTS OF OXYGEN ON BURNING OF ELECTRICAL INSULATION

Eight wire samples were selected for testing. They represented standard types of aircraft wire produced by different manufacturers. Some of the samples from different manufacturers had the same type of insulating material. Since the supply of wire was limited, not all samples with similar insulating material were exposed to all tests if preliminary tests indicated that results would be duplicated. Wires are identified as to insulating material and type as follows:

- Wire A. MIL-W-5274A, Type 1, Class A—Extruded polyvinyl chloride primary insulation, extruded nylon outer protective coating 20 gage
- Wire B. MIL-W-8777 (150°C)—Silicone rubber, glass, and Dacron braid, 20 gage
- Wire C. Same as wire B (different manufacturer)
- Wire D. MIL-W-16878, Type E (200°C)—Teflon, 20 gage
- Wire E. Same as wire A (different manufacturer)
- Wire F. Same as wire B (different manufacturer)
- Wire G. MIL-C-25038 (fire resistant)—Asbestos, 16 gage
- Wire H. MIL-W-7139 (400°F, flame resistant)—Glass and Teflon, 20 gage.

In order to determine the general burning characteristics of these wires in a typical spacecraft atmosphere, several samples were tested in an atmosphere of pure oxygen at a pressure of 10 in. Hg (5 psi). A 10-inch length of each wire was looped between two clamps in a circuit and subjected to a 50-ampere current. The following results were observed:

- Wire A. Insulation melted, bubbled, smoked considerably, then turned black. After about ¼ minute, the wire burst into flame.
- Wire B. Insulation melted, dripped, and started smoking after about ½ minute. Wire burst into bright flame in approximately 1 minute.
- Wire C. Insulation blackened, bubbled excessively, smoked and split in one spot and exposed the wire before flame appeared. Wire burst into very bright white flame in approximately 15 seconds.
- Wire D. Insulation turned cherry red. Wire burst into small blue-green flame in approximately ¼ minute and broke a few seconds later.
- Wire G. Insulation blackened, smoked, and turned cherry red. Wire broke after approximately 1½ minutes. When examined after the tests, the insulation appeared brittle but not burned.

TABLE 10.—*Minimum Burning Current* [AFTER KLEIN ¹²⁵]

| Chamber content | | Burning current, amp, in wire— | | |
|----------------------------|----------------------------|--------------------------------|-------|-------|
| O ₂ , in. Hg | N ₂ , in. Hg | A | E | F |
| 4.0 | 0.2 | 48 | ----- | 50 |
| 4.0 | 6.0 | 50 | ----- | 58 |
| 4.0 | 10.0 | 78 | ----- | ----- |
| 4.0 | 12.0 | >80 | ----- | 62 |
| 4.0 | 18.0 | ----- | ----- | 62 |
| 4.0 | 20.0 | ----- | ----- | 62 |
| 5.0 | .2 | 46 | ----- | ----- |
| 5.0 | 6.0 | 48 | ----- | 62 |
| 5.0 | 12.0 | 68 | ----- | ----- |
| 5.0 | 13.0 | 80 | ----- | ----- |
| 5.0 | 14.0 | >80 | ----- | ----- |
| 6.0 | .2 | 44 | 44 | 48 |
| 6.0 | 6.0 | 48 | 48 | 54 |
| 6.0 | 12.0 | 50 | 50 | 54 |
| 6.0 | 18.0 | 70 | 70 | 56 |
| 8.0 | .2 | 40 | 36 | 46 |
| 10.0 | .2 | 38 | 36 | 44 |
| *6.15 | *23.11 | >130 | ----- | ----- |

* Ambient.

The three specific tests on these wires are described in the following paragraphs.

Minimum Burning Current

A 10-inch length of wire was placed between two alligator clamps in a test circuit. With the desired atmosphere established in the test chamber, the current passing through the wire was steadily increased until the wire started to burn. The amount of current required to start burning was considered the burning current. Burning current was measured and recorded at several different atmospheric conditions, and the results are shown in table 10.

Only a limited number of tests were conducted on wire B because results duplicated those of wire F. Ignition of wires D and H was erratic and the small flames were self-extinguishing; wire H sometimes burned for a short time with a small blue flame when subjected to current of 70 amperes in pure oxygen at pressures of 6 and 10 in. Hg (3 and 5 psi); wire G did not burn at all.

Data from table 10 are plotted in figure 34. The oxygen partial pressure of the atmosphere was held constant and nitrogen was added to vary the total pressure. Conditions represented by the areas above and to the left of each curve are considered safe for the specific oxygen partial pressure since fire would not result. The curves for polyvinyl-chloride-insulated wire level off when nitrogen is added, indicating that fire from wire with this type of insulation can be prevented with proper atmospheric conditions. These conditions, however, require the ratio of the partial pressure of nitrogen to that of oxygen to be greater than about 6. The curves for wire F indicate that at higher currents, adding nitrogen has little or no effect, and no practical atmospheric composition will prevent this type of wire from burning. It is not obvious how the molecular structures of these compounds determine the disparate responses to nitrogen quenching.

Burning Adjacent Wires

Pieces of wire 5 inches long conducting no current were placed in planes perpendicular or parallel to, and ½ inch from, a 5-inch length of wire conducting current.

Results are given in table 11. Results of these tests indicate that when sufficient oxygen exists in the atmosphere for a current-conducting wire to burn, flame will spread to an adjacent wire lying either perpendicular or parallel to the burning wire, whether or not the adjacent wire is conducting current.

Extreme Current

Tests were performed to simulate a short circuit close to the current source. Twenty-eight volts were shorted across a 1-foot length of wire in pure oxygen and in an oxygen partial pressure of 6 in. Hg (3 psi) with 12 in. Hg (6 psi) of nitrogen. Currents as high as 160 to 180 amperes were measured in the circuit. Results of these tests, presented in table 12, are similar to results of previous tests. The wire melted so fast in one case that the insulation was not ignited, and gases from the overheated Teflon, in another case, tore the insulation off the wire.

It would thus appear that in general, the asbestos-insulated wire (G) would be best as far as the fire hazard is concerned. In the absence of nitrogen the silicone rubber-glass-Dacron insulation (B and F) appears safer than does the polyvinyl chloride (A and E). Only when the partial pressure of nitrogen is increased to the point where it is more than 6 times that of oxygen does the polyvinyl-chloride-covered wire begin to appear safer than wires B and F. The glass-Teflon wire (H) appears to be superior to wires B and F in both the adjacent-wire and extreme-current tests. There is a question, however, regarding the toxicity of burning Teflon. This is discussed below.

TOXICOLOGY OF BURNING INSULATION

In a sealed cabin, the products of combustion of most materials present hazards which might

conceivably match those of the fire itself. The chlorinated plastics such as polyvinyl chloride and the fluorinated hydrocarbon polymers such as Kel F and Teflon have been mentioned in several broad reviews of space-cabin environments as presenting special hazards. It appears worthwhile at this time to review the toxicology of the pyrolysis products of these electrical insulations.

Polyvinyl Chloride

A study in 1954 by Coleman and Thomas of the Joint Fire Research Organization, Boreham Wood, England,⁴⁸ defined quite adequately the thermal decomposition products of various polyvinyl chlorides. The results of pyrolysis at 300°, 600°, and 900° C are reported. The samples were burned in air. Enough oxygen was present in the air to burn to completion 1 gram of the sample. The 0.25

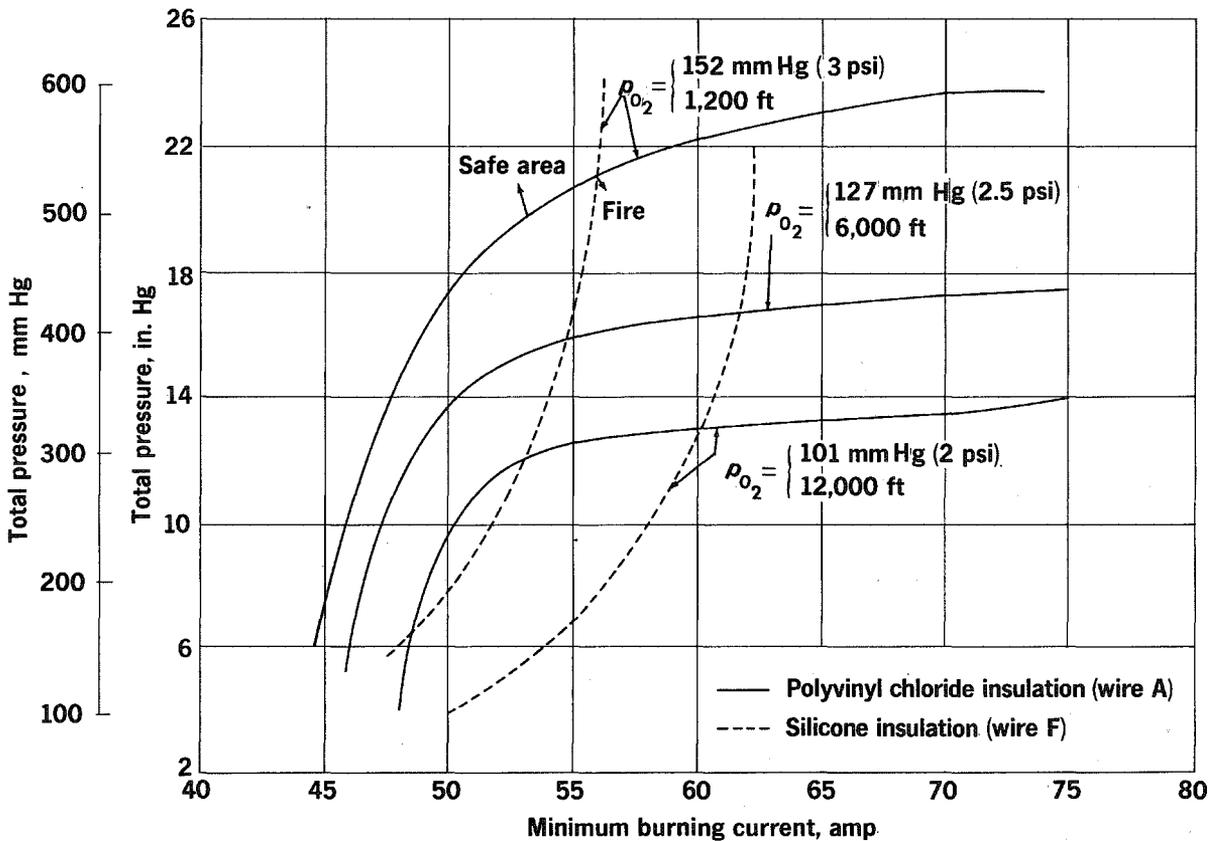


FIGURE 34.—Ignition limits of aircraft wire. (AFTER KLEIN.¹²⁵)

TABLE 11.—*Results of Shorting Adjacent Wire* [AFTER KLEIN ¹²⁵]

| Chamber content | | Plane | Wire | | Results |
|----------------------------|----------------------------|------------------|----------------|-------------------|---|
| O ₂ , in. Hg | N ₂ , in. Hg | | Con- ductor | Noncon- ductor | |
| 6.0 | 0.2 | Parallel..... | A | A | Nonconductor burned with 60 amp current in conductor. |
| 6.0 | 12.0 | Parallel..... | A | A | Nonconductor burned with 70 amp current in conductor. |
| 6.0 | .2 | Perpendicular... | A | A | Nonconductor burned with 60 amp current in conductor. |
| 6.0 | 12.0 | Perpendicular... | A | A | Nonconductor burned with 70 amp current in conductor. |
| 6.0 | .2 | Perpendicular... | F | F | Nonconductor burned with 60 amp current in conductor. |
| Ambient | Ambient | Perpendicular... | F | F | Nonconductor burned with 70 amp current in conductor. |
| 6.0 | 12.0 | Perpendicular... | F | F | Nonconductor burned with 70 amp current in conductor. |
| 6.0 | .2 | Parallel..... | F | H | Conductor burned with a bright flame but did not ignite nonconductor. |
| 6.0 | .2 | Parallel..... | A | H | Conductor burned with bright flame; nonconductor slightly weakened at one point where Teflon appeared to be burned out. |

gram samples burned in the apparatus were equivalent to 3 pounds of plastic burned in 1,000 cubic feet of air. Table 13 represents the results along with the maximum permissible concentrations corresponding to the U.S. Maximum Allowable Concentrations (MAC). The principal products were hydrogen chloride (HCl), carbon dioxide (CO₂), and carbon monoxide (CO), with carbonyl chloride (phosgene) (COCl₂) of small account compared with the other gases. Little chlorine was evolved. The maximum permissible concentrations for exposure of ½ to 1 hour of hydrogen chloride (HCl) and carbon monoxide (CO) were surpassed in all cases studied. On occasion, phosgene (COCl₂) reached levels which were above the permissible concentration for exposures of prolonged nature, but below that for ½ to 1 hour. About 30 percent of the chlorine in the plastic was liberated as hydrogen chloride, a pungent compound which would give warning of its presence. Products of burning in 100 percent oxygen environments were not found in the literature.

Teflon

The history of toxicity of burning Teflon has been apparently replete with exaggeration. Recent reviews of the subject have been published by Zapp of the E. I. du Pont Company in a monograph,^{252, 253} and by the Polychemicals Department of that company.⁶⁵

Chemically, Teflon fluorocarbon resins are analogs of polyethylene and polypropylene in which the hydrogens are replaced by fluorine. In the past decade, the formulation of Teflon has changed to give a variation of the old tetrafluoroethylene (TFE) resin that would lend itself to conventional melt-processing methods. This new melt-processable polymer, Teflon FEP-fluorocarbon resin (fluorinated ethylene propylene) was introduced in 1956 and finally placed in commercial production during 1960. According to E. I. du Pont & Co.:⁶⁵

Teflon resins show complete thermal stability up to about 400° F. By using the most refined analytical equipment, some traces of decomposition products can be detected at temperatures between 400° F (205° C) and 450° F (232° C). Above 450° F weight losses be-

come sufficient to provide a means of expressing decomposition rates. By comparison with most organic materials, weight losses of Teflon resins are extremely small. At 500° F (260° C) they are small enough to be essentially negligible from the standpoint of service life. The 500° F continuous service rating of TFE resins is based in part on this performance. FEP resins exhibit changes in physical strength above 400° F (205° C), largely accounting for the lower temperature rating for these products.

The pyrolysis products of Teflon have been studied.^{26, 134, 170, 202} Because of extremely low decomposition rates, complete identification of the products has not been possible with existing analytical techniques. It is known that the mechanism of decomposition is primarily one of reverting to the original gaseous monomers (the basic substances from which the resins are synthesized) as well as to some of the gases listed below. This means that the TFE resins produce tetrafluoroethylene and the FEP resins a mixture of tetrafluoroethylene and hexafluoropropylene.

These substances comprise the major portion of the decomposition products. Tetrafluoroethylene and hexafluoropropylene are relatively nontoxic and markedly less hazardous in this respect than the vapors from such commonly used solvents as carbon tetrachloride, benzene, and carbon disulfide. At temperatures between 400° F and 800° F the remaining portion of decomposition products consists of fluorocarbon gases varying in chain length from C₃ to C₅ (also relatively nontoxic) with small quantities of hydrogen fluoride, silicon tetrafluoride (from the glass equipment), and an incompletely characterized waxy sublimate. At 750° F and above, small amounts of the toxic gas perfluoroisobutylene have been isolated. Free fluorine has never been found among the decomposition products of Teflon, and its formation is not favored thermodynamically. If the pyrolysis is carried out in moist air, more hydrogen fluoride may be liberated. However, this substance is rarely detected at temperatures below 750° F (400° C).

Teflon fluorocarbon resins are "non-flammable" and do not propagate flame in air (ASTM-470 vertical flame test). Decomposition products will burn at temperatures above 1,274° F (690° C) but combustion is not self-

TABLE 12.—*Effect of Extreme Current on Wire*
[AFTER KLEIN¹²⁵]

| Chamber content | | Wire | Results |
|----------------------------|----------------------------|------|---|
| O ₂ , in. Hg | N ₂ , in. Hg | | |
| 6.0 | 0.2 | A | Wire broke like a fuse; insulation badly singed and destroyed but there was no open flame. |
| 6.0 | 12.0 | A | Wire broke like a fuse and an explosive-like orange flame completely burned the wire. |
| 6.0 | .2 | F | Wire broke like a fuse and insulation completely burned with a bright flame. |
| 6.0 | 12.0 | F | Wire broke like a fuse and insulation completely burned; the burning was slow with a yellow flame, but it was complete. |
| 6.0 | .2 | H | Insulation shot off the wire without any burning of the insulation; wire was scattered throughout the chamber. |
| 10.0 | .2 | H | Wire broke like a fuse and a very small blue-green flame appeared at insulation where Teflon was exposed; otherwise insulation looked good. |
| 6.0 | 12.0 | H | Wire broke like a fuse 4 in. from the end and separated from the insulation; there was no flame and no damage to the insulation. |

sustaining since the heat liberated is not, in itself, sufficient to maintain the polymer at decomposition temperatures. Combustion products consist primarily of carbon dioxide, carbon tetrafluoride, and small quantities of hydrogen fluoride. The effects of pure oxygen

TABLE 13.—Concentrations of Toxic Gases Evolved From Chlorinated Plastics Decomposed in Air by Heat, and Maximum Permissible Concentrations [AFTER COLEMAN AND THOMAS ⁴⁸]

| Sample | Wt. of sample, gm | Temp., ° C | Concentrations of gases, ppm | | | | |
|---|-------------------|------------|------------------------------|-----------------|-------------------|-------------|-----------------|
| | | | HCl | Cl ₂ | COCl ₂ | CO | CO ₂ |
| Chlorinated polymethyl methacrylate (45% carbon, 27% chlorine)--- | 0.55 | 350 | 6,000 | Nil | 3 | n.d.* | n.d.* |
| | 0.50 | 550 | 6,000 | Nil | 5 | 22,000 | 26,000 |
| | 0.50 | 950 | 15,000 | Nil | n.d.* | 14,000 | 60,000 |
| Polyvinyl chloride, unstabilized (57% chlorine)----- | 0.25 | 300 | 13,000 | Nil | Nil | 5,000 | 6,000 |
| | 0.25 | 600 | 15,000 | Nil | <1 | 7,000 | 15,000 |
| | 0.25 | 900 | 15,000 | Nil | 3 | 5,000 | 29,000 |
| Vinyl and vinylidene chloride copolymer, unstabilized (61% chlorine)--- | 0.25 | 300 | 14,000 | Nil | Nil | 2,000 | 4,000 |
| | 0.25 | 600 | 18,000 | Nil | 5 | 11,000 | 21,000 |
| | 0.25 | 900 | 17,000 | Nil | 10 | 5,000 | 29,000 |
| Polyvinyl chloride, stabilized, "dioctyl" phthalate plasticizer (33% chlorine). | 0.25 | 300 | 5,000 | Nil | Nil | 7,000 | 8,000 |
| | 0.25 | 600 | 7,000 | Nil | Nil | 7,000 | 24,000 |
| | 0.25 | 900 | 8,000 | <1 | <1 | 10,000 | 30,000 |
| Polyvinyl chloride, stabilized, tricresyl phosphate plasticizer (31% chlorine). | 0.25 | 300 | 6,000 | Nil | Nil | 6,000 | 6,000 |
| | 0.25 | 600 | 7,000 | Nil | Nil | 6,000 | 15,000 |
| | 0.25 | 900 | 8,000 | <1 | <1 | 9,000 | 21,000 |
| Polyvinyl chloride fabric (French)--- | 0.50 | 550 | 29,000 | n.d.* | n.d.* | 4,000 | 20,000 |
| Safe for prolonged exposure----- | | | 10 | 0.35-1.0 | 1.0 | 100 | 5,000 |
| Safe for ½ to 1 hr.----- | | | 50-100 | 4 | ----- | 400-500 | |
| Dangerous for short exposures (usually quoted as ½ to 1 hr)----- | | | 1,000-2,000 | 40-60 | 25.0 | 1,500-2,000 | |

*n.d.=not determined.

environments on combustion are, as yet, not recorded. In very hot fires, which cause appreciable decomposition of Teflon, heat is absorbed from the surroundings as heat of decomposition. This property tends to limit the damage to Teflon resins in such applications as electrical insulation subject to high thermal transients. Underwriters Laboratories have classified Teflon TFE- and FEP-fluorocarbon resins as "self-extinguishing, Group I," with respect to fire hazard.

The pathological effects of these combustion products are of interest. The pyrolysis products of Teflon produce a syndrome similar to "metal fume fever."^{66,171} It is called "polymer fume

fever" or the "polymer shakes." It is similar to influenza in symptomatology and passes off without treatment or apparent aftereffects 1 to 2 days after exposure. Observations indicate that these attacks have no lasting effects, and that the effects are not cumulative. When such an attack occurs, it usually follows exposure to vapors evolved from the polymer at the very high temperature (up to 800° F or 423° C) used in resin processing operations, or from smoking cigarettes or tobacco contaminated with the polymer. The causative agent in the decomposition products has not been identified, since it has not been possible to produce the syndrome in laboratory animals.

It is possible, however, to kill animals with pyrolysis products of Teflon. Harris⁹⁸ has exposed rats for 4 hours to the products evolved at 250° C and produced slight respiratory irritation. Exposure for ½ hour to the products evolved at 260° C caused more severe respiratory irritation in the same rats. Exposure for 2 hours to the products liberated at 300° C, which included a fine sublimate, led to severe dyspnea and the death of one rat next day; the remaining rat was very ill and was sacrificed. Exposure for periods of 1 hour and of ½ hour (separated by a day) to the products liberated at 315° to 325° C produced delayed death in one rat and very severe toxic effects in the other. Post-mortem examination of the rats left no doubt that death and severe illness had been due to hemorrhage and edema of the lungs. Other organs were also congested.

Du Pont⁶⁵ reports that tests have been conducted with laboratory animals exposed to fabricated forms of Teflon and other common polymers at high temperatures. An example is the work in which several kinds of wire constructions were studied for toxicity effects. In these tests, approximately 20 grams of sample were heated in a temperature range of 392° F (200° C) to 662° F (350° C); rats were exposed for periods up to 4 hours to the resultant pyrolysis products carried in an airstream of 2 liters per minute. The ranges of temperatures causing products lethal to one or more rats after 4 hours of exposure are shown in table 14. Although rats exposed for 4 hours to polyvinyl chloride in these tests did not succumb, clinical response was severe and major pulmonary injury was observed 12 days after exposure.

In 1960, The American Conference of Governmental Industrial Hygienists set the tentative threshold limit of 0.005 ppm of Teflon pyrolysis products without specifying what products. In 1962, the Armed Forces⁶⁰ threshold values were given as 0.05 mg/cu m "as fluorine." No scientific basis for these figures has apparently been stated.

Silicone Rubber

The Dow Chemical Co. was contacted for information as to the toxicology of the pyrolysis products of silicone insulation. Data on the

TABLE 14.—*Lethality of Polymers at High Temperatures* [AFTER E. I. DU PONT DE NEMOURS & CO.⁶⁵]

| Material heated | Temp. causing products lethal to 1 or more rats after 4 hr exposure | |
|--------------------------------|---|------------|
| | ° F | ° C |
| Teflon 1 TFE resin | 572 to 662 | 300 to 350 |
| Teflon 6 TFE resin | 482 to 572 | 250 to 300 |
| Teflon 100 FEP resin..... | 482 to 572 | 250 to 300 |
| Silicone rubber..... | 482 to 572 | 250 to 300 |
| Polychlorotrifluoroethylene... | 392 to 572 | 200 to 300 |
| Polyvinyl chloride..... | 572* | 300* |

*No rats succumbed after 4 hr exposure.

stability of silicones obtained in the Dow Corning Laboratories and supported by independent groups elsewhere indicate that degradation of methylpolysiloxane polymers, which constitute the major portion of the material in question, does not take place to any measurable extent below 200° C. Table 15, taken in part from the data of Scala and Hickam,¹⁹⁰ shows that even at 250° C oxidative degradation is extremely slow. It is only at temperatures of 300° C and above that the rate becomes significant.

Treon et al.²¹⁸ of the University of Cincinnati, under a Wright Air Development Center contract, studied the effect on animals of vapors generated by dropping silicones onto

TABLE 15.—*Pyrolysis Products of Methylpolysiloxane in Air* [AFTER SCALA AND HICKAM¹⁹⁰]

| Temp., °C | Run time, hr | Moles gas/gm sample, ×10 ⁵ | | | |
|-----------|--------------|---------------------------------------|-----------------|----|----------------|
| | | H ₂ | CO ₂ | CO | O ₂ |
| 200..... | 6.0 | 0 | 0 | 0 | 0 |
| 250..... | 6.3 | .59 | 1.56 | 0 | 88.0 |
| 250..... | 11.0 | .55 | 1.83 | 0 | 93.7 |
| 300..... | 6.0 | 13.44 | 21.0 | 0 | 139.0 |

hot Inconel. Their report showed that dimethylpolysiloxanes in contact with the metal at temperatures in the range of 500° to 600° F resulted in the production of a dense fog in which formaldehyde and carbon monoxide could be detected. Under the conditions of the experiments all the animals that were subjected to the fog formed in this manner survived exposure of 2½ hours or less. At 3.3 hours or longer some deaths resulted. Guinea pigs and mice were more susceptible than rats, hamsters, cats, or rabbits. It seems from these observations that there is little likelihood of injury resulting from local heating at temperatures below 300° C. In the same series of experiments, it was found that at much higher temperatures (in the range of 1,400° F), oxidation was apparently so rapid and complete that the decomposition products were either nontoxic or relatively low in toxicity.

The Boeing Co. has studied the toxicology of

various burning electrical insulations by exposing mice in bell jars to the vapors from overheated wires. This study was performed under the Dynasoar contract. No reports have been obtained from Boeing or the Air Force Systems Command.

The choice of insulation for space-cabin use is a rather difficult one. It would appear that glass fibers and asbestos are the best materials. One must be careful, of course, that the organic binders often used with these materials are not in themselves excessively flammable and toxic when heated. The choice between silicone and fluoroplastics is difficult. Fluoroplastics may have a slight edge in that they decompose at a somewhat higher temperature, but the products are possibly slightly more toxic. There are really not enough data on equivalent systems to make a decision at this point. Asbestos and/or glass fibers with small amounts of fluoroplastic or silicone binders would probably be the best solution. Polyvinyl chloride does not seem to be as safe for space-cabin use.

Fire and Blast Hazards From Meteoroid Penetration

THE PENETRATION OF SPACECRAFT CABINS by meteoroids has been a subject of much speculation and controversy. A review of the problem has been recently presented by Davidson and Sandorff.⁵⁸ This report of the NASA Research Advisory Committee on Missile and Space Vehicle Structures points out the data gaps which need to be filled before a more definitive prediction of the probability of vehicle penetration by meteoroids can be made. It points out the very important fact that present data and predictions involve so much inaccuracy that merely to cover the range of uncertainty in engineering design introduces a gross and intolerable weight penalty.

It is not within the scope of this report to review in detail experiments which define either the mass-frequency parameters of the meteoroid problem or the equations for hypervelocity penetration. What will be discussed are several recent experiments which appear to fill in enough of the gaps to set at least a one-order-of-magnitude envelope on the problem. This will be done only for the purpose of weighting the meteoroid factor in our discussion of cabin atmospheres. The several biological experiments which define the "soft" side of the problem will also be covered.

Throughout this section the word "meteoroid" will be used as a general term to refer to particles traveling in space. The word "meteor" is used to denote only the luminous phenomena exhibited by particles as they enter the atmosphere at high speeds. "Meteorite" will designate a body of extraterrestrial origin found on the surface of the earth.

NATURE OF THE METEOROID HAZARD

Meteoroids appear to be of asteroidal and cometary origin. Most, if not all, of the meteorites found on earth appear to be of asteroidal origin. The cometary particles appear to be of two types: periodic and sporadic. The meteor showers of the periodic type appear to be associated with particular comets or the scattered remains of comets. About 30 percent of the incoming flux appears to be associated with specific streams of particles and the remainder are classed as "sporadic." Some recent measurements have led to the hypothesis that all materials are members of streams.⁸⁷ The random directions of meteors during most periods may well be a result of the fact that the earth is simultaneously immersed in many streams of varying intensity. Intensity fluctuations of even the well-defined streams may occur because of actual changes of intensity at the stream cores or because the earth does not always pass through the core. Perturbation forces modifying the stream have been defined and appear adequate to explain grossly the scattering of both asteroidal and cometary particles.

Ground Observation of Meteors

Observation of meteors has been accomplished by (1) photographic analysis of meteor trails, (2) radar analysis of ionization trails, and (3) radio interference studies.

Photographic. Current study of meteors is being accomplished by use of a new Whipple camera system using super-Schmidt cameras. A calibrated rotating shutter system inter-

mittenly interrupts the light path and allows velocity information to be obtained from film strips. The brightness of the trail is measured on the logarithmic visual magnitude scale. A light source of zero magnitude is as bright as 1 standard candle viewed from 1 km. On this scale, the sun has a magnitude of -26.7 and the full moon -12 . As the brightness of a body decreases, the number on the scale increases. Present cameras can record meteors as faint as $+5$ visual magnitude. The ratio of brightness intensity I between two steps of visual magnitude M is given by the equation:

$$I_1/I_2 = 10^{-0.4(M_1 - M_2)} \quad (8)$$

From this light input, the mass of the meteoroid is determined. As discussed below, it is this step which is the greatest source of error in evaluation of the mass-frequency curves.

Radar. Radar scanning of ionization trails of meteoroids has the advantage of permitting study in the presence of full sunlight and moonlight. It is now possible to detect particles of a size equivalent to a meteor of $+10$ visual magnitude. By using multiple high-efficiency antenna systems, the trajectory of the meteoroid may be plotted as well. Radar analysis can theoretically be improved to allow sensitivity to $+16$ visual magnitude.⁸⁷

Radio. The ionized trails of incoming meteors generate waves of radio frequency. These waves can be studied with the "beat frequency" techniques. As a rule, these measurements give only flux data. Since a given frequency is sensitive to meteors of a given size, care must be taken to define the meteor size limits of flux measurements.

A major uncertainty in all these measurement systems is the lack of confirmation by analysis of the meteoroid being studied. There is no absolute standard. Sorely lacking are data on mass, size, shape, density, porosity, aerodynamic drag, and luminous efficiency of the meteoroid in question. Mass and density are usually determined by assumption of a figure for luminous efficiency. This factor is discussed below in greater detail.

Meteoroid velocities relative to earth as determined by the observations from earth lie

between 11 km/sec and 72 km/sec. The 11 km/sec figure is determined by the minimal velocity a particle would have if, starting from rest, it fell a great distance only under the influence of the earth's gravitational field. The upper limit is based on the assumption that the meteoroid is at maximum velocity (42 km/sec) in a retrograde orbit about the sun and runs head on into the earth moving at 30 km/sec. Figure 35 represents the velocity distribution of 359 meteors: 74 from known large showers (cross hatched) and 285 from sporadic sources. The lower brightness limit was a visual magnitude of $+4.5$.

Satellite and Space-Probe Observations

Direct observations of meteoroids have been made by sounding rockets, satellites, and space probes. Most particles are detected by microphones on the skin, though wire-wound coils or grids have also been used. The wire is broken or reduced in diameter by impact and the resistance is recorded electrically. The velocity of impact is usually assumed to be 30 km/sec, and from momentum considerations the minimum mass may be estimated. It should be noted that the microphones and wire sensors have not been calibrated by using particles at hypervelocity meteoroid speeds. Another factor impeding the accuracy of this

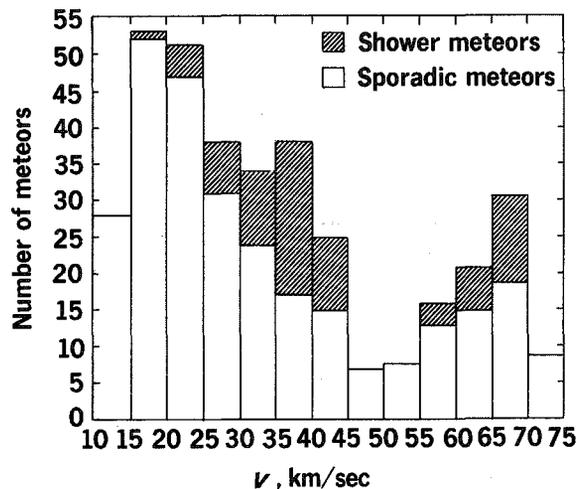


FIGURE 35.—Distribution of corrected velocities for 285 sporadic and 74 shower meteors. (AFTER HAWKINS AND SOUTHWORTH.⁹⁰)

method has recently been uncovered. This is the fact that for periods within 6 hours after launch, very high count rates have been recorded. Subsequent ground tests showed that the microphone pickups probably recorded creaking of the satellite skin as it changed its configuration under thermal stress. Only recent studies have accounted for this factor. Discrepancies between the microphone sensors and wire-grid sensors on Midas II satellites have been noted by Soberman and Lucca.²⁰⁶ The Venus fly-trap experiments in which a recoverable plastic bag is opened to sample the meteoroid population has added a new dimension to analysis of the actual particles. Micron-sized holes were found which showed jagged and irregular edges as well as round ones.²⁰⁵ Soberman concluded from these studies that the particles are probably irregular in shape and are frangible. They shatter easily and do not break the wire grids as often as was calculated. It is also possible that they are of fluffy or porous structure with a density as low as 0.05 gm/cm^3 .^{99, 167}

In all these satellite studies it must be remembered that the meteoroid flux rate is not constant. Even after the visible large-particle showers and known seasonal variations are subtracted from the data, it appears that a fluctuation in flux rate of one or two orders of magnitude is possible. These fluctuations have periods of only several days. Sampling satellites must, therefore, operate for periods of weeks in order to average out these variations.

Meteoroid Mass-Frequency Data

Until recently, there has been a wide range of estimates in the mass-frequency spectrum of meteoroids. Figure 36 is a sample of the past uncertainty. It is taken from the data of Whipple^{228, 229} and Watson.²²⁵ Also included are the results of satellite experiments in the small-particle range. This lower mass range may be of importance in the design of extravehicular structures and personal equipment. It is unfortunate that the most critical particle size is in a range that is entirely in the realm of extrapolation. Deviation of the low-mass data from the Watson and Whipple extrap-

olation is a function of the inherent errors of measurement already discussed.

Several indications in the past have suggested that previous estimations of the density of meteorities were high. The wire-grid satellite experiments of Soberman²⁰⁵ which have been mentioned suggested that most materials had lower densities than were estimated for meteorite data. Recent studies on Satellite S-55A (Explorer VIII or 1960 Xi 1) have corroborated this hypothesis.⁵ On the satellite were pressurized semicylinders of beryllium copper with a wall thickness ranging from 1 to 5 mils. Pressure loss upon puncture was recorded. In addition, stainless steel sheets (3 to 6 mils thick) backed with a current-carrying foil were placed on the surface of the satellite. Punctures were detected by grid breaks. Impact microphones and CDS light detectors also monitored the skin. In 2 days of useful satellite life, microphone impacts occurred as frequently as previously recorded on other satellites. However, no punctures of the thin pressurized cans or steel panels were recorded. These findings were far more in line with the prediction of Watson than with that of Whipple.

It is of great significance that recent studies by McCrosky¹⁴² and McCrosky and Soberman¹⁴³ of the results of the Trailblazer I experiment (NASA Langley and MIT Lincoln Laboratories) have radically modified the luminous efficiency factor in interpretation of mass from meteor-trail photographic analysis. The studies by Cook et al.⁵¹ of three asteroidal meteors have also contributed to a new evaluation of the mass-frequency analysis of Whipple.²³⁰ It will be worthwhile to present Whipple's review of the new data which establishes a fresh picture of the meteoroid hazard with changes of several orders of magnitude from previous figures.

The physical nature of meteoroids has been more clearly defined by the above papers. The drag equation by means of which velocity and deceleration of meteors is translated into mass and density is

$$m = \frac{2}{\tau_0} \int \frac{I}{V^3} dt \quad (9)$$

For known velocity V and observed intensity I , the mass m may be calculated when the luminous efficiency τ_o is known. Deceleration measurements then establish the density as well as the mass scale. In the Trailblazer I experiment,¹⁴³ the luminous efficiency was experimentally defined. From a rocket an iron sphere of known mass was ejected down into the atmosphere at 10 km/sec. The meteor trail was photographed and a value of luminous efficiency

was obtained as $\tau_o = 8 \times 10^{-19}$ zero magnitude (phot) $\text{gm}^{-1} \text{cm}^{-3} \text{sec}^4$. The $\log \tau_o$ was converted to a value for the more frequent stony meteorite through the correction of Cook et al.,⁵¹ by a log factor of -0.80 . This figure was then converted to the visual scale by a log factor of -0.72 . The resultant $\log \tau_o$ for stony meteoroids is -19.63 on the visual scale.

In compromise with the empirical studies of Cook et al., a value of $\log \tau_o = -19.42$ zero mag-

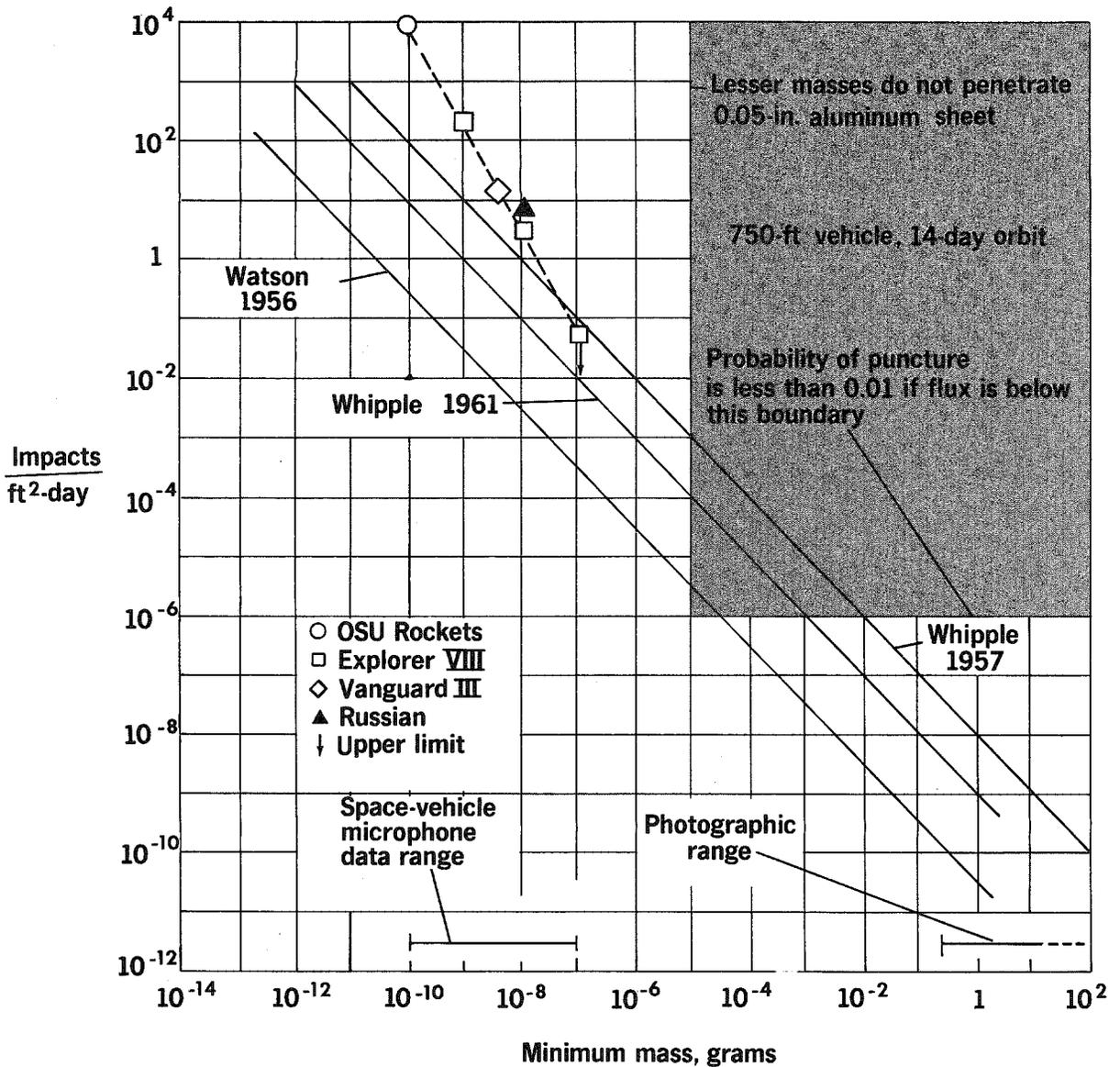


FIGURE 36.—Estimates of the meteoroid flux in the vicinity of the earth. (AFTER DAVIDSON AND SANDORFF.⁵⁸)

nitude (visual) $\text{gm}^{-1} \text{cm}^{-3} \text{sec}^4$ was actually used to calculate the mass m_o of a meteor traveling at 30 km/sec with a visual magnitude of zero. This critical constant $m_o=1 \text{ gm}$.

In order to calculate new frequency-mass curves, the density of the average particle is required. Whipple used the equation of Jacchia¹¹⁶ which relates density ρ to the drag coefficient Γ and shape factor A through a constant K , such that $\log K=6.203$:

$$K^3=2\rho^2(\Gamma A)^3\tau_o^{-1} \quad (10)$$

Whipple, assuming $\Gamma A=0.92$ and the value of τ_o calculated from equation (10), arrived at the mean density of stony meteoroids as $\rho=0.44 \text{ gm cm}^{-3}$. The value of $m_o\rho^2$ was then calculated to be $0.196 \text{ gm}^3 \text{cm}^{-6}$.

The flux rate of meteoroids for a randomly oriented surface above the earth has been calculated by Hawkins and Upton.¹⁰² Assuming that $m_o=1 \text{ gm}$ and correcting Hawkins' flux rate by a factor of $\frac{1}{2}$ for self-shielding, Whipple calculated the flux rate N as

$$\log N = -1.34 \log m + 2 \log(0.443/\rho) - 14.48 \quad (11)$$

Correspondingly, the older "Watson law"²²⁴ becomes

$$\log N = \log m + 2 \log(0.433/\rho) - 13.80 \quad (12)$$

Equation (11) is probably trustworthy to within a factor of 5.¹⁰⁰ Figure 37 is a mass-frequency plot representing the new Whipple prediction of equation (11) (labeled 1963A) and the older prediction (Met. risk 1957).²²⁸ Also compared in this plot are the predictions derived from the "Watson law" as corrected in equation (12) (labeled B), and the determinations of McCracken et al.,¹⁴¹ Hemenway and Soberman,¹⁰⁴ and van de Hulst¹¹² for zodiacal light. The curves also fit the flux rates predicted by Millman and Burland,¹⁶¹ though the fit may be entirely fortuitous.^{100, 101} Most encouraging is the meeting of Whipple's extrapolation from large-particle data with McCracken's extrapolation from small-particle data (at $m=10^{-6}$ or 10^{-7} gm). It is hoped that the recent work

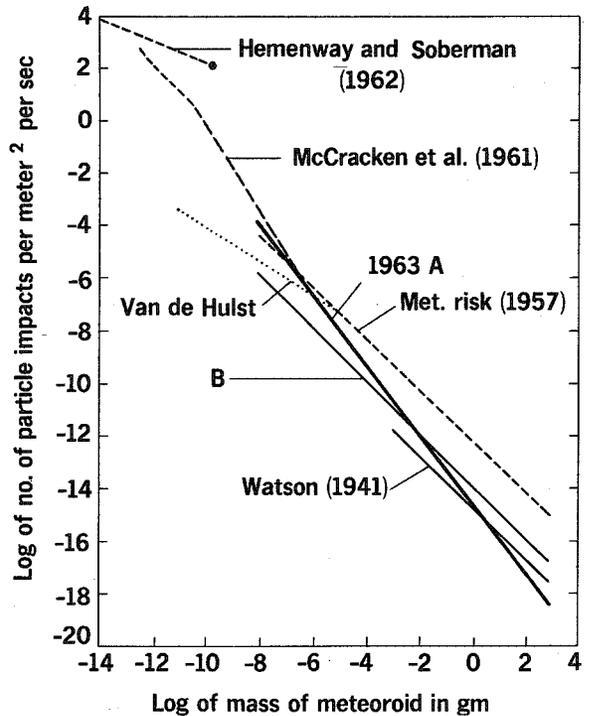


FIGURE 37.—Cumulative meteoroid impact rate near the earth. (AFTER WHIPPLE.²³⁰)

of Hawkins and Southworth at the Harvard Radar-Meteor Project will give more precise data in the 10^{-2} to 10^{-4} gm range. Whipple²³⁰ reports that preliminary results of this project fall in line with his current extrapolation.

Hawkins¹⁰⁰ has recently reported that it is also possible to determine the mass of the meteor from the ionization efficiency. This method gives an entirely independent estimate of the mass of meteoroids and is actually being used to determine the flux of meteoroids. Hawkins states:

In many respects the determination from ionizing efficiency may be more reliable than the determination from luminous efficiency. Although the luminous efficiency has been calibrated by artificial meteoroid injections, the problem of estimating the effective luminous efficiency of a meteoroid is difficult. The artificial meteoroids were composed of iron and there are many different electron transitions involved in determining the luminous efficiency of all the possible constituents in a meteoroid. However, for the ionizing probability each atom has one main energy level only and the extrapolation is perhaps less subject to error.

Vehicle-Penetration Parameters

The immediate result of meteoroid impingement on a vehicle structure is erosion or penetration of the skin. Much theoretical and experimental work has gone into the analysis of hypervelocity impact and cratering. Earlier work on lower velocity impact (<10 km/sec) and extrapolations to the meteoroid velocity range has been reviewed by Herrmann and Jones.^{105, 106} Much of the following discussion is taken from these papers. It is generally believed that the stress waves in hypervelocity penetration are many orders of magnitude higher than the strength of the target. Upon impact, target material, even if brittle, will flow like a liquid. Penetration appears to occur in a time equal to only one reverberation of the stress waves through a plate target in contrast to the multiple reverberations of wave systems in impacts at lower velocity. Projectile and target material are projected both forward and backward as a spray of fine particles. For thicker targets and for threshold penetration, the fluid phase will occupy only the initial part of the impact period. Stress waves are then attenuated to the degree where the target acts once again as a solid and material strength becomes important. The final phase of penetration involves all possible combinations of spallation, plugging, petalling, and ductile failure of the residual target material.

As very high meteoroid velocities are reached, additional phenomena are encountered. Melting and vaporization of the projectile are intensified by the heating due to entropy gain across the shock wave at the target-projectile interface. The liquid phase continues for longer periods of time and may be ejected out of or through the crater. The model for threshold penetration presents a picture similar to threshold penetration at somewhat lower velocities, but the fluid and vapor phases last longer.

Mathematical models of the penetration phenomenon are numerous. Most assume a fluid target with either a rigid or hydrodynamic projectile. Bjork's theory has served as a reasonable first approximation for predicting cratering under hypervelocity impact.^{13, 14} Strength, work hardening, and so forth, of both

the target material and the projectile are neglected. A theoretical, though experimentally valid, equation of state relates the internal energy, pressure, and specific volume of the material. Solving the problem for the cylindrical projectile with Length/Diameter=1, Bjork computed the equation:

$$p = K(m_p V)^{1/3} \quad (13)$$

where

- p depth of penetration, meters
- m_p mass of projectile, kg
- V velocity, m/sec
- K for iron projectile and target, $6.06 \times 10^{-3} \text{ m}^{2/3} \text{ sec}^{1/3} \text{ kg}^{1/3}$; for aluminum projectile and target, $10.9 \times 10^{-3} \text{ m}^{2/3} \text{ sec}^{1/3} \text{ kg}^{1/3}$

Some recent equations for the 30 km/sec range of velocities involve a thermal model in which the kinetic energy is entirely converted to heat of fusion or vaporization. In spite of the general absence of equations for low-density, porous, stony particles, much progress has been made in the theoretical realm. The empirical formula of Herrmann and Jones¹⁰⁶ appears to be generally accepted as including most of the pertinent variables and quite reliable for penetration calculations. Hypervelocity-impact laws appear to scale linearly the mass of projectile with volume of the crater

TABLE 16.—Comparison of Penetration Formulas for Aluminum and Iron Targets (Meteoroid Density, 0.44 gm/cm³; Velocity, 22 km/sec) [AFTER WHIPPLE²⁸⁰]

| Author | Aluminum | | Iron | |
|---|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| | $p/m^{1/3}$, cm/gm ^{1/3} | $P/m^{1/3}$, cm/gm ^{1/3} | $p/m^{1/3}$, cm/gm ^{1/3} | $P/m^{1/3}$, cm/gm ^{1/3} |
| Herrmann and Jones ¹⁰⁶ ----- | 1.29 | 1.94 | 0.56 | 0.83 |
| Bjork ¹³ ----- | 3.06 | 4.58 | ----- | ----- |
| Whipple ²²⁸ ----- | ----- | 6.04 | ----- | ----- |
| Bruce ²⁹ ----- | 3.56 | 5.34 | 2.05 | 3.07 |
| Öpik ¹⁶⁷ ----- | 2.13 | 3.19 | 1.30 | 1.95 |

for similar materials. The Herrmann-Jones formula for depth of penetration p into a semi-infinite target of density ρ_t and Brinell hardness H by a projectile of density ρ , mass m , and velocity V is:

$$p = 0.6 \left(\frac{6}{\pi} \right)^{1/3} \frac{\rho^{1/3}}{\rho_t^{1/3}} \log_e \left[1 + \frac{(\rho/\rho_t)^{2/3} (\rho_t V^2/H)}{4} \right] m^{1/3} \quad (14)$$

Depth of penetration P of the projectile into a thin target of finite thickness can be obtained from $P/p=1.5$.

Whipple²³⁰ has compared the Herrmann-Jones penetration equation with equations of other investigators for a model meteoroid with a density of 0.44 gm/cm³ and velocity of 22 km/sec. Table 16 is a compilation of these results. Most of these other equations are for projectiles and targets of the same density, a most unlikely event. The lower penetrations of the Herrmann-Jones prediction would appear more in line with the reality of meteoroid hazards.

Estimates of Meteoroid-Penetration Hazard

The probability of damage to a spacecraft from a perforating meteoroid impact involves the statistical problem of the likelihood of meteoroid encounter during a given mission. This encounter probability depends on the size of vehicle or component, the space environment in question, and the duration and path of flight.

Whipple's recent prediction of perforation probability makes use of the new equations for flux rates (11) and (12) and the most recent penetration equation of Herrmann and Jones (14). The "best estimate" is a combination of equations (11) and (14) for the perforation rate N of randomly oriented surfaces near the earth:

$$\log N = -4.02 \log P - 13.33 \quad (15)$$

This "best estimate" line is plotted in figure 38 as the relation between average time to perforate and thickness of aluminum skin. The "optimistic" curve for small particles is a plot of the combination of the revised "Watson law" (12) and the Herrmann-Jones equation

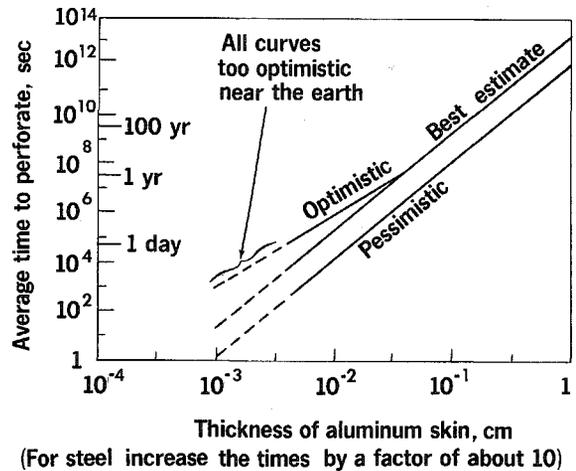


FIGURE 38.—Meteoroid perforation of thin metal skin in space. (AFTER WHIPPLE,²³⁰)

(14). The "pessimistic" line is a plot of equation (11) in combination with equation (14) in which $P/2=0.75 p$.

For a spherical satellite of 3 meters' diameter and surface of $\pi d^2=28$ square meters, the average time for penetration of the vehicle wall (0.03 cm of aluminum) is 2.3 years by the "best estimate." The corresponding figure was given as 6 hours by the 1957 estimate of Whipple.²²⁸ This involves a correction factor of 3,000. As we have seen, this factor arises from favorable corrections in meteoroid frequency, mass, and density data as well as from the penetration data.

At this time, uncertainties still remain. Density and fragility data are still the weakest links. There is partial cancellation of the density factor in the combination flux rate equation (11) and penetration equation (14). Equation (15) may be corrected for new density figures by the factor $(0.44/\rho)^{1.34}$. Uncertainty regarding the density factor throws a "halo" about the lines of figure 38 of about 1 order of magnitude. Whipple feels that this holds for skin thickness above 0.03 cm. The curves are probably too optimistic for thinner shells near the surface of the earth. The "dust belt" about the earth²²⁹ increases the flux rate of smaller particles above the calculated levels. On the other hand, the zodiacal-light data suggest that the curves are too pessimistic for

great distances from the earth.¹¹² It is pertinent at this point to relate that a piece of an Atlas booster skin section was recently recovered with what appears to be meteoroid cratering. The actual structure is at General Dynamics/Astronautics, San Diego, California. A photograph showing a hemispherical-lipped crater 0.045 inch in diameter and several shallow craters is available at the Lovelace Foundation (GD/A photograph 86597A, unclassified). Many such craters were apparently found in this stainless-steel skin section which was picked up in Africa. This is the only space-vehicle specimen of which we are aware that has what appears to be meteoroid cratering of this type.

Penetration Barriers

It is beyond the scope of this report to dwell on the various devices being studied as penetration barriers against meteoroids. It is worthwhile, however, to approximate the degree of protection that barriers may offer in our evaluation of the meteoroid hazard discussed above. The original idea of Whipple that a thin external shield will shatter the meteoroid and thus spread the impact energy over a wide area has motivated recent experimental study of this concept.

Bumper Shields. Humes et al.¹¹³ have recently investigated the effects of bumper thick-

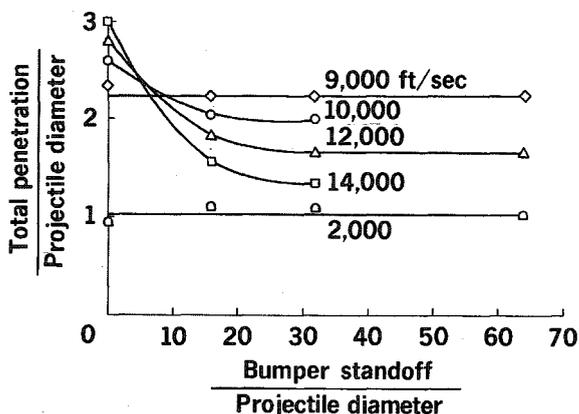


FIGURE 39.—Total penetration (bumper plus crater depth in quasi-infinite target) as a function of bumper standoff distance. (Bumper thickness)/(Projectile diameter)=0.50. (AFTER DAVIDSON AND SANDORFF⁵⁸ FROM DATA OF HUMES ET AL.¹¹³)

ness and standoff distance with copper projectiles. The bumper was half as thick as the projectile diameter, the near-optimum thickness. Results of these experiments are seen in figure 39. The total penetration (the sum of the bumper thickness and the depth of the deepest hole in the semi-infinite target) is plotted against the bumper standoff distance with the copper-projectile velocity as a parameter. At speeds up to 9,000 ft/sec the projectile pierced the bumper as an unbroken body. At higher velocities the projectile was shattered. The fragment size decreased as the velocity increased, thus decreasing the depth of the holes in the semi-infinite rear target. This occurred only when the standoff distance was sufficient to permit the fragments to scatter and not more than one impinged at any one point. Thus, the amount of damage was directly related to the size of the fragments. The decrease in total penetration was observed as the velocity increased from 9,000 ft/sec to the maximum test velocity of 14,000 ft/sec.

Nysmith and Summers¹⁶⁵ studied the mode of failure of parallel aluminum sheets bombarded with glass projectiles. They observed that with impact velocities greater than 20,000 ft/sec a plate behind a bumper fails in a different manner than with lower speed impacts. Figure 40 is a graphic result of their study where t is the sum of the thicknesses of parallel sheets and d is the diameter of the glass projectile.

At the highest test velocities, the projectile and material removed from the bumper are shattered into a thin shell of fine fragments which travel in a diverging pattern. This ruptures or cracks the plate behind the bumper before it is perforated by any fragments. Tests at impact velocities of 20,000 ft/sec indicated no change in the ballistic limit when the relative thicknesses of the bumper and the rear sheet were changed if the sum of their thicknesses was held constant. Going to the extreme of a 1 mil bumper, however, resulted in a great loss in performance because the projectile was not shattered. Nysmith and Summers conclude that for impact at meteoric speed, a sheet behind the bumper is more likely to be ruptured by a spray of fine particles than to be penetrated by individual particles.

Bumper Cores. Rolsten et al.¹⁸³ of General Dynamics/Astronautics have recently studied the principles of meteoroid protection under NASA contract. In this, the most sophisticated study of protection engineering, the "bumper concept" was investigated with shield materials of various types and thicknesses, at various separations from the main skin. The bumpers were separated by core materials of various types. In general, findings are similar to those of the above investigators. The core material between bumpers was investigated in great detail. Even though the optimum system was not determined, the general principles of energy absorption by cores were outlined. It is worthwhile to review these principles since they may reduce, by a factor of 2 or more, the penetration hazard for a given total skin and bumper weight.

The energy-absorbing or core material placed between the bumper and the vehicle hull may insulate, support, stiffen, and hold the bumper and hull plates in their respective positions. From the standpoint of protection from meteoric particles, this energy-absorbing material is to be sacrificed to save the vehicle hull. Adequate core material proved to be either fibrous, such as glass fibers, Refrasil (H. I. Thompson Fiber Glass Co.), Min-K (Johns-Manville), Linde S-10 (Linde Co.), Tipersul (E. I. du Pont de Nemours), Crystal-M (Minnesota Mining & Manufacturing Co.) and metal wool; or sponge or foam, such as cellular magnesium (Dow Chemical Co.). From the experimental data it was found that the energy-absorbing material must have moderate compressive and shear strength, low density, directionality of mechanical properties, and low ablation rates. In addition, the material must not measurably contribute to the shock cone or to the fast-moving fragments. Also, it should be capable of reducing the velocity of all particles moving toward the main hull. Thermal stability, moderate toughness, and a uniform texture are also desirable.

The preliminary experiments show that insulating materials increase the protection from meteoric particles when used as core materials in the bumpered systems. The exact principle whereby fibrous material furnishes this in-

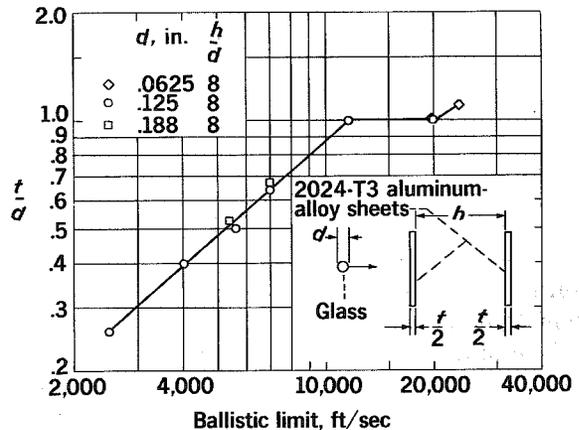


FIGURE 40.—Effect of thickness on the ballistic limit. The ballistic limit is the minimum velocity required to penetrate or rupture the rear sheet. (AFTER NYSMITH AND SUMMERS.¹⁶⁵)

creased protection has not been determined. On the basis of these preliminary data, it can be concluded that energy-absorbing material placed between the bumper and the main hull of the vehicle will significantly reduce the weight per unit area of the meteoroid-protection system. For example, the total weight per unit area can be lowered from approximately 8.8 to 5.9 lb/sq ft by the incorporation of a 1-inch-thick pad of fibrous potassium titanate placed flush with both the 0.063-inch aluminum bumper and the vehicle hull. It should be recognized that further improvement may be forthcoming, since the panels studied may not actually represent the minimum spacing for the 5.9 lb/sq ft panel. New and more efficient fibrous core materials may also be found.

What is the mechanism of action of these materials? Differences in impact behavior for the same total weight of several test panel configurations can be attributed to projectile fragmentation on acceleration, mode of projectile impact (flat face or edge), or changes in test panel design. Apparently, materials such as pressed fine fibers and foams transfer or accept momentum or energy from the particles moving from the bumper toward the hull plate. Any reduction in particle velocity corresponding to the momentum transfer may release large quantities of kinetic energy. This reduction in

velocity indicates that large amounts of the kinetic energy associated with the velocity change must be consumed in melting, vaporizing, and/or pulverizing the core material. Fine fibers provide large surface areas to absorb energy as well as to reflect and refract the impact shock waves. Furthermore, the fine material eliminated the possibility that the forces of impact would remove and accelerate large solid fragments of core material toward the vehicle hull.

The spray pattern, when a fibrous material was placed between the bumper and vehicle hull, was masked somewhat by the material destroyed and by gases and fragments rebounding from the surface of the plate. However, there were usually 3 to 10 closely grouped small craters or nicks in the vehicle hull. The impact pattern was usually very small in comparison with that on similar test panels in which core material was not used. There appears to be an optimum density and thickness for the core material. Under the test conditions, the optimum density is apparently greater than 10 and less than 45 lb/cu ft. The optimum thickness of this sacrifice material was evidently not greater than 1 inch under the test conditions.

Thus, the basic principles of core protection systems have been moderately well defined.

In a recent report under NASA contract, D'Anna et al.⁵⁷ have evaluated the possible role of self-sealing elastomers as penetration barriers. The basic philosophy behind the shift in concept from a simple double wall to a sealing barrier was the fear that at meteoritic velocities the impacting conglomeration of fragmented particles from the front shield, though not completely penetrating the inner pressurized shell, may still possess sufficient energy to spall particles from the back face of the inner shell. These studies were only preliminary. It still remains to be demonstrated whether the overall protection efficiency of the self-sealing elastomer core is greater than that of the fibrous cores described above.

Penetration Hazard Estimates for Vehicles With Bumper Systems

How must the figures for probability of penetration be revised? It is still premature

to estimate the effect that protective bumpers and cores will have in decreasing the penetration probability of spacecraft. Davidson and Sandorff⁵⁸ point out that even for the more conservative equations for penetration and simple bumper effect, meteoroid bumpers can diminish by a factor of 4 the total structural weight required for a given degree of protection. The core materials further diminish this by a factor of about 2. The latest predictions of Whipple would appear to be on the conservative side by at least an order of magnitude if ideal bumper configurations were to replace the single-sheet skin in penetration equations.²²⁸ For a 3-meter-diameter spacecraft in the vicinity of the earth with idealized, integral, wall-shield system (bumper and core) equivalent in weight to a 0.03-cm aluminum skin, this would give an overall projected possibility of penetration of about once every 23 years.

EFFECTS OF METEOROID PENETRATION ON INTERIOR OF SPACE CABINS

As has been pointed out above, the meteoroid penetration of vehicle walls results in passage of molten and vaporized materials (projectile and wall) into the cabin space or fuel compartments. Spallation of the inner wall in partial-penetration conditions may introduce high-velocity particles into the interior with direct damage to personnel and equipment.

Introduction of molten and vaporized material into the interior of the vehicle might be expected to create local temperature and pressure conditions which could cause ignition of propellants, initiate chemical reactions in materials, and directly ignite flammable materials within the cabin. Also possible is the subsequent oxidation of the vaporized materials to form a flash hazard in the cabin atmosphere.

In evaluating the total fire hazard, it must be remembered that spallation of the cabin wall may result in secondary missiles which may penetrate containers, disrupt tubes and pipes, and even cut electric wires. The release of flammable liquids and gases by these secondary projectiles creates fire hazards which have already been discussed. Ignition of these materials by the simultaneous appearance of molten liquids and vapors would follow the patterns

described in previous sections. Disruption of electric wires by secondary missiles would also create the "break spark" ignition hazard in addition to molten-liquid and hot-vapor hazards. Impingement of a metal fragment against a cabin structure might even create a friction spark which could ignite flammable materials within the cabin. The most significant hazard in cabin penetration, however, appears to be the formation of an "explosive" flash of oxidizing metal vapors in the gaseous environment of the cabin. The rest of this chapter will be devoted to an analysis of the flash hazard.

Penetration of Test Cylinders Containing Pressurized Oxygen

It is worthwhile to review the effect of meteoroid penetration of oxygen-filled structures. Recent studies by General Dynamics^{139, 183, 184} show that pure liquid or gaseous oxygen at relatively low pressures has a marked effect on the penetration damage to cylinders containing it.

In preliminary control studies, cylinders containing water at pressures from 20 to 60 psi were hit with projectiles impacting at 17,000 ft/sec.^{139, 184} There was catastrophic ripping of the vessel wall. The kinetic energy of the projectile is apparently delivered to the cylinder wall at a high rate. This energy supplements hoop tension and causes wall failure at the point of impact. Gas-filled structures behave in a different manner. The kinetic energy is delivered to the vessel walls at a much slower rate than in liquid-filled vessels. This is due to the lower density of the gas and lower speed of sound through the medium. Failure occurs by spallation, puncture, and continued flight of the hypervelocity particles through the gas and out the opposite side of the tank. If, however, the crack or tear produced in the wall of the pressurized gas cylinder exceeds the critical crack length of the material for the wall stresses which prevail, catastrophic fracture of the tank wall may occur just as in the case of a liquid-filled tank.

In the study of the oxygen-filled cylinders, a heavy test vessel was designed 5 inches in diameter and 6.75 inches long. The end diaphragms were replaceable targets of varied

materials and thicknesses. Explosively accelerated steel projectiles were used in this study. In the first test, the front and back diaphragms were fabricated from 5 Al—2.5 Sn—Ti alloy and the system was pressurized to 20 psi with pure gaseous oxygen. A 0.2110-gm projectile impacted at 15,900 ft/sec formed a 0.33-inch-diameter hole and a 0.75-inch-diameter oxidized and burned area in the front diaphragm. Impact with the titanium-alloy diaphragm fragmented the projectile but did not prevent particles from penetrating the rear diaphragm. This rear diaphragm burned rapidly in the oxygen-rich environment and produced a burned-out area about 4 inches in diameter. Ignition appears to have originated from at least three points in the back diaphragm. In photographs of one test cylinder, it was demonstrated that the projectile broke into at least two pieces as evidenced from two flame jets. Details of the burning could not be followed because the entire area of the front diaphragm was obscured with the cloud of many fine particles "of titanium alloy, titanium oxides, iron and iron oxides." Oxidation was quite rapid as evidenced by the progressive increase in illumination of this cloud of material.

In another test, the front and back diaphragms (0.010 inch thick) of the test cylinder were made of 301 extra-full-hard stainless steel and the system was pressurized to 60 psi with pure gaseous oxygen. The 0.2154-gram projectile, with an impact velocity of 13,600 ft/sec, formed a 0.25-inch-diameter hole in the front diaphragm. Fragmentation of the projectile was extensive as evidenced by the numerous small holes in the rear diaphragm. An explosion was initiated as a result of the impact and the rear diaphragm was ruptured, but only after it was penetrated by the forward-moving fragments.

Studies on liquid oxygen were performed with the same test cylinder at 60 psi. In the first test, the front diaphragm of the titanium (6 Al—4 V—Ti) test panel ruptured from the impact of the 0.97-gram projectile traveling at 12,300 ft/sec. A flap of titanium was ripped from the front diaphragm (0.016 inch thick) as the liquid-oxygen pressure was released. This flap of metal burned (about 10

percent burned) in the oxygen atmosphere. The rear diaphragm (0.016 inch thick) was neither pierced nor damaged.

In the second test, the front and back diaphragms (0.016 inch thick) of the test cylinder were fabricated of 2024-T3 aluminum. A 0.097-gram projectile with an impact velocity of 12,300 ft/sec formed the two holes (0.20 inch and 0.10 inch in diameter) in the front diaphragm. There was extensive fragmentation of the projectile on impact, as evidenced by the numerous small holes (1 hole with a 0.15 inch diameter, plus 12 smaller holes) in the rear diaphragm. Slight oxidation occurred only at the rear diaphragm. Sequence photographs showed a jet of oxygen escaping from the punctures produced in the rear diaphragm of the pressurized aluminum (2024-T3) structure. There was no apparent burning of these aluminum diaphragms, in contrast to the titanium diaphragms in the previous test.

It would thus appear that titanium-alloy walls increase the "flash oxidation" hazard in a closed system filled with oxygen. Elevated pressures as found in gaseous or liquid-oxygen storage systems increase the danger of explosive reactions. More severe flash and burning of metals is to be expected from punctures at meteoroid velocities. A study published by the G. C. Marshall Space Flight Center¹⁸¹ covers in great detail the reactivity of oxygen with titanium systems.

Penetration of Model Space Cabins by Simulated Meteoroids

Recent studies by Gell et al.⁸⁹ and McKinney¹⁴⁵ at Ling-Temco-Vought Co., Dallas, Texas, have covered, in greater detail, the hazard to inhabitants of spacecraft cabins penetrated by meteorites. The preliminary studies of Gell et al.⁸⁹ made use of projectiles of S-aluminum accelerated by a shaped charge to velocities of 8 km/sec for large particles (about 2 mm diameter) and 20 km/sec for smaller particles (about 10 microns diameter). Particles passed through a vacuum tube (175 μ Hg) to impact against a target diaphragm of 0.07-inch aluminum forming the walls of 2-cu-ft and 4-cu-ft test chambers. This simulates the impacting of an aluminum

wall of a spacecraft by particles at low meteoroid velocity *in vacuo* with subsequent decompression of the contents. The atmospheric contents studied were: (a) air at sea-level pressure, (b) air at $\frac{1}{2}$ atmosphere with oxygen partial pressure at sea level, (c) 100 percent oxygen at sea-level pressure, and (d) 100 percent oxygen at 5 psi.

Effects on the Cabin. Impaction of the particles against the wall resulted in melting and/or vaporizing of the particle and wall with cratering in the manner demonstrated in the General Dynamics/Astronautics experiments described previously. Shrapnel from spalled material of the inner side of the wall was evident. Penetration of the wall resulted in passage of melted or vaporized material into the cabin atmosphere. A very rapid, almost explosive, oxidation occurred. An intense flash of light was evidenced for a period of 0.8 to 1.2 milliseconds. Open-shutter photographs were taken of the flash in the test chamber through an aluminum-coated Mylar filter having a transmissibility of approximately 0.1 percent. The flash occurring in various atmospheres of oxygen and nitrogen was of great interest. The flash observed in runs (a) and (b) with sea-level oxygen partial pressure in air were of similar intensity. In the presence of 100 percent oxygen (runs (c) and (d)) the flash extended to about 8 inches from the diaphragm. It is of interest that in 100 percent oxygen the flash was greater at 5 psi than at sea-level pressure. The peak flash intensity varied from a low of about 3 million lumens for a standard atmospheric composition at sea-level pressure to approximately 20 million lumens for a pure oxygen atmosphere at 5 psia. In comparison, a standard General Electric No. 5 flashbulb reaches a peak intensity of only 1.2 million lumens. Temperature measurements taken in free air at a distance of 1 inch from the flash indicated values in excess of 1,500° F. The method of measurement was not recorded.

Gross Effects on Animals. White rats were exposed within the chamber by fastening them to boards placed below the central axis of the internally concave diaphragm. The animals were within 2½ inches of the lower border of the diaphragm. Even when exposed in air

environments, all the rats demonstrated hair and skin burns of varying degree and extent. Minor injuries were demonstrated and in most cases subjective symptoms of shock were present. In two cases, there were fractured backs with total paralysis of the lower extremities. None of these animals succumbed in the test, but post-mortem studies were made. In the final test, a rat was exposed to oxidative explosion in 100 percent oxygen. The result was catastrophic with instant death of the creature. There was total charring of the body. Microscopic damage involved second- and third-degree burns of the skin and extensive lung damage.

Personal Protection Against Meteoroid Penetration. Is there the possibility of personal equipment to furnish protection against meteoroid penetration? The meteoroid hazard must be considered for persons working in orbit outside cabins or on an atmosphere-free body such as the moon. One must, of course, take into consideration the reduced shielding potential in constructing the hazard picture. Since this problem is not pertinent to the space-cabin atmosphere per se, it will not be further analyzed.

Personal meteoroid-protection equipment within a cabin is a possibility. It will have to be considered only in the high-risk missions that have been mentioned. McKinney¹⁴⁵ has related some very preliminary experiments performed at Ling-Temco-Vought on the protective effects of "chain-mail" clothing placed external to a loose fibrous paper shield. The only available "chain-mail" was a loosely woven metallic mesh found on the outside of a lady's pocketbook. This material apparently reduced by 80 percent the penetration of hypervelocity (35,000 ft/sec) particles into the fibrous backing. It would appear that other materials of this type should be tested for protective efficiency.

PATHOLOGICAL PHYSIOLOGY FROM METEOROID PENETRATION OF CABINS

These preliminary studies of Gell have been recently followed up by McKinney and Stemberge¹⁴⁶ at Ling-Temco-Vought. Although the final report was not available at the time this paper was written, the facility has been

visited and the experiments in progress observed. The results to be presented were related to the author by Mr. McKinney. Much of the statistical analysis has not yet been performed and so only a semiquantitative evaluation can be made at this time.

The earlier studies of this series were performed with silicon carbide pellets (density approximately 2.5 gm/cm³) projected by a shaped charge to a maximum of 25,000 ft/sec or about 8 km/sec, just below minimum meteoroid velocity. It was discovered by accident that glass pellets (density approximately 2.3 gm/cm³) could be accelerated up to velocities of 35,000 ft/sec (11 km/sec) by the same system. Whether these velocities represent gaseous discharge or actual gross projectiles was not made clear. The more fragile glass pellets probably simulated the total meteoroid impact picture more closely than did the silicon carbide. Rats were placed on wooden boards 2½ inches from the diaphragm and below the central axis of the concavity. Piezoelectric pressure sensors were placed 1 inch below the animal boards for analyzing blast overpressures in the vicinity of the rats.

In evaluating damage to the diaphragms, it was noted that the glass pellets at 35,000 ft/sec (11 km/sec) produced larger holes and more severe flashes than did the silicon carbide pellets at 25,000 ft/sec (8 km/sec). Titanium-alloy diaphragms produced more severe flashes in 100 percent oxygen environments than did aluminum alloys. This is what was observed by the General Dynamics group¹⁸³ at lower velocities. Another interesting penetration study involved the use of plastic-impregnated Fiberglas diaphragms. These were of the same general thickness as the aluminum and titanium specimens and were studied in an evaluation of helmet penetration. Surprisingly, Fiberglas-plastic diaphragms resisted penetration better than did the metals. There was also much less flash than with the metal diaphragms. A ¼-inch-thick diaphragm of aluminum was required to completely stop penetration by glass at 35,000 ft/sec (11 km/sec), whereas Fiberglas-plastic from ⅛ inch to ⅜ inch thick provided the same resistance to penetration. McKinney suggests that the plastic

probably vaporizes at a lower temperature and acts in the manner of an ablating coating on a reentry body in resisting the thermal effects of the impact phenomenon. This resistance to penetration requires further study. It will be mentioned again in Part III of this report when the case for glass-fiber cabin walls is reviewed.

Pathology in Animals From Flash Oxidation and Hot Particles

The burning of animals by the flash of oxidizing metallic vapors was studied under varying atmospheric conditions. Under particle impact at 35,000 ft/sec rats exposed to 100 percent oxygen at pressures greater than 3.5 psi received total-body burns. In spite of the fact that the light flash was greater at 3.5 psi than at sea-level pressure, it is reported that the burning was more severe at sea-level pressure. At all pressures in 100 percent oxygen, the tongues were also burned. Presence of nitrogen in the chamber reduced burn areas roughly in proportion to the partial pressure of nitrogen. In pure nitrogen, no burns were seen though the hair was singed by the hot vapor and molten material ejected from the diaphragm. In air, a burned area about $\frac{1}{2}$ inch in diameter was found on the hair with occasional penetration to the skin. In general, only the terminal 0.25 to 0.5 inch of hair was burned in air. The higher the pellet velocity, the greater the flash and the more extensive the burn.

Some attempts were made to study the burning of rat hair by match squibs under varying oxygen conditions. Rat hair did not flame up in 100 percent oxygen at 5 psi, but did so in 100 percent oxygen at sea level. When hairs were put on a hot calrod heating element at an undetermined temperature, the hair was charred but did not burst into flame, even in a 100 percent oxygen environment. Human hair freshly clipped from subjects behaved similarly in these tests.

Because hair appeared to be the prime fuel source of the burning rats, attempts were made to clip the exposed animals. Apparently, even the nonremovable hairs about the eyes and in the limb folds were enough to cause skin burns in these animals. McKinney removed all the hair from several animals by dipping them in a

depilatory fluid with the trade name of Nair. These animals showed much less skin burn than did even the clipped animals. The fluid, however, proved to be a skin and eye irritant and itself produced enough pathology to obscure the detailed burn picture in the depilated animals.

The problem of shrapnel wounds from the hot or molten wall and projectile fragments was reviewed. Apparently hair protects the animals from all but the larger spalled particles which give typical shrapnel wounds. Animals depilated with Nair, however, showed an interesting wound picture. Several pellets of 20- to 40-micron size were found embedded in the tissues of these animals. On occasion, the abdominal wall of the depilated rats explosively disrupted, spewing fecal contents all over the cabin. McKinney feels that the heated pellets may have converted the liquid of the gut contents to steam to produce the explosive disruption. There are other possible explanations. It is hard to imagine that the heat content of several 20- to 40-micron particles found in the animals and the cabin would be great enough to cause a steam explosion. It is possible that larger metal particles were overlooked in the search for the initiating agents. If the small 20- to 40-micron particles were indeed responsible, disruption of the gastrointestinal tract was as likely caused by shock-wave implosion of the wall of the tract at gas pocket sites in the lumen. Small particles traveling at hypervelocities would probably have enough kinetic energy to generate these tissue shock waves. These matters are in the realm of speculation since no good data are available for either case.

The intense flash oxidation of metallic vapor in the vicinity of the rat appears to be responsible for corneal opacities which were found in those animals that survived. No details were available as to the precise correlation between the severity of burns and atmospheric conditions. No chorioretinal burns were observed. Only focal necrosis of the corneal epithelium was evident. Birefringent particles of what appeared to be aluminum oxide were found in some of the corneas.

The pulmonary pathology is of great interest. In those animals exposed in a sea-level air

environment, "only dilatation of the alveolar ducts" was noted. Dr. Stembridge of the Department of Pathology, Southwestern Medical School, who did the post-mortem studies, reported that these findings were not typical of any blast injury he had seen in small animals. He was not sure exactly what these microscopic findings represented. In those animals exposed to 100 percent oxygen at sea level or 5 psi environments, there was found pulmonary edema, hemorrhage, alveolar wall fragmentation, and atelectasis. Black birefringent particles of aluminum oxide were found "in a few but not in all the animals with this lung pathology." Some of the animals showed "centrilobular alveolar emphysema."

It was the opinion of Dr. Stembridge that blast was not the cause of this lung pathology. Peak overpressures in sea-level-pressure air environments were reportedly "not much different than those experienced in the 100% oxygen at sea level pressure." In view of the differences in intensity of light flash, this is somewhat surprising. It suggests that the primary cause of overpressure is the initial impact and penetration and not the flash oxidation. We were not able to review any of the pertinent pressure tracings and are unaware of any apparent contribution of the flash phenomenon to the pressure profiles. The presence of aluminum oxide particles in the alveoli of some animals suggests that inspiration by the animals during or immediately after the flash oxidation brought hot gases along with the oxide particles to the alveoli. These gases may have been the primary cause of lung pathology. Absence of aluminum oxide in some of the animals with lung pathology may represent the fact that some animals lived longer and inspired more fine particles than did others, or that the blast caught animals in different phases of the respiratory cycle. Since a short-rise short-duration blast actually forces air out of the trachea,²³³ the phase of inspiration is probably not important. It is doubtful that passage of particles to the alveoli is more dependent on the relative timing of the flash and respiratory phase than is the passage of hot gases. The impression that the amount of aluminum oxide was probably correlated

with survival time has been seconded by Dr. Mercer of the Aerosol Physics Section, Lovelace Foundation.

Mortality in Animals and Humans From Blast Effects

The cause of death of these animals exposed to the explosive flash is of immense interest. Was blast really a factor in mortality? It has been only speculated in the past that the blast overpressures of the meteoroid impact would probably be the primary cause of death, with burns as a secondary factor. In the present studies, piezoelectric sensors detected maximum peak overpressures of 36 to 38 psi in several runs in the 5 psi 100-percent oxygen chambers. The rise time to peak pressure was only 15 microseconds and the duration of overpressure was "of about the same time span as the rise." Most peak overpressures were about 22 to 25 psi and of the same rise time and duration. Pressure sensors were placed 1 inch below the rat boards and, therefore, several inches below the actual axis of penetration of the diaphragm. The measured overpressures were probably lower than the peaks experienced by the rat bodies, but how much lower is difficult to say. The rat board may well have "protected" the sensor from the direct blast wave. It is important to realize that overpressures of this short duration have been poorly studied in the past. The role of chamber and barrier geometries is also not well known for these short durations. The importance of these factors has been pointed out in the Lovelace Foundation study for AEC Operation Teapot.²³² Could lung blast have been a cause of death in these animals?

Blast Hazards in Experimental Animals. The effects of fast-rising short-duration blast waves on rats and other animals will be reviewed next. The studies of White, Richmond, and their associates at the Lovelace Foundation shed some light on the lung pathology that may be expected from these short-duration blasts.^{178, 235} Figure 41 represents a composite graph of maximum overpressure against overpressure duration for small and large animals as studied by the Lovelace Foundation and other

groups. Although some of the data are fragmentary and incomplete for durations much shorter than 1 millisecond, a general pattern is quite clear. It is seen that both overpressure and duration determine the lethality. It is also clear that for fast-rising overpressures there is a critically short pulse duration below which overpressure required for mortality rises rapidly. For durations longer than the critical, it is only the magnitude of overpressure that is significant. The critical duration varies with animal size, being on the order of many hundreds of microseconds for small animals and a few to many tens of milliseconds for larger animals. There is a close correspondence between shock-tube data and data derived from direct exposure to high-explosive blast charge. The lower curve includes the data for rats and suggests that for periods as short as 800 microseconds, overpressures of about 70 psi are required to kill rats. If the curve were extrapolated to the durations of about 30 microseconds experienced in the meteoroid impact studies at Ling-Temco-

Vought, it would appear that several hundred psi would be required.

One factor has been overlooked here. The Lovelace Foundation curves were for ambient pressures of 14.7 psi. The Ling-Temco-Vought studies were performed at 5 psi. Preliminary studies of blast at elevated pressures performed by Richmond¹⁷⁷ have corroborated the predicted phenomenon that the ratio of overpressure to ambient pressure appears to be the critical factor in lethality. When one considers the implosive effect of a fluid pressure wave on the alveoli, it appears that the lower the air density at the fluid-air interface, the greater the implosion and spallation for any given overpressure. It would seem that with an ambient pressure of 5 psi, a 36 psi peak overpressure would be equivalent in pathological effects to about 108 psi overpressure with 14.7 psi ambient pressure. This equivalent pressure would, however, still appear to be inadequate for production of lethal lung blast damage in rats exposed for durations of less than 30 microseconds (fig. 41).

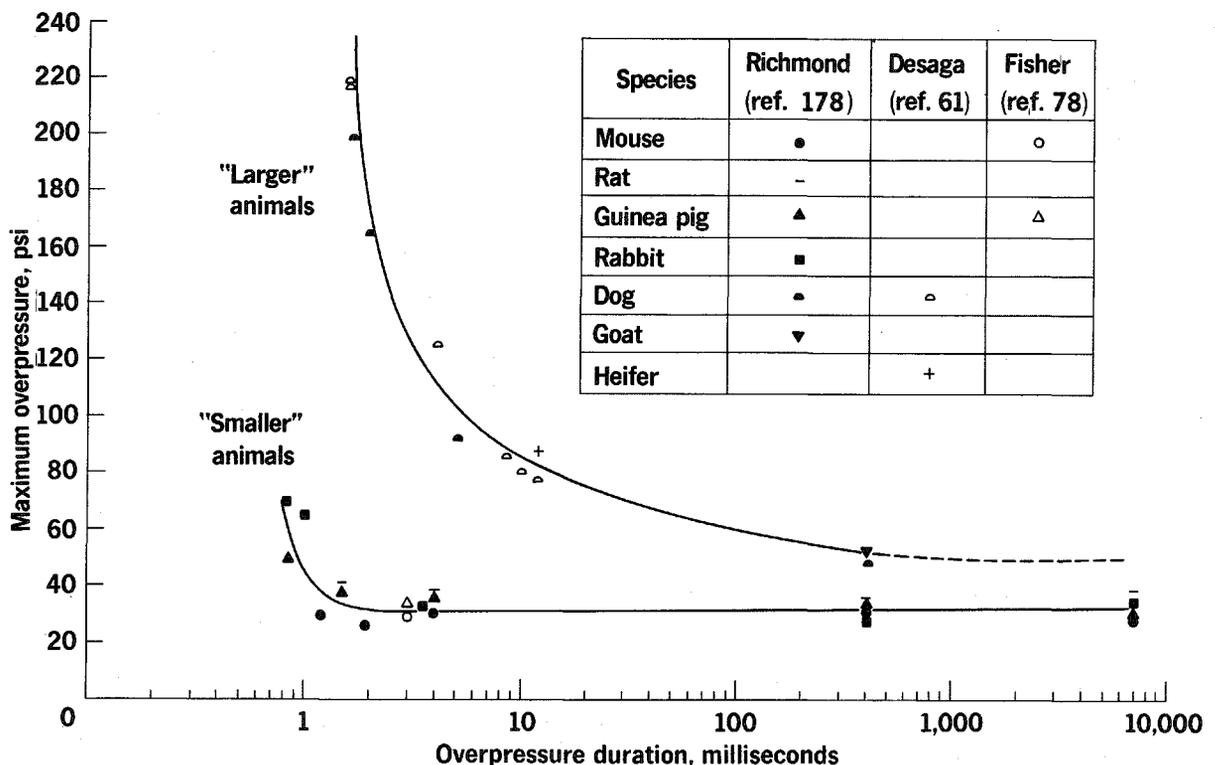


FIGURE 41.—Lethality curves for "larger" and "smaller" animals. (AFTER WHITE,²³³)

It is possible, however, that some nonlethal lung damage may be experienced under these conditions.

Another aspect of the Ling-Temco-Vought experiments which cannot be accurately defined is the effect of reflected waves on the animals. McKinney was unaware of reflections in his recordings and so we can assume that none were present. White²³³ has pointed out that the distance from the end plate of a shock tube markedly affects the mortality of animals. Table 17 indicates how this distance from the end plate determines the delay time between application of incident and reflected waves and the resultant changes in resistance to overpressures. The peak resistance appears at 6 to 12 inches (0.63 to 1.36 msec delay). Here, reflected-wave overpressures of 57 to 59 psi are required for 50 percent mortality as opposed to 36 psi when there is almost no time separation between overpressures.

This increase in tolerance was associated with a quantitative variation among three variables; namely, an increase in magnitude of the incident pressure, the reflected pressure, and the time between arrival of the incident and reflected pulses. To reduce the variables and to extend the work to other species, experiments were performed with incident and reflected overpressures of about 18 and 52 psi, respectively, a total overpressure combination which when applied "simultaneously" to animals exposed against the end plate was 100 percent fatal to mice, rats, guinea pigs, and rabbits. Under these circumstances, only the time between the incident pressure rise and the subsequent increase in pressure due to reflection was the variable.

Figure 42 shows these results. Of interest is the ability of the animals to detect time differences. Mortality for the mouse, for instance, dropped from 100 percent to 63 percent at $\frac{1}{2}$ inch with a time interval between overpressures of about 50 microseconds. At 1 inch, equivalent to a 100-microsecond interval, mortality was 29 percent. At 2 inches, where a 200-microsecond interval separated the two steps comprising the pressure pulse, mortality was zero. Each of the other species exhibited similar behavior, though the larger the animal,

TABLE 17.—*Mortality Data for Guinea Pigs for Fast-Rising, Long-Duration Shock-Tube-Produced Overpressures When Incident and Reflected Overpressures Are Applied in Two Steps*
[AFTER WHITE²³³]

| Distance from end plate, in. | Number of animals | Overpressures associated with 50 percent mortality, psi | | Time between application of incident and reflected pressures, msec |
|------------------------------|-------------------|---|------------|--|
| | | Incident | Reflected* | |
| 0 | 140 | 12.1 | 36.7 ± 0.7 | 0 |
| 1 | 75 | 13.4 | 40.8 ± 2.1 | ** .10 |
| 2 | 78 | 15.6 | 48.3 ± 1.3 | .20 |
| 3 | 87 | 16.9 | 52.8 ± 1.9 | .30 |
| 6 | 99 | 18.7 | 58.6 ± 1.6 | .63 |
| 12 | 109 | 18.2 | 57.1 ± 1.1 | 1.36 |

*All plus-or-minus figures refer to the standard error of the mean.

**Estimated.

the more slowly mortality decreased with increasing distance from the end plate. Only the guinea pig failed to drop to zero mortality. Animals no larger than rabbits were studied. Another way to express this result is to say that for very short separations in time (<200 to 400 microseconds) between arrival of the incident and reflected pulses, the animal "sees" them as one pulse. This is evidenced by the fact that mortality is higher than it would be from either of the pulses applied alone. For periods longer than this, the animal obviously makes an adaptation so that application of the first pulse protects him from the second. The mathematical chest model of Bowen and Holladay (discussed subsequently) has explained how phase differences between pressure pulses in the gas medium of the lung may bring about these results.

Blast Hazards in Humans. How do these blast data apply to humans? It is obvious that extrapolation of animal data to humans may be made only when keeping in mind all the environmental and time variables that have been discussed. The British have pointed out that man may tolerate as much as 350 to

450 psi for pulses of 1 to 3 milliseconds. Fisher et al.^{77, 78} used high explosives to produce fast-rising pressure pulses from 1 to 3 milliseconds in duration. They showed that the overpressures associated with 50 percent mortality (P_{50}) in mice, guinea pigs, rabbits, monkeys, and goats were near 27, 32, 55, 100, and 200 psi, respectively. The authors related the P_{50} data to the weight of the three smaller animal species by the equation

$$P_{50} = 0.24W^{2/3} + 23.7$$

where

P_{50} local static overpressure, psi
 W body weight, gm

From this relation, P_{50} for 60 and 80 kg men was predicted to be 390 and 470 psi, respectively. The same authors cited 12 human exposures to bombs dropped on British cities under circumstances wherein the pressure could be estimated. One fatality occurred at 450 psi. There were, however, 10 survivors at pressures between 170 and 450 psi and one between 500 and 600 psi.

The results of Desaga⁶¹ indicate that an estimated 235 psi for 4 to 6 milliseconds is another possible point on the overpressure-duration curve. During World War II, 2 deaths were found among 13 men exposed to blast from a high-explosive bomb in an open-topped concrete gun emplacement. Estimates of the overpressure which occurred in a corner where the fatally injured men were located were said to involve an incident overpressure of 57 psi which reflected to a maximum of 235 psi.

The most recent extrapolation to humans from the Lovelace Foundation blast studies is presented in table 18.¹⁷⁹ These human extrapolations and test pressures are far more severe than the peak overpressures of 36 to 38 psi for <50 microseconds recorded in the Ling-Temco-Vought study. It is apparent that a human sitting in the center of even a 100-cu-ft cabin would probably not suffer from lethal blast injury when exposed to meteoroid penetration of the cabin by particles similar in size, density, configuration, and velocity to those of the Ling-

TABLE 18.—*Tentative Estimate of Pressure-Duration Relationship for 50-Percent Lethality in Adult Humans (70 kg)** [AFTER RICHMOND AND WHITE¹⁷⁹]

| P_{50} , psi | Pulse duration, msec |
|-----------------|----------------------|
| 42 to 57..... | 400 |
| 46 to 64..... | 60 |
| 51 to 70..... | 30 |
| 78 to 108..... | 10 |
| 148 to 204..... | 5 |
| 345 to 474..... | 3 |

*Applies to sharp-rising overpressures of ideal or near-ideal wave forms.

Temco-Vought study. One must consider, however, the rare chance that a very large meteoroid may penetrate the cabin and produce much higher overpressures with longer durations. This may conceivably occur without complete destruction of the cabin and with a repairable hole in the wall. What would be the pathology from these higher blast pressures? Both meteoroid blast and explosions from other causes will result in tissue damage of the same general character. This will now be discussed.

Pathology of Blast Damage in Animals

The pathology of lung blast was briefly described in Part I of this report in regard to the oxygen toxicity factor. The general biophysical mechanisms of injury by fast-rise short-duration blasts as postulated by White^{233, 235} and Clemedson^{40, 41} are outlined in greater detail below.

Mechanisms of Blast Injury. A blast wave impinging on a biological target transfers momentum to tissue masses according to the laws of momentum transfer. The acceleration and peak velocity of any organ or tissue mass gaining the momentum of the wave is inversely related to the mass. Shearing forces and local stresses are thus the rule in the heterogeneous multiphase matter which comprises the animal body. These stresses and shearing forces ultimately determine the local pathology.

In fast-rising short-duration blasts, the great inertia of the large structures such as the chest and abdominal walls limits initial movement of these structures. Since there is little time for flow of fluid or air, most of the pathology would be expected to arise from compression by the induced pressure pulse which moves at close to the specific speed of sound through the "tissue and gas phases" of the body. Damage would appear to be primarily at density interfaces in the path of this pulse.¹⁴⁶ Whether on the basis of shearing, spalling, or direct compressive effects on closed gas pockets, the tissue-

air interfaces should be the sites of greatest damage.

What is the actual local mechanism responsible for tissue damage? Because of poor coupling and compressive effects at the air-body interface, shock waves from air blast are converted to subsonic pressure waves in body tissue.⁴¹ In underwater blast exposure, however, shock waves most probably enter the body with much less energy loss.²³⁹ The relatively undegraded shock waves in tissues in underwater blast should result in spallation at density interfaces more readily than in air blast.

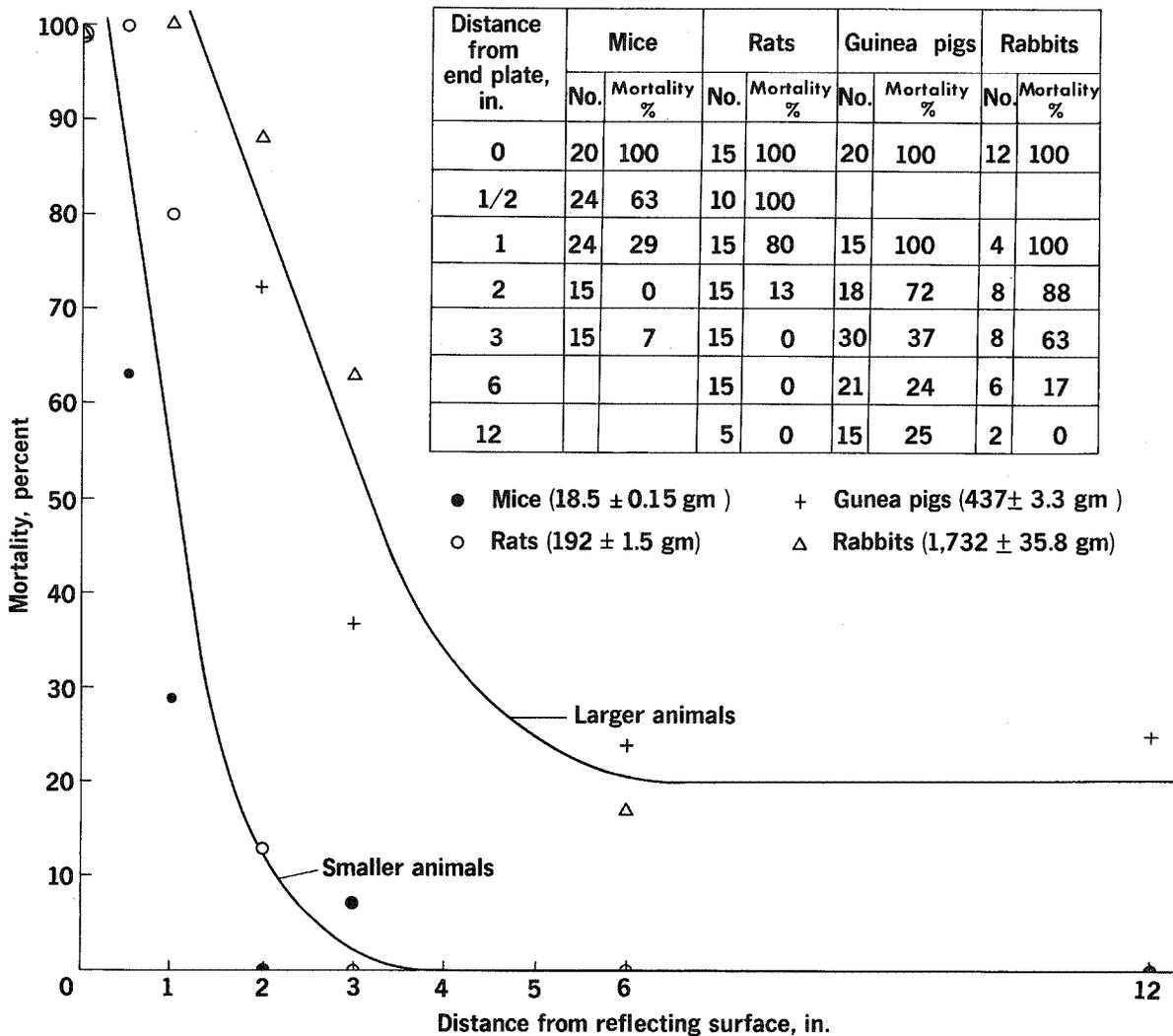


FIGURE 42.—Mortality change with exposure. Incident overpressure, 17.8 psi (av.); reflected overpressure, 52.1 psi (av.); overpressure duration, 6 to 8 seconds. (AFTER WHITE.²³³)

The spallation of metal from the inner wall of the cabin as a result of the shock wave passing through the cabin wall has already been discussed. The same events should occur as a shock wave passes from the semiliquid tissue phase at the alveolar wall to the gaseous phase within the alveoli.¹⁴⁶ A negative reflection is set up which places the alveolar wall at the air interface in severe tension. As suggested by Schardin¹⁹¹ the alveolar lung cells and blood capillaries would be expected to spall into the alveolar space. This would result in hemorrhage, pulmonary edema, and general frag-

mentation of the alveolar wall. That a subsonic pressure pulse can cause this spallation is still open to question.

One may also consider the lung as a mass of tiny air bubbles in a liquid matrix as have Clements⁴² and Schardin.¹⁹¹ A shock wave may compress these tiny air bubbles and build up large gas pressures. As the shock wave passes, the imploded bubbles may then expand explosively, setting up multiple shock waves emanating radially. These could compound the damage initiated at the spallation stage. The relative contributions of spallation and im-

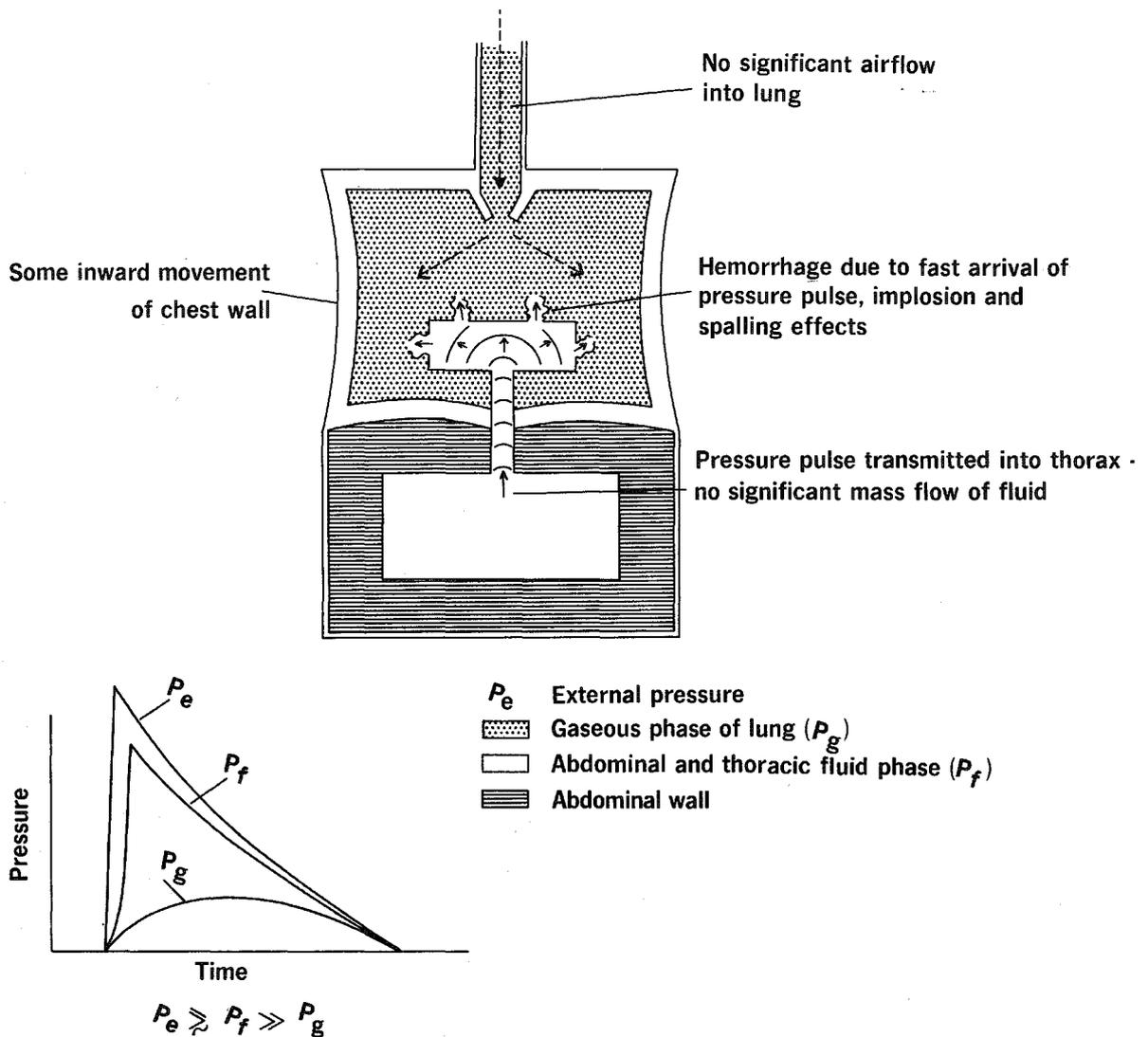


FIGURE 43.—A model of the fast-rise short-duration blast mechanism. (AFTER WHITE.²³³)

plosion to lung damage have not been determined. There has been no direct evidence for either spallation or implosion factors in the basic mechanism of lung damage in underwater or in air blast. Fragmentation of alveoli, however, does occur.

One can get a general picture of the dynamics of fast-rise short-duration blast injury from a model of the chest-abdomen system as in figure 43. This diagram focuses on the pressure differentials between external pressure P_e , thoracic fluid phase P_f , and pulmonary gaseous phase P_g . These pressure predictions were made by White several years ago.²³⁵ In this model, the fluid phase experiences a pressure peak almost coincident with and smaller than the external wave. There was predicted only a mild compression of the gas phase because the "piston action" of the abdominal and chest wall was anticipated only for slow-rise long-duration blast. The rise to peak pressure in the alveoli was also thought to be quite rapid. Of importance is the fact that there is no pressure pulse of significance passing down the trachea. Oscillation of external pressures due to the multiple reflection problems within a closed cabin and resonances of vibrating mechanical systems within the total body structure are, of course, not accounted for in this idealized model.

Clemedson^{40, 41} has recently pointed out the complex degradation of the pressure pulse patterns in rabbits exposed to air blast. At the air-body interface the shock wave is converted to a pressure pulse primarily because of an impedance mismatch between air and body which causes a reflection of the shock-wave energy. After entering the body, the pressure pulse is modified by interaction with inhomogeneous tissue elements that cause dispersion, divergence, and attenuation. The velocity of this pulse is sonic or subsonic and must be thought of as a pressure pulse and not a shock wave. The velocity of sound in muscular tissue is 1,580 m/sec; in fat, about 1,450 m/sec; and in bone, 3,500 m/sec. In lungs, the velocity is reduced to 15 to 30 m/sec by the presence of gas in the medium.

Clemedson postulated that as the air shock wave encompasses the body, a pressure

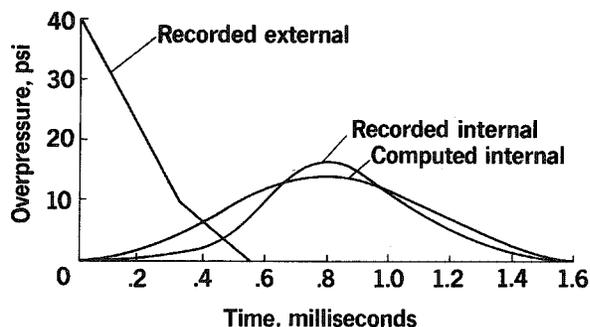


FIGURE 44.—Lung pressures after fast-rise short-duration blast. (AFTER BOWEN AND HOLLADAY.²³)

pulse passes around the body through the chest and abdominal walls. Pressure wavelets probably propagate inward to the internal organs and so pressures converge on the central organs from all sides. The pressure pulses converge on the alveoli at much reduced velocities because of the presence of the low-density air. (Vascular fluid channels do represent a high-velocity path through the lungs). Alveoli are compressed, giving an internal gaseous pressure pulse that overshoots the level of the external blast wave at that time. Figure 44 indicates the measured alveolar pressure of Clemedson⁴¹ in the "recorded internal" curve. The lag of 0.8 second to peak pressure in the alveoli is seen in comparison with the application time of external air pressure. It would appear that damage to the alveoli is caused by the compression stress on the inner wall or by tension stress after sudden reexpansion as the pressure pulse passes. This matter is still open to question. Disturbance of surface tension in the water film lining the alveoli may well be a factor.⁴²

A recent mathematical model of the chest has been presented by Bowen and Holladay of the Lovelace Foundation.²³ The lung is treated as an air-filled cavity and the chest wall and abdomen are treated as two classical damped spring-mass piston systems. The only force allowed to act on the system is the difference between external blast pressure and the pressure inside the cavity. The equation of motion of the pistons, an empirical airflow equation, and a pressure-volume (adiabatic) equation of the piston effects are combined to give a mathe-

mathematical model of the system. The "computed internal" curve simulating lung gas pressure after exposure to a fast-rise short-duration external blast wave is recorded in figure 44. The "recorded internal" curve is from the paper of Clemedson⁴¹ where lung pressure traces were recorded with implanted lead zirconate titanate transducers during the external blast pattern. There is no indication of an "implosion effect" in the alveolar pressure tracing.

It can be seen that the lung pressure peak occurs after a greater delay and is somewhat higher than the original prediction by White. Bowen and Holladay²³ believe that this is probably due to several factors. One is the failure of the body tissues to transmit any significant shock wave because of poor coupling of the shock wave at the air-body surface and further reflection and degradation of the shock wave at the tissue density interfaces. This impedance mismatch results in a net compression of gaseous lung volume by gross movement of chest wall and diaphragm. The inertia of the thoracoabdominal system helps account for the relatively slow response time compared with previous predictions (fig. 43) and, moreover, can produce an overshoot of lung pressure that reaches peaks higher than external pressure.

The mathematical model of Bowen and Holladay has also been used to explain the effects of the "two step" fast-rise blast picture previously discussed. Figure 45 represents the predicted pressure pulses for given time intervals t' between external pressure rises. It can be seen that at $t'=1.15$ msec the oscillating pressure waves from the first shock wave are "out of phase" with the pressure pulses produced by the second step. This may reduce the peak pressure pulse in the alveoli and thereby decrease damage to the wall or may counter the reexpansion of the alveoli and decrease the tension stress on the walls.

The model is currently being revised to include the response of the complex resonant vibrating systems of the chest and abdomen to applied vibratory forces. Closer fits to the empirical data have already been obtained. The model has recently been used to predict,

with moderate success, the effects of explosive decompression on the chest. Since the blast wave of meteoroid impact will probably be followed by a decompressive event, the mathematical model could be useful in predicting this complex interaction. Bowen and Holladay hope to be able to study this in the near future.

Tissue Pathology. Since atmospheric conditions appear to play a major role, the actual pathological physiology of blast injury is also of interest to the present study. There have been many reviews of this subject, but those of Clemedson³⁹ and, more recently, White²³⁵ appear to be the most excellent. Much of the pathology studied was produced by high-explosive fast-rising short-duration blast and is quite pertinent to the present problem. The general pathological picture after exposure to blast from small explosive charges corroborates the hypotheses of White²³³ regarding the basic biophysical factors involved. We shall present the material directly from the review of White.²³⁵ References to the actual experiments will not be included but may be found in White's paper.

If an animal is shielded from an otherwise fatal explosive charge by a steel box from which the head protrudes, there is no detectable damage providing the head and neck are padded to avoid violent contact with the steel wall of the box. This is so, even if a tracheotomy tube is attached to a funnel facing the charge, indicating that the propagation of the blast overpressures down the respiratory tree is not of primary significance. Other measures for protecting the trunk of the animal from the "blow" of the blast wave also give protection as illustrated by such things as a rigid plaster of Paris cover and appropriate padding with sponge rubber, but not a thin plaster bandage applied to the chest and abdomen to avoid overdistension of the thorax. Such observations suggest that it is the impact of the blast wave and overpressure against the body wall that is critical and not the negative phase of the pressure pulse. This view is also supported by the protection offered by experimental pneumothorax which if unilateral or bilateral offers considerable protection to the lung on the side of the pneumothorax.

Animals immersed hind feet first in water up to the diaphragm and exposed to an underwater charge show only abdominal pathology. When immersion of the abdomen and thorax is arranged, there is abdominal damage and also pulmonary lesions plus signs of central nervous system damage. These facts and those above, along with electrocardiographic signs of anoxic cardiac disturbances, suggest that gaseous emboli arising in the chest during or subsequent to the blast and migrating

via the circulation to the heart and central nervous system might be one important pathophysiologic event that could well prove fatal of itself.

Air emboli have been visualized by many investigators on the arterial side of the circulation in dogs, rabbits, guinea pigs, rats and man exposed to blast overpressures. Studies with experimental air emboli [injected by needle] have demonstrated that (a) injected air migrates to the most superior portions of the vascular system and the consequence to the animal is largely influenced by body position, and (b) the detailed anatomy involved and blood flow as well as the amount of intravascular gas are of considerable significance. There is an element of chance in certain experiments wherein a single air embolus may migrate into a large coronary

vessel or vital area of the central nervous system with death resulting in a few minutes. Almost immediate signs of severe and progressive anoxia of the myocardium demonstrable with the electrocardiogram are seen, both in blast and experimental arterial air embolism, with death often following fibrillation that develops fairly quickly.

In contrast, animals severely injured from blast do not die immediately but apparently suffer various degrees of broncho-venous or alveolar-venous fistulas through which air may enter the pulmonary venous circulation with each respiratory cycle "pumping" additional air into the circulation. The result can be massive air embolism involving the heart, brain and other organs. Further, it is important to recognize

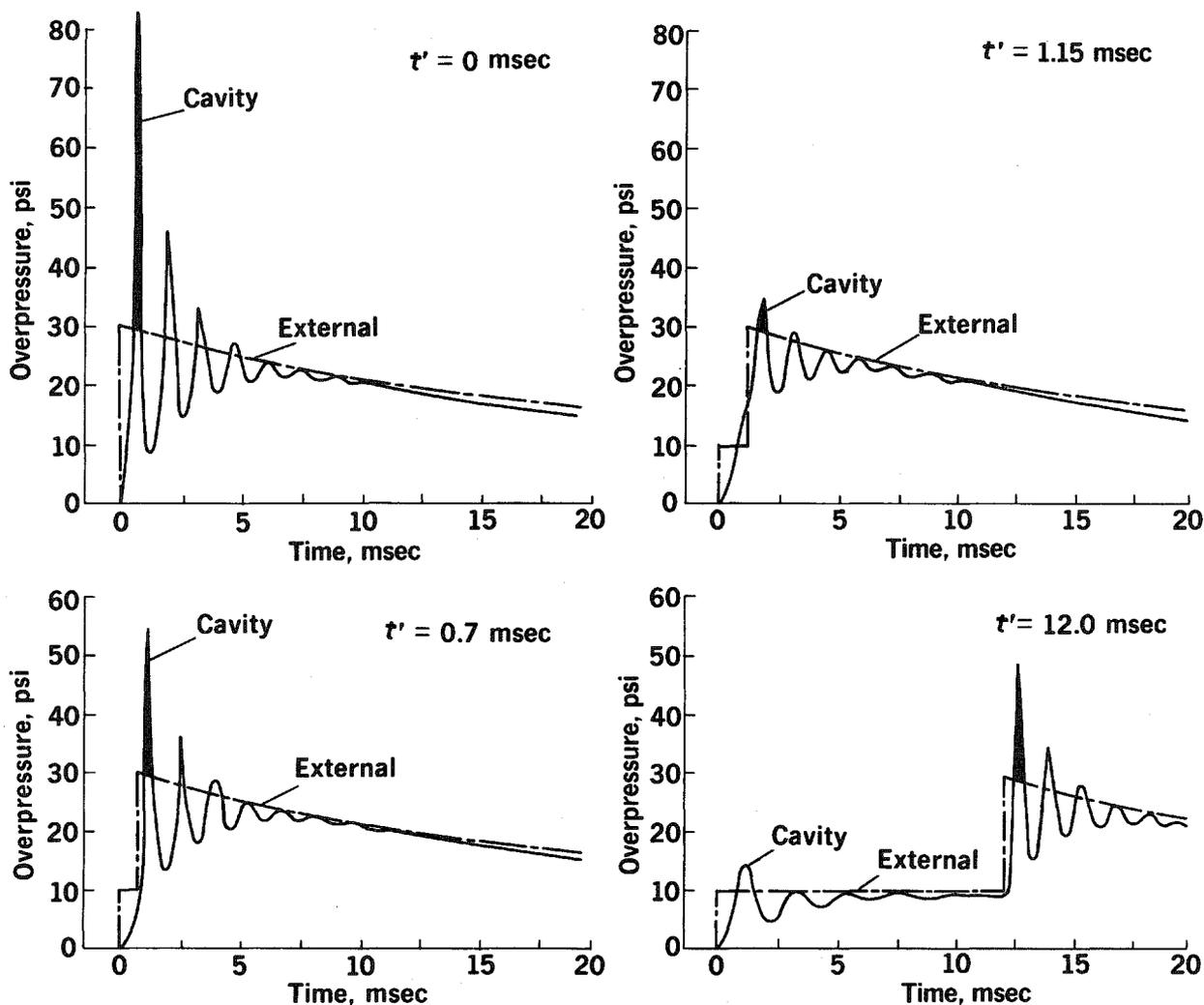


FIGURE 45.—Effect of stepwise pressure loading on pressure in simulated lung, i.e., cavity pressure. Time t' is duration of initial wave; darkened area is overshoot impulse. (AFTER BOWEN AND HOLLADAY.²³)

that under circumstances of moderate lung damage, pulmonary vasoconstriction and hemorrhage—particularly the latter—can act protectively in that the fluid “seals” the alveolar-venous or bronchovenous fistulas. An animal so situated may escape immediate death from emboli, but then faces the dangers from continued hemorrhage and edema. To these two factors, which in themselves embarrass the pulmonary circulation, are added the additional effects of transient circulatory arrest; bradycardia; lower systemic arterial pressure; vasoconstriction, followed by vasodilatation; increased venous pressure; and nonfatal, acute insult to the heart, signs of which are known to persist in some cases for days in animals and man. . . .

Additional observations bearing upon the existence of air emboli in animals exposed to blast include reports that: (a) electrocardiographic evidence of hypoxia and myocardial damage, which appear after exposure of animals to blast, can be reversed by use of a compression chamber; (b) animals, otherwise fatally injured by blast, can be saved but not invariably so by immediate compression; (c) the electrocardiographic changes following arterial air emboli are similar in man and animals to the findings after exposure to blast; and (d) compression markedly improves the electrocardiographic signs of coronary malfunction produced by experimental arterial air emboli.

The significant role of aeroemboli brings up the problem of simultaneous decompression which will occur immediately after the blast overpressure in space cabins. Expansion of the intravascular bubbles upon decompression will certainly aggravate the condition. Pressure suits at 5 psi may still present an aggravating pressure environment for the embolic condition. It would appear that a cabin atmosphere of 100 percent oxygen would be more favorable than one containing an inert gas. Aeroemboli would probably appear, but would be absorbed at a faster rate. Even if the cabin were to be self-sealing, a transient switch to a 100 percent oxygen pressure-suit environment after blast would probably be a wise move. This act would reduce the effects of whatever gas may be “pumped” into the circulation after the overpressure event is completed and would simultaneously protect against inhalation of residual metal oxides that may be floating about the cabin. Part I of this report covers the dangers of prolonged exposure to high oxygen tension after blast.

In addition to damage to the heart directly from coronary air embolism and indirectly from hemorrhage,

edema and the subsequent anoxia and dilatation, there apparently occurs significant bruising of the heart sometimes noted under the term “commotio cordis.” Internal and external hemorrhagic areas and bruising of the epicardium and myocardium do occur but rarely rupture. . . . The damage which can occur at air-fluid junctions due to differences in tissue density has been mentioned earlier. This, of course, can damage both the heart and the lung. In the former case, the pathologic signs and the immediate and persistent electrocardiographic findings can be, in part, a reflection of such injury and may involve early fatality or delayed effects in surviving animals. It is difficult, if not impossible under certain specific circumstances, to establish whether the critical etiologic factors involve air emboli or commotio cordis as the single cause of death or malfunction, if indeed, such is the case.

Various signs of focal damage to the central nervous system have been described involving lethargy and paralysis of the posterior extremities, . . . ataxia, and a variety of other symptoms . . . in water blast where the animals’ heads were not immersed. . . . [There have been] reported delayed electroencephalographic signs of circulatory disturbances or cerebral hypoxia in monkeys exposed to blast. From what is known today, air embolic insult to the central nervous system offers adequate explanation of nervous symptoms and pathology, and it is doubtful that the mechanism involving transmission of hydrostatic “shock” waves from the body fluids into the closed cranium . . . plays a significant role. It is conceivable that air embolism to vital nervous centers, particularly in animals exposed to blast with the head uppermost, can contribute to early death as well as to delayed focal signs.

Pathology is noted in the air-containing organs other than the lungs—that is, the ears, paranasal sinuses, and gastrointestinal tract. Symptoms of very mild blast, of course, are often related to the ears and sinuses. Rupture of the eardrum and sinus bleeding are probably not a threat to the organism. Rupture of the viscera is relatively rare unless total body displacement and impact also occur. Abdominal pathology is more prominent in underwater blast situations. However, ear damage may temporarily impair hearing and, therefore, communication is disturbed.

Though no precise explanations of the causes of death and the etiologic events applicable to blast can be set forth, it appears clear that: (a) direct damage to the heart can, but rarely causes death immediately; (b) coronary air emboli can and do produce almost immediate death, but typically the fatally injured animal expires in from 2 to 10 minutes; (c) suffocation due to hemorrhage and edema with concomitant hypoxia probably produces fatality in a somewhat

longer period, though it is not common for animals who survive 15 to 20 minutes to succumb later; (d) malfunction of vital centers of the central nervous system may be a factor in early death from massive air embolism which is to be distinguished from damage due to frank physical head trauma; and lastly (e) the animal escaping early death may face the challenge of delayed complications from post-concussion pneumonia, perforations of the abdominal viscera, peritonitis, prolonged coronary signs with possible infarction and persistent local areas of damage in the central nervous system.

Typical time curves of mortality appear in figure 46. Most animals are dead within 30 minutes. The initial steep portions of the curve (5 to 10 minutes) may be due to hemorrhage or massive arterial emboli involving the heart or central nervous system. The following less steep portion probably represents continued hemorrhage, aeroemboli, or progressive pulmonary edema. The flat part of the curve after 30 minutes is probably indicative of death due to continued pulmonary edema, prolonged subacute hypoxemia from lung damage, late hemorrhage, or progressive right-sided heart failure.

Translational Aspects of the Blast Hazard. Complicating the meteoroid blast effect is the actual movement of the astronaut by transla-

tional wind loads. Also, secondary to the blast is injury by missiles of disrupted cabin structures. Since these problems are not to any major degree dependent on the oxygen concentration within the cabin they will not be reviewed in detail. The absolute level of overpressure and, therefore, the wind effect is determined by the ambient density. The lower the density, the less wind effect in translation. The focusing of shock waves and other geometric blast anomalies created by cabin configurations and structures makes a theoretical assessment of the actual cabin problem most difficult. The studies of the Lovelace Foundation have covered translational impact damage and the geometric variables involved.^{232, 233, 234} These reports also cover the problem of secondary missiles arising from blast environments, as does the report of Bowen et al.²⁴

Thus, blast injury following impact by a large meteoroid presents a serious and complicated hazard. As has been pointed out, such an event can be expected only once in about every 30 years in a well-shielded, spherical 3-meter-diameter space cabin in the vicinity of the earth. In the asteroidal belt between Mars and Jupiter,

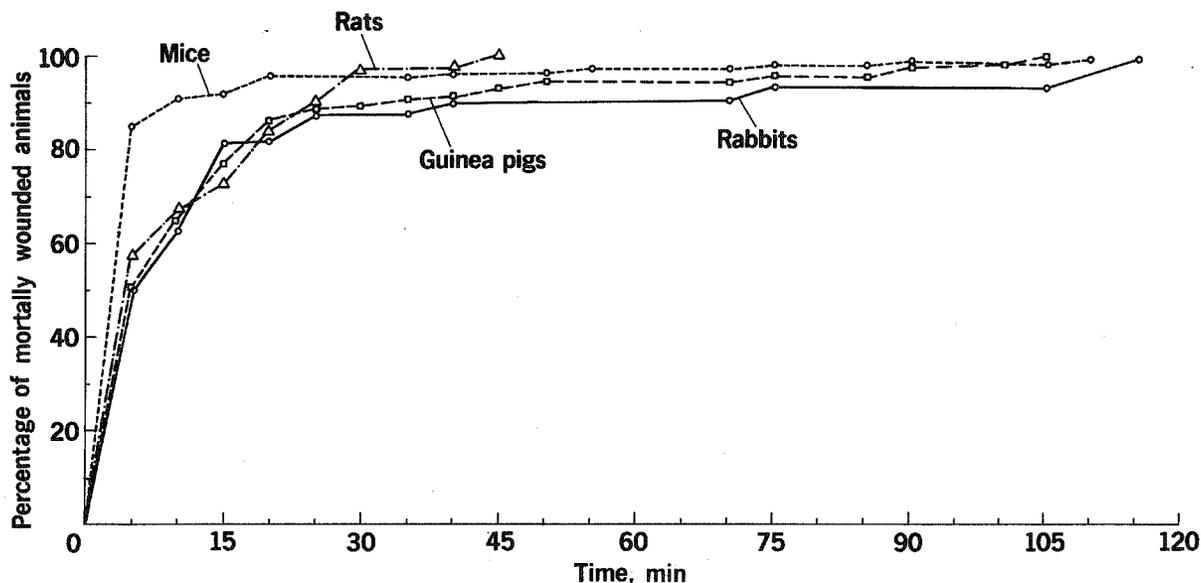


FIGURE 46.—Cumulative percentage of mortally wounded animals dying over a 2-hour period from exposure to sharp-rising overpressures of 3 to 4 milliseconds' duration. (AFTER WHITE.²³³)

the probability of such an event increases considerably. For missions of this type, it would be wise to review the therapeutic approaches to blast injury as outlined by White.^{233, 235} This problem will not be considered here beyond the coverage in Part I of this report.

Hazards to the Eye from Oxidative Flash Exposure

An area which has been studied in only a preliminary way is the eye hazard resulting from the oxidative flash of vaporized metals. It was mentioned earlier that McKinney found corneal burns associated with aluminum oxide particles embedded in the epithelium. The absence of obvious chorioretinal burns does not preclude flash-blindness problems. As was mentioned above, titanium targets gave flashes of greater intensity than did aluminum or steel. Magnesium targets would be expected to behave like titanium in this respect.

The study of Gell et al. at Ling-Temco-Vought⁸⁹ revealed that in 100 percent oxygen environments, even aluminum targets penetrated by hypervelocity particles gave light flashes of 20 million lumens or about the equivalent of 17 General Electric No. 5 flashbulbs. This was reported to be a light flux of 273,000 foot-candles (lumens/ft²), but the exact location of the detector relative to the diaphragms is not clear. The flash duration, as determined from camera frame analysis, was 0.8 to 1.2 milliseconds. How dangerous is this light flash to the human eye?

The general problem of high-intensity light flash has received much emphasis from those groups interested in nuclear flash effects and optical problems in orbital flight in near-solar orbits such as trips to the planet Mercury. These data will be reviewed briefly in order to extrapolate from the study of Gell et al. to the meteoroid flash hazard in humans.

Retinal Burns. Danger to the eyes from exposure to intense light fields has been well documented in case reports of eclipse blindness.¹¹⁵ The testing of atomic weapons resulted in additional cases of retinal burns from unprotected ocular exposure to the flash of the fireball.^{169, 185} Animal experimentation has established the concept that the mechanism is the same in both cases.^{31, 32, 237} Visible light is

concentrated upon the retina by the optical system of the eye, forming an image of thermal intensity as the light is absorbed primarily by the retinal pigment and converted into heat. If a critical amount of heat is generated, irreversible coagulative destruction occurs.³¹

Recent studies of retinal burns by coherent light (lasers)^{234, 255} approach the short durations found for simulated meteoroid flash in the Ling-Temco-Vought studies. Laser outputs of 0.1 joule per 0.5-millisecond pulse emitted in a coherent, monochromatic (wavelength 694.3 m μ) beam 1 cm in diameter produced burns in the eyes of adult pigmented rabbits. Pupils were dilated with Neo-synephrine and eyes were 30 cm from the emission face of the ruby. Lesions were similar to those in rabbits exposed to nuclear flash.³²

The estimated chorioretinal burn threshold for the dilated human eye is about 0.66 cal/cm²-sec.⁹⁶ It is calculated that the thermal level would be reached at 240,000 lumens/ft².¹⁵⁹ This would be present in most tactical exposures to nominal-yield nuclear explosions. Ham et al.⁹⁶ have predicted that the human retina would receive a threshold burn lesion at 9 to 14 miles from a 1 to 100 KT nuclear weapon if atmospheric visibility were 25 miles, maximum dark adaptation prevailed, and a normal blink reflex were present. A computer model for prediction of retinal burns has recently been presented by Wray.²⁴⁶ No actual testing of the model is reported.

Flash Blindness. In many flash exposures the energy absorbed will not be adequate to produce a retinal burn, but the effects of the light will be sufficient to cause an alteration in the sensitivity of the retina due to the excessive bleaching of the visual pigments of the rods and cones. In this case, transient visual impairment will result, lasting until the eye can readapt.

Three factors contribute to the relative scotoma and lowering of visual acuity during and following exposure of the eye to high-intensity light. These are glare from the light source, bleaching of the visual pigment with the resultant time interval necessary for readaptation, and afterimages. Because of the interrelationship of these three factors, the effects of

intense stimuli are complicated and difficult to estimate.¹⁵⁹

Glare is defined as any degree of light falling upon the retina in excess of that which enables one to see clearly; that is, any excess of light which hinders instead of helps vision. Glare can be further differentiated into:

(1) Veiling glare: created by light uniformly superimposed on the retinal image which reduces contrast and, therefore, visibility

(2) Dazzling glare: adventitious light scattered in the ocular media so as not to form part of the retinal image

(3) Scotomatic or blinding glare: produced by light of sufficient intensity to reduce the sensitivity of the retina.

Although all three types of glare are present in the case of high-intensity light, the effects of the first two are primarily evident only when the source is present. The third type, scotomatic or blinding glare, is especially significant in this study because it plays the greatest part in producing those symptoms (afterimages) which persist long after the light itself has vanished. The afterimage is a prolongation of the physiological processes which produced the original sensation response after cessation of stimulation. An afterimage may be experienced if the gaze is directed to a bright light bulb for a short time. If the bulb is then switched off an image of the bulb will continue to be perceived. This prolongation of the visual sensation shows that the processes which occur within the retina have persistence.

The afterimage is essentially a temporary blind area or scotoma in the field of vision. The time duration of this blind area is proportional to the intensity and duration of the light exposure. The greater the intensity and/or the longer the duration of exposure, the more intense and, to a certain extent, the more persistent the afterimage. Ordinarily, the sequence of events following stimulation of the retina by a flash of light is the primary sensation of light followed by a series of positive and negative afterimages. With moderate light intensities, afterimages are not noticed because of the complex action of successive stimulation and continuous movement of the eye. However, if the original

stimulation is of sufficient duration and intensity, the sensation will persist with an intensity adequate to reduce or entirely obliterate foveal perception until the effect is dissipated. This is the primary factor in flash blindness.

Before World War II several investigators attempted to relate the intensity of light flashes to the alterations in sensitivity of the dark-adapted eye. Their experiments utilize illuminances of less than 50 lumens/ft². They found no alteration in the course of dark adaptation and a general correlation with the reciprocity law for momentary losses of sensitivity.^{2,212} The reciprocity law indicates that within certain limits $L \times T = K$ when L is in units of luminance of the dazzle and T is the duration of the dazzle. This expresses a total summation with the effect being the same for a luminance decreased by one-half but maintained twice as long and one that is doubled but lasts half as long.

The development of the atomic weapon, with its attendant hazards, provided impetus for further investigation. Crawford, in 1946,⁵³ and Fry, in 1951,⁸⁶ utilized a light source of moderate intensity and confirmed the validity of the law of reciprocity. Whiteside, in 1952, attempted to simulate the dazzling effect of nighttime atomic explosions by using the sun as a light source.²³⁷ Several years later he reported on a method whereby he visualized from afar the flash of a 20 KT explosion, measured his recovery, and reported the time required to regain visual discrimination.²³⁸

More recently, Metcalf and Horn¹⁵⁹ reported an investigation they made on the effects of high-intensity light flashes on visual recovery. They studied the visual recovery of four human subjects after exposure to illumination ranging from 60 to over 12,000 lumens/ft² at the dilated eye (Neo-synephrine). Exposure times were limited to 0.1 second, the approximate human blink time. They found that recovery time plotted against illumination at the eye produced the curve seen in figure 47. This gives a straight line in a semilog plot, as seen for higher illuminations at the eye in figure 48.

As would be expected, the luminance of the object to be visualized after a flash determines

the recovery time. Figure 49 illustrates the change in recovery time when the luminance of the test target is varied. Each of the four points represents the average illumination and recovery time for 15 trials at the indicated test target luminance. The log of source of luminance for each of the four trials was 6.6810 (4,798,000 foot-lamberts). Average recovery time was 4.8 seconds for the 71 ft-l test target, 14.6 seconds for the 7 ft-l test target, and 35 seconds for the 0.45 ft-l test target. The dashed curves have been drawn with the slope of the regression line determined in the main experiment. Several points on these extrapolated curves were spot checked and found to be in close agreement. It is seen that recovery time is markedly reduced if instrument illumination is increased. For example, the normal luminance of red-lighted instruments has been found to vary from 0.02 to 0.05 ft-l,¹¹⁸ approximately equal to the readaptation test stimulus used in the major part of this experiment. Assuming 60 percent reflectance for the instrument dial

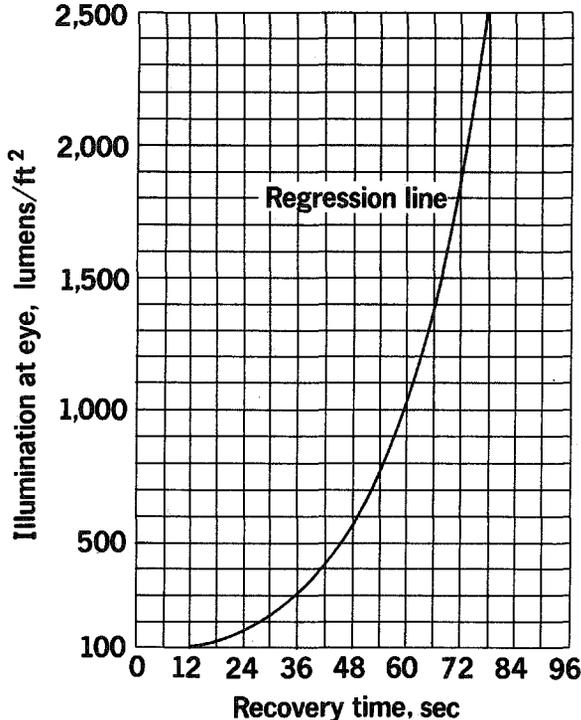


FIGURE 47.—Recovery as a function of illumination at eye. (AFTER METCALF AND HORN.¹⁶⁹)

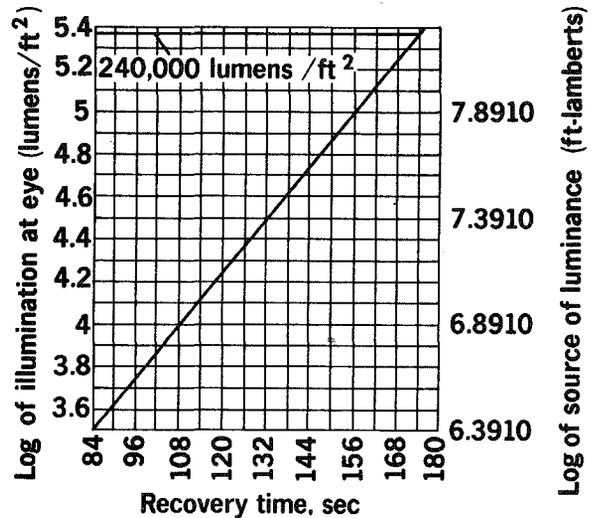


FIGURE 48.—Recovery as a function of log of illumination at eye. (AFTER METCALF AND HORN.¹⁶⁹)

and an illumination on the instruments of 65 lumens/ft², the recovery time would be reduced by a factor of 18. Thus, exposure to a luminance of 5,000,000 ft-l, comparable to viewing an overcast with a 50 percent reflectance illuminated by a normal weapon at a distance of 2 to 3 statute miles, would result in a recovery time of approximately 5 seconds as compared with about 90 seconds for ordinary, red-lighted instruments. The recent data of Severin and his associates^{198, 199} corroborate these recovery-time figures, but stress the variability from subject to subject in the slope of the recovery function (fig. 50). The pupillary factor was also demonstrated as seen in figure 51.

Do the recent Ling-Temco-Vought studies by Gell et al.⁸⁹ and McKinney¹⁴⁵ shed any light on the problem of recovery time after meteoroid flash oxidation inside space cabins? McKinney attempted a preliminary study of recovery of vision in rats exposed to flashes of about 273,000 lumens/ft² lasting periods of 0.8 to 1.2 milliseconds in the meteoroid impact chamber. Observations of surviving animals free of corneal burns suggested that they were blinded by the flash for at least 15 to 20 minutes. Blindness was determined by a crude conditioning experiment. The conditioning stimulus was a pencil poked at the corneas of the animals until a

uniform withdrawal was obtained by mere sight of the pencil. The conditioned animals were exposed to the impact flash and immediately retested for the withdrawal response. There was apparently a 15 to 20 minute lag from time of flash to first response. It must be pointed out that in these preliminary studies, there were no control animals blindfolded during the blast. The relative roles of noise, blast overpressure, hypoxemia, and light in the "visual disturbances" are still a matter which can be resolved only after a more definitive study.

How do these recovery times in the rats compare with those of humans exposed to light of similar intensity from other sources? The human experiments reported above suggest that the 15 to 20 minute recovery time is high for the light factor alone. The illumination of 273,000 lumens/ft² reported in the Ling-Temco-Vought experiments produced no retinal burns in spite of the 240,000 lumens/ft² estimated as the probable threshold for retinal burns in humans.¹⁵⁹ Species differences could, of course, play a role. It would appear, however, that an even greater factor is the geometry of

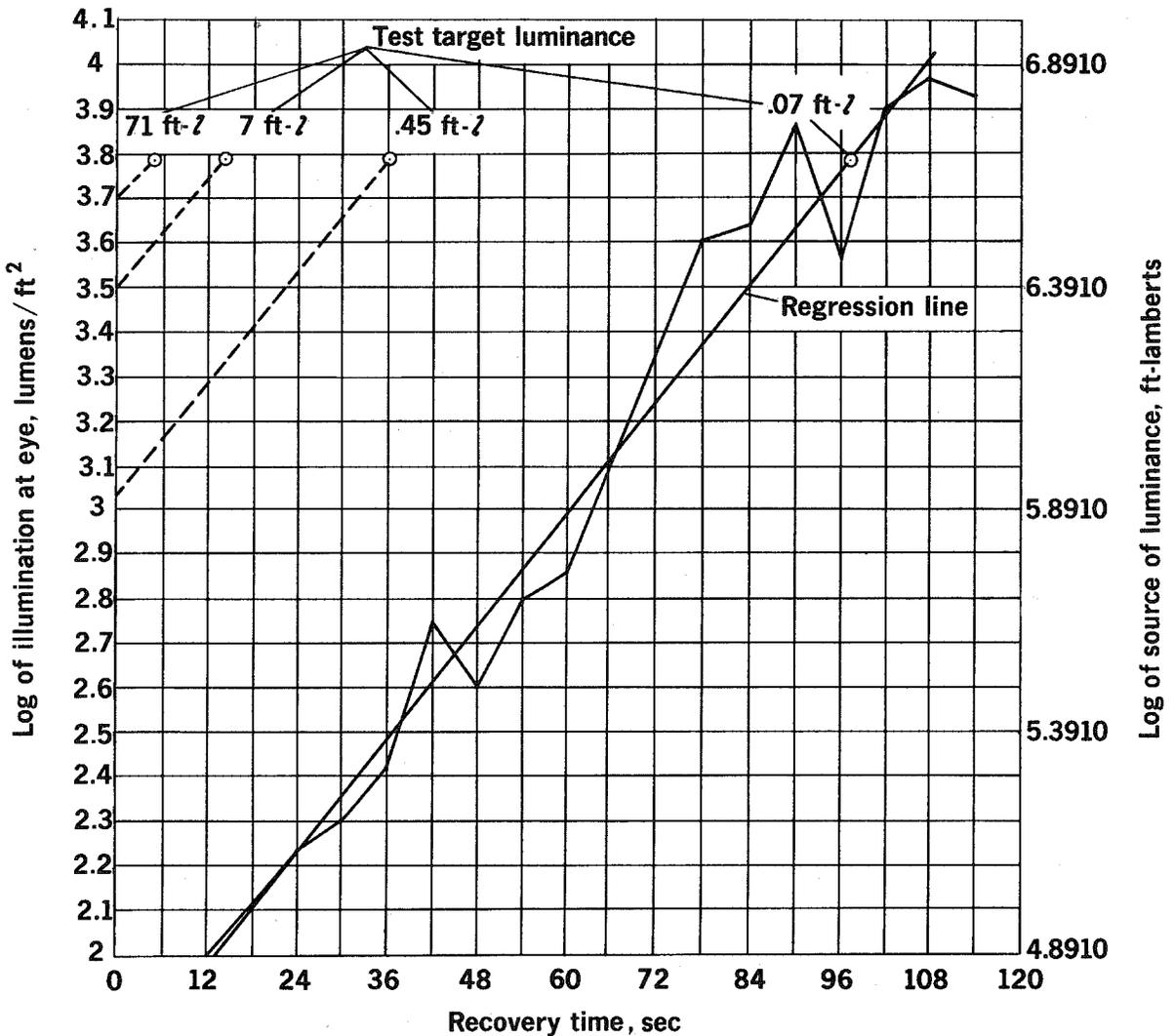


FIGURE 49.—Recovery as a function of test target luminance. (AFTER METCALF AND HORN.¹⁵⁹)

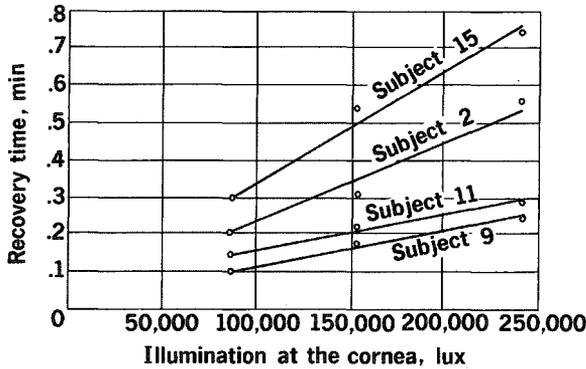


FIGURE 50.—Variability in recovery time from subject to subject. Luminance of testing patch was 0.06 ft-lambert. (AFTER SEVERIN ET AL.¹⁰⁹)

exposure. The thermal threshold for rabbits varies from 1.0 to 15 cal/cm², depending on image size, rate of energy delivery, and pulse shape.⁹⁶ In the human experiments the subjects were looking directly at the light source. The main penetrations of the diaphragms and probably the focal point of the flash in the Ling-Temco-Vought experiments were above and behind the rats' eyes. Thus the rats' eyes were probably exposed to much less illumination than actually reported in the test chambers. The light flash of only 0.8 to 1.2 milliseconds' duration in the Ling-Temco-Vought experiments precludes blinking. Visual recovery in the human experiments after exposure to 240,000 lumens/ft² for 0.1 second would be approximately 3 minutes (fig. 48). Yet, exposures to less than 273,000 lumens/ft² for only 0.001 second in the rat experiments required 15 to 20 minutes for recovery, or 5 to 7 times as long. Since the (Illumination × Time) factor appears to determine recovery time, it would seem that the relatively prolonged period of recovery in the rat is due to some peculiar quality of the light or, what is more likely, to the many complicating factors already mentioned in the meteoroid flash experiments. It cannot, at this time, be concluded that the light flash resulting from meteoroid penetration requires greater time for visual recovery than do light flashes of the same intensity and time from other known sources. It is obvious that much work is required in this area.

What does a meteoroid flash mean to the crew inside a cabin several yards in diameter? From the data of Gell and McKinney it would appear that the zone of flash oxidation produced by a meteoroid in the low velocity range extends only about 8 inches from the cabin wall. The problem of corneal burns would arise only if, by chance, the eyes were within this flash zone. There would also be a possibility of chorioretinal burn only if the crew were looking directly at and were close to the flash from such a small particle. The chances of being exposed to much larger meteoroids are even lower than those predicted for minimal penetration particles. It is only remotely possible that a large enough particle could enter a cabin and produce a flash large enough to blind the crew permanently without killing them or destroying the craft. It is very possible that the flash from even a minimal penetration particle would blind the crew for periods up to several minutes even when they were at the center of the cabin. What are the solutions to this flash problem?

The two obvious solutions to the meteoroid flash problem are either to prevent the light from reaching the eye or, if this is impossible, to increase the luminance of the instruments after exposure of the eye by flooding them with white lighting. Auxiliary storm lights have been used in aircraft for years to combat the relatively mild flash blindness (afterimage formation and loss of dark adaptation) resulting from exposure to lightning flashes. Such lights could be used after meteoroid

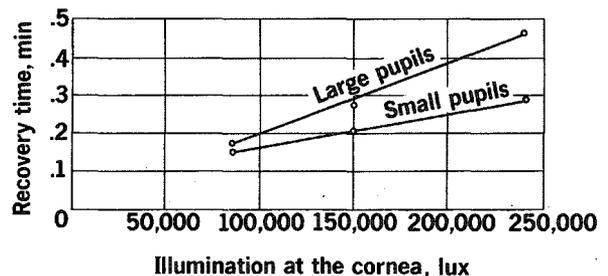


FIGURE 51.—Effect of pupil diameter on recovery times (mean for 15 subjects). Luminance of testing patch was 0.06 ft-lambert. (AFTER SEVERIN ET AL.¹⁰⁹)

flash as well. The problem of preventing light from reaching the eyes has been recently studied in the case of nuclear weapons. The use of reversible electroplating shutters and electrochemical light modulators with very rapid response time has been reviewed by Aitken¹ and Fox⁷⁹. Design specifications for current devices are for 50-microsecond maxi-

mum rise times and clearing in 1 second with an open-state transmission of 33 percent for visible light. Some crude early working models of these flash goggles are available, but they are not entirely satisfactory. It would appear that these devices will be of practical value only in missions involving the high-particle-density asteroid belts.

Problems of Fire Prevention and Extinguishment in Space Cabins

THE PROBLEMS of prevention and extinguishment of fires in space cabins are, except for a few specific situations, not much different from those at sea level or in aircraft conditions. The unusual atmospheric environment and limitations of space and firefighting equipment compound the general problem. The zero-gravity environment modifies firefighting procedures in a rather profound way and will be given detailed treatment in this report.

FIRE PREVENTION

The selection of optimum material with the lowest potential as an ignition source, the highest ignition temperature, slowest rate of combustion, lowest explosion potential, and lowest potential as a source of toxic combustion products is of paramount importance. These factors should be considered in choosing materials for use in the location categories of the following list, taken from Ciccotti.³⁵ It would seem that displays and controls, oxygen plumbing, and miscellaneous instruments should be upgraded to the category of "other potential fire sources."

Major potential fire sources:

- Power supply (nuclear reactor, solar cells plus batteries, or fuel cells)
- Navigation and communication equipment
- Attitude-stabilization system
- Rocket for initiating rotation
- Electrical wiring

Other potential fire sources:

- Air circulating and filtering equipment
- Temperature-regulating equipment

- Furniture
- Clothing
- G-load protective pallet
- Escape mechanisms (atmospheric reentry)
- Communication equipment, telemetering, monitoring
- Food-preparation equipment
- Emergency oxygen, water and food reserves
- Entertainment equipment
- Waste-disposal equipment
- Housekeeping equipment
- Safety equipment, hull-repair gear
- First-aid kit
- Atmosphere-analysis equipment
- Space suits
- Miscellaneous lines and cables
- Data-recording equipment
- Possible fire sources:*
 - Food-storage locker
 - Acoustic shielding
 - Insulation
- Improbable fire sources:*
 - Protective shell, gastight
 - Meteorite bumper (outer protective shell)
 - Humidity-control equipment
 - Plumbing for oxygen, water, etc.
 - Radiation shielding
 - Observation windows
 - Access doors, air locks
 - Fire extinguishers
 - Displays, controls
 - Utensils, tools
 - Observation aids
 - Internal partitions, decks
 - Miscellaneous instrumentation

Much of the discussion that follows has been stimulated by the reports of Ciccotti³⁵ and the Lockheed-California Company.¹³⁶

Structural Materials

Current design concepts of aerospace craft attempt to limit the amount of combustible materials to the minimum required for pilot comfort and capsule operation. Examples of combustible materials that should be minimized or possibly eliminated from space cabins have also been given by Ciccotti.³⁵

| | |
|-----------|-------------------|
| acrylics | polyesters |
| cellulose | polyethylene |
| cotton | polystyrenes |
| enamel | rayon |
| epoxy | rubber |
| grease | shellac |
| lacquer | silk |
| lanolins | Teflon |
| leather | varnish |
| magnesium | vinyls |
| neoprene | vulcanized fibers |
| nylon | wood |
| paints | wool |
| phenolics | |

There is, of course, an irreducible minimum. Clothing and maps fall into this category as do books and papers required for normal mission work and, on extended trips, for relaxation. The foam rubber or foam plastics in seats are also required. Although these materials have relatively high spontaneous-ignition temperature, they are often placed near potential "hot spots." This should be avoided. Fireproofing of fabrics should be accomplished, keeping in mind the principles of oxygen effects outlined in Chapter 2. No material which supports combustion in high-oxygen environments after the ignition source is removed should be used. These tests should be performed at the maximum temperature expected at the potential locations within the cabin. Textiles and papers should all be made flame-resistant to this degree, and the flame-resistant treatment should be unaffected by aging, dry-cleaning, or laundering. Flammable waste and baggage should be isolated in flameproof

aluminum-alloy containers or compartments. Some of the newer high-temperature non-metallic materials such as perfluoroalkyl triazine elastomers have been discussed in a recent review.¹²²

Magnesium should be avoided in potential fire zones whenever possible, since it can be ignited relatively easily by burning flammables used in flight vehicles. As has been discussed in the section on meteoroid penetration, magnesium supports combustion under certain conditions, especially in high-oxygen environments.⁴⁶ When magnesium casings are used, if they are completely filled with a reasonable bulk of fluid the fire resistance is generally satisfactory. Magnesium parts should be coated with a fire-retarding coating which prevents "weeping out" of easily ignitable eutectic material and contains molten material to some extent.^{49, 136}

When magnesium is used in high-speed rotating equipment, it should be tested for failure conditions which cause high friction temperatures, since ignition of magnesium by friction can occur, and criteria have not been established for analytical evaluation of the potential hazard condition. (See Chapter 1 of this report.)

Electrical Insulation and Plastics

The electrical insulation problem has been covered in Chapter 4. It would appear that basic glass-fiber or asbestos insulation with silicone or fluoroplastic binders would be the safest. Polyvinyl chlorides should be avoided.

Hydraulic Fluids

The presence of hydraulic lines, pumps, and actuators within cabins should also be avoided. The problem surrounding the dieseling effect, spraying, and hot-plate combustion of these materials with high spontaneous-ignition temperatures should be kept in mind whenever operational necessity requires these materials within cabins. If design priorities require the hydraulic systems within cabins, the flame hazard in high-oxygen environments, as outlined in Chapter 3, should be kept in mind as a major criterion in the choice of fluid.

TABLE 19.—*Thermal Properties of Liquid Rocket Oxidizers* [AFTER LOCKHEED-CALIFORNIA CO. 136]

| Oxidizer | Formula | Molecular weight | Freezing point, °F | Boiling point, °F | Liquid density, gm/cc | Viscosity, centipoises | Comments |
|--------------------------|---|------------------|--------------------|-------------------|------------------------|------------------------|--|
| Bromine pentafluoride | BrF ₅ | 174.92 | -78.34 | 104.54 | 2.466 at 77° F | No info | Equipment must be kept clean to prevent possibility of fire and explosion. Reacts explosively with most organic substances and very rapidly with many inorganic compounds. |
| Bromine trifluoride | BrF ₃ | 136.92 | 47.84 | 260.6 | 2.843 at 47.8° F | No info | |
| Chlorine trifluoride | ClF ₃ | 92.457 | -117.4 | 52.34 | 1.75 at 68° F | No info | |
| Fluorine | F ₂ | 38.0 | -369.4 | -306.4 | 1.108 at -305° F. | 0.555 at -303.2° F. | Gas and liquid ignite nearly anything. |
| Hydrogen peroxide | H ₂ O ₂ | 34.016 | 30.4 | (**) | 1.543 at 60° F | 1.272 at 67° F | May cause spontaneous combustion if allowed to remain in contact with readily oxidizable organic materials. |
| 90% hydrogen peroxide | 90.0% H ₂ O ₂ 10.0% H ₂ O. | 31.24 | 12.7 | 285 | 1.3922 at 68° F | 1.301 at 64.4° F | Explosive hazard due to catalytic decomposition if tanks are not vented. |
| Iodine pentafluoride | IF ₅ | 221.91 | 47.3 | 206.6 | 3.50 at 206.6° F | No info | Liquid oxygen mixed with organic substances is explosive. |
| Liquid oxygen | O ₂ | 32.0 | -361.12 | -297.4 | 1.14 at -299.2° F. | 0.119 at* -250° F. | |
| Nitrogen tetroxide | N ₂ O ₄ | 92.02 | 12 | 70 | 1.45 at 68° F | 0.4720 at 48-47° F. | Not flammable but supports combustion. |
| Ozone | O ₃ | 48 | -313.78 | -168 | 1.46 at -168° F | 1.42 at -297.4° F. | Gas and liquid are explosive. |
| Oxygen fluoride | OF ₂ | 54 | -370.84 | -228.64 | 1.53 at -228.64° F. | 0.2826 at -229° F. | Spark explodes moist gas but not dry gas. |
| Nitrogen trifluoride | NF ₃ | 71.01 | -357.88 | -184 | 1.537 at -200° F. | No info | Explodes on contact with organic matter. |
| Perchloryl fluoride | ClO ₃ F | 102.3 | -230.8 | -52.2 | 1.434 at 68° F | 0.184 at 68° F | Forms explosive mixture with organic materials. |
| Red fuming nitric acid | 84.0% HNO ₃ * 14.0% NO ₂ 2.0% H ₂ O. | 59.09 | -50 | 140 | 1.573 (max.) at 60° F. | 1.37 at 77° F | |
| Tetra-nitro methane | C(NO ₂) ₄ | 196.042 | 55.4 | 258.3 | 1.65 at 55° F | No info | Very explosive, tricky, undependable. |
| White fuming nitric acid | 97.5% HNO ₃ * 2.0% H ₂ O 0.5% NO ₂ . | 59.912 | -45 | 186 | 1.46 to 1.52 at 68° F. | 0.84 at 68° F | Explosive with hydrocarbons and organic material. |

*Average composition.

**Decomposes before boiling.

Propellants

Whenever possible, rocket propellants for self-maneuvering devices should be stored outside the cabin. Refilling of these personal devices should be performed in parts of the cabin which are well isolated from the crew compartments. All precautions used in launch-pad environments should be followed. A matter frequently overlooked in the handling of fuel is the static charge built up by friction during loading of tanks and containers.¹³⁶ In the past, explosions have arisen from this ignition source. It is possible, but not probable, that the sloshing of combustible fluids in flight can build up a charge to some degree. The presence of inerting agents in the gases pressurizing these fuel tanks can considerably reduce this hazard.

Whenever possible, fuel or oxidizer materials inside cabins should be selected for highest freezing point, highest boiling point, highest autoignition point, and narrowest limits of flammability. Tables 19 and 20 review some critical properties of these fluids. Design of pipes should include the optimum diameters and loopings to keep detonation hazards to a minimum (see Chapter 1). The engineering considerations in safe storage and handling of specific propellants and oxidizers have been outlined in the Lockheed report¹³⁶ and will not be detailed here. It must be remembered in dealing with oxygen or other oxidizers that most are shock sensitive; that is, they tend to cause an explosion or a fire in combination with a combustible such as oil, grease, dust, lint, metal chips, some valve-seat material, rust, and so on. Valves in oxidizer systems should, therefore, be of the type which do not allow quick opening, whenever quick opening can cause a hazardous surge shock, or the surge should be reduced to a safe level by proper orifices.^{10, 63, 175}

Ignition Sources

The many sources and conditions for ignition were outlined in Chapter 1. Basic design features of space cabins should, of course, avoid these conditions or reduce them to a

minimum. General approaches are listed below and discussed in the following paragraphs.¹³⁶

(a) Avoid whenever possible equipment which may cause ignition in flammables, especially in areas of potential leakage of flammables.

(b) Make equipment and lines containing hot gases or hot air as leakproof as possible by proper design.

(c) Insulate, shroud, or cool hot surfaces.

(d) Arrange ignition sources remote from liquid flammables and combustibles.

(e) Separate ignition sources from combustibles and flammables by compartmentation or other equally effective means.

(f) Prevent sparking and arcing of electric or electronic equipment.

(g) Prevent static discharge sparks.

(h) Make electric and electronic equipment explosion proof.¹⁷³

It has been pointed out in Chapter 1 that hot gases are ignition sources if their temperatures reach or exceed the hot-gas ignition temperature of a flammable fluid, vapor, or gas. Therefore, whenever possible, equipment and/or lines carrying hot gases should not be located in a compartment with potential leakage of flammables if the hot-gas temperature is equal to or exceeds the minimum hot-gas ignition temperature of the flammable minus 50° F. Thus:

$$\text{Max. temp. of hot gas} < (\text{Min. hot-gas-ignition temp. of material} - 50^\circ \text{F})$$

If hot-gas equipment and/or lines are located in a compartment with a potential flammable leakage, they should be optimally protected against occurrence of leakage.

For hydrocarbons the hot-gas ignition temperature is roughly twice the autogenous ignition temperature in °C, whereas for hydrogen and carbon monoxide it is only slightly higher than the spontaneous-ignition temperature. If the potential fire and explosion hazards due to hot-gas ignition are to be evaluated for flammables for which the ignition temperatures under high-oxygen conditions are not known, the ignition temperatures should be established by testing.

TABLE 20.—*Thermal Properties of Liquid Rocket*

| Fuel | Formula | Molecular weight | Freezing point, °F | Boiling point, °F | Liquid density, gm/cc |
|--------------------------|---|------------------|--------------------|-------------------|-------------------------|
| Aluminum trimethyl..... | Al(CH ₃) ₃ | 72. 072 | 59 | 258. 98 | 0.8 at 68° F..... |
| Anhydrous ammonia..... | NH ₃ | 17. 03 | -107. 86 | -28. 03 | 0.6386 at 32° F..... |
| Aniline..... | C ₆ H ₅ NH ₂ | 93. 124 | 21. 02 | 364 | 1.022 at 68° F..... |
| Decaborane..... | B ₁₀ H ₁₄ | 122. 312 | 211. 5 | 415. 4 | 0.78 at 212° F..... |
| Diborane..... | B ₂ H ₆ | 27. 69 | -265. 9 | -134. 5 | 0.43 at -187.6° F..... |
| Ethylene oxide..... | (CH ₂) ₂ O..... | 44. 05 | -170. 5 | 51. 3 | 0.8711 at 68° F..... |
| Propyl nitrate..... | C ₃ H ₇ NO ₃ | 105. 094 | < -150 | 231 | 1.059 at 59° F..... |
| UDMH..... | (CH ₃) ₂ NNH ₂ | 60. 1 | -70. 7 | 144. 5 | 0.7782 at 80° F..... |
| Ethanol..... | C ₂ H ₅ OH..... | 46. 068 | -173. 47 | 173. 3 | 0.7894 at 68° F..... |
| Furfuryl alcohol..... | C ₄ H ₃ OCH ₂ OH..... | 98. 10 | -23. 8 | 339. 8 | 1.135 at 68° F..... |
| Liquid hydrogen..... | H ₂ | 2. 016 | -434. 56 | -422. 99 | 0.070 at -423.4° F..... |
| Isopropyl alcohol..... | C ₃ H ₇ OH..... | 60. 094 | -129 | 180. 2 | 0.785 at 68° F..... |
| Methanol..... | CH ₃ OH..... | 32. 04 | -144. 22 | 148. 5 | 0.7915 at 68° F..... |
| Pentaborane..... | B ₅ H ₉ | 63. 172 | -52. 28 | 140. 11 | 0.61 at 68° F..... |
| Anhydrous hydrazine..... | N ₂ H ₄ | 32. 05 | 34. 05 | 236 | 1.005 at 68° F..... |
| Hydrazine hydrate..... | N ₂ H ₄ ·H ₂ O..... | 50. 06 | -40 | 245. 3 | 1.035 at 68° F..... |
| Diethylenetriamine..... | (NH ₂ C ₂ H ₄) ₂ NH..... | 103. 1 | < -38 | 404 | 0.948 at 77° F..... |
| U-Deta..... | | 72 | < -121 | 161 | 0.858 at 60° F..... |
| JP-4..... | | 125 | -76 | 296 | 0.825 at 60° F..... |
| JP-5..... | | 169 | -40 | 432 | 0.845 at 68° F..... |
| JP-6..... | | | -65 | 250 | 0.840 at 68° F..... |
| RP-1..... | | | -40 | | 0.815 at 68° F..... |

* OC=open cup; CC=closed cup.

In regard to item (c), keep the surface temperature of any component that is in an area of potential leakage of flammables or in a flammable-containing tank, line, or device below a temperature that is equal to the most applicable minimum autogenous ignition temperatures of the flammable minus 50° F. Thus:

Max. surface temp. < (Min. autogenous ignition temp. - 50° F)

If surface temperature exceeds the maximum allowable, insulation, compartmentation, or equivalent protection should be provided. A careful comparison should be made between the maximum theoretical surface temperatures of

components and the maximum allowable surface temperatures over the entire ground and flight regime of the vehicle under normal and abnormal conditions. The unusual conditions which should be especially considered are ground crashes, abnormal and emergency descent, and overheat conditions. In these reviews, consideration should be given to the fact that reduction or elimination of convection and reduction of heat dissipation at high altitudes and in space can create high-temperature hot spots on operating equipment.

Item (f) can be complied with by the use of capacitors across potential arc points; by use of abrasion-resistant electric wiring; by enclosure of wiring which has inadequate abrasion resistance in rigid or flexible conduits; by

Fuels [AFTER LOCKHEED-CALIFORNIA CO.¹³⁶]

| Viscosity, centipoises | Flash point,* °F | Auto- ignition, °F | Flammability limits | | Comments | |
|-----------------------------|---------------------|--------------------------|------------------------|-------------------|--|---|
| | | | Lower, percent | Upper, percent | | |
| No info..... | ----- | ----- | ----- | ----- | Spontaneously flammable in air, decomposes explosively in water. | |
| 0.00982 at 68° F (gas)..... | ----- | 1, 204 | 16 | 25 | Unstable to sudden heat and sunlight. | |
| 5.299 at 59° F..... | 158 OC, 168 CC..... | 1, 415 | ----- | ----- | Vapor explosive when mixed with air. | |
| Solid at room temp..... | ----- | ----- | ----- | ----- | Explodes in O ₂ at 212° F, stable in air. | |
| 0.245 at -197.3° F..... | ----- | ----- | 25 | 75 | Flashes at very low temperature. | |
| 0.32 at 32° F..... | <0..... | 804.2 to 1,060 | 3.0 | 100 | Extremely flammable. | |
| 0.51 at 100° F..... | 70 OC, 68 CC..... | 379 | 2 | 100 | Classified by ICC as nonflammable. | |
| 0.405 at 104° F..... | 34 OC, -6 CC..... | 454 | 2.5 | 95 | | |
| 1.075 at 77° F..... | 54 OC..... | 700 | 3.28 | 18.95 | | |
| 5.6 at 68° F..... | 167 OC..... | 915 | 1.8 | 16.2 | | |
| 0.0139 at -423.4° F..... | ----- | 1, 076 | 4 | 74.2 | | |
| 2.3 at 68° F..... | 53 CC..... | 750 | 2.02 | 12 | | |
| 0.623 at 59° F..... | 52 CC..... | 878 | 6 | 36.5 | | |
| 0.342 at 55.8° F..... | ----- | ----- | ----- | ----- | | |
| 0.95 at 68° F..... | 124 OC, 104 CC..... | 329 | 4.7 | 100 | | Sudden exposure of even small quantity of liquid to air will result in explosion. |
| 2.0 at 68° F..... | ----- | ----- | ----- | ----- | | May cause spontaneous combustion. |
| 6.6 at 70° F..... | ----- | ----- | ----- | ----- | Dangerous. | |
| 1.96 at 60° F..... | 46 OC..... | ----- | ----- | ----- | Low fire hazard. | |
| 0.83 at 60° F..... | <0..... | 484 | .8 | 5.63 | | |
| 2.2 at 68° F..... | 140..... | 473 | .6 | 4.53 | | |
| ----- | ----- | 450 | .6 | 3.7 | | |
| 16.5 (cs)..... | 110..... | ----- | ----- | ----- | | |

proper support of electric wiring; by protection of wiring against pulling out of connectors, terminals, and ground studs; and by proper grounding.

All electric and electronic equipment and wires with sufficient energy to ignite flammables should be considered as ignition sources, regardless of how well they are protected. Only low-energy electric or electronic equipment which has been demonstrated not to be an ignition source for all flammables concerned, under any possible oxygen environment and under any failure condition, should be considered safe. Electric equipment and wiring should be located as remotely as possible from components carrying flammables and oxidizers. If this is not possible, electric equipment and

wiring should be arranged above and not below components carrying flammable fluids and oxidizers.

Sealed-type electric connectors should be used in potential fire zones. The connector materials should not be adversely affected by fluids such as fuel, oil, and cleaning agents or by temperature. All these connectors should either be safetied or be of a type that is inherently safetied. The wall connectors for electric wires should be made so that they do not allow propagation of flames through them under the most severe conditions of fire, vibration, and duration of exposure likely to occur at their location.

The wall connectors for fire detection and fire extinguishing systems should operate properly

under the most severe conditions of fire, vibration, and duration of exposure likely to occur at their location. Fire-wall connectors for other fire control equipment should operate properly under the most severe condition of fire and vibration likely to occur at their location for at least 5 minutes. If connector failure occurs after this time, the failure should not cause actuation of the attached equipment.

To prevent static discharge sparks (item (g)), reduce electrostatic accumulation by use of semiconducting material on external plastic surfaces, by bonding of isolated metal surfaces to basic structure, and by use of static dischargers located remotely from explosive materials or vents.¹⁷³

To make electric and electronic equipment explosion proof¹⁷³ (item (h)), all electric equipment including connectors, terminal blocks, and ground studs located in compartments with flammables or possible flammable leakage should be explosion proof. The following methods of making electric equipment explosion proof are acceptable:

(i) Using flameproof casings and structures: The criteria for flameproofing must be containment of flames and prevention of ignition. Explosion-proof testing should be conducted with the combinations of flammables and air or flammables and oxidizers which are likely to contact the equipment; or with substitutes of proven equal ignition and flame-propagation characteristics. The testing should be performed at ground level and at altitude, with a mixture ratio and pressure which is most conducive to flame propagation and ignition.

(ii) Enclosing in a hermetically sealed case.

(iii) Potting or coating: Only potting and coating material which will not be ignited by overheating or failed electric equipment should be used.

Details regarding engineering practices suggested for accomplishing the above may be found in the Lockheed report.¹³⁸

Maintainability, Accessibility, and Inspectability

Good maintainability, accessibility, and inspectability are absolute requisites for preserving the functional integrity which is necessary for prevention of fires and their spread,

and for timely and easy detection of hazardous conditions.

All equipment containing flammables or constituting an ignition source should be easily accessible without removal of the equipment or surrounding parts in the area. All seams, connectors, flanges, seals, and so forth, of flammable fluid and oxidizer systems should be easily inspectable. Fuel and oxidizer line connectors should be easily maintainable with standard tools to assure proper tightening by maintenance personnel.

Access doors in fire barriers separating potential fire zones should be constructed so that service handling or flame exposure does not damage them to such an extent that fire is permitted to spread to the adjacent zone. Access doors should not be used in any barrier which separates a combustion-system area from the rest of the vehicle.

In laying out the interior cabin design, the limited volume must not be allowed to overshadow the consideration of equipment accessibility. A fire in the back of an instrument panel in which relatively large chassis were closely fitted would necessitate flooding the entire compartment with extinguishing agents even if the fire were in one localized area. Attempts should be made to avoid placing in obstructed locations any items that would be apt to overheat or burn. This, of course, can be done only after matters of greater design priority have been met. The accessibility factor, however, is very often overlooked.

Compartmentation and Isolation

Concepts that place electrical equipment and auxiliary power systems in completely separated unpressurized compartments greatly reduce the probability of fire. However, the arcing of electrical contacts in these vacuum environments must be kept in mind. Lack of gas for convection cooling in extracabin vacuum areas may also create unexpected hot spots adjacent to the cabin wall. These should be avoided by appropriate design practices. The cooling systems for nuclear or direct solar heating power units may be at a very high temperature and should be kept as far from the cabin wall as possible.

A much overlooked factor in cabin design is the location of redundant items. Because of the relatively short "free-mean-life-to-failure" of certain critical electronic components, two- or three-time redundancy features need to be employed to increase the probability of continuous operation. Generally, this is done by placing items side by side. Very often the fact is overlooked that fire or explosion hazards in the vicinity of, or even within, one of the redundant units may incapacitate the others. By planning the separation of these items in isolatable compartments, this loss of effective overall redundancy can be avoided. The redundancy of firefighting equipment in each of these compartments would appear to be a worthwhile goal.

Materials used for fire barriers should prevent flame penetration and/or propagation under the most severe conditions of fire, vibration, and duration of exposure likely to occur at their location. Aluminum alloy or equally fire-resistant materials should be used for ventilation flow-control barriers. As discussed above, magnesium should be avoided in barrier design.

Baggage and cargo compartments should have no electric or flammable equipment except compartment lights and fire detectors. Electric wiring and lines carrying flammable materials should be excluded from baggage and cargo compartments or they should be separated from each other and from the compartments by rugged fire-barrier materials. Inaccessible compartments containing combustibles should have fire or smoke detection equipment, and built-in extinguishing equipment wherever possible. Walls of these compartments should also be as "airtight" as possible to restrict oxygen in case a fire does start.

The Civil Aeronautics Manual 4b characterizes four classes of compartments and Asadourian⁷ has outlined optimum means of protection for each class. Table 21 represents this classification.

Exceptionally Hazardous Equipment

There are many extremely hazardous devices which might find their way in and about space cabins. These will be only briefly outlined:

(1) Electroexplosive systems such as igniters, squibs, flares, destructors, ejectors, and so forth. Ammunition for firearms is included in this category.

(2) High-pressure gas compressors such as those found in hydraulic systems, moisture separators, and refrigeration systems. The problems of dieseling effects and lubrication failures in these devices have already been discussed in Chapter 1.

(3) High-speed rotating equipment.

(4) High-pressure vessels and lines (up to 7,500 psi).

(5) Electric batteries, regardless of chemical systems involved (silver oxide-zinc, silver oxide-cadmium, nickel oxide-cadmium; all with potassium hydroxide electrolytes). Any battery will emit gas during charge if the charging end voltage is exceeded. Both oxygen and hydrogen are released and create a serious hazard. Vented batteries with pressure-relief valves are preferred over sealed units. Hydrogen-oxygen fuel cells require consideration.

(6) Oxygen-breathing systems. Much of this problem has been covered in Chapter 1 and in references 18, 63, 64, and 183.

Whenever possible, these systems should be located outside of the manned cabin and should be isolated from the cabin by the appropriate barriers.

Crash-Fire Prevention Systems

A fire resulting from crash landing of a space vehicle may compound the hazard of an otherwise minor crash and make rescue difficult. Crashes in uninhabited areas will probably be the rule and require that the emergency be handled entirely by the crew. It is in crash conditions that ignition sources such as hot surfaces, friction sparks from abrading metal, exhaust flames, and electric sparks and arcs are more important than the others, though just about any ignition condition may exist. The fuel types span the range already discussed, but combustible fluids and vapors play a more significant role in crashes than in the usual flight mishaps.

The capacity to jettison hazardous materials helps enormously in prevention of crash fires

and is probably the greatest major design factor that can be brought to bear. Friction sparks from the undercarriage striking the ground can be reduced by avoiding the use of magnesium, titanium, or steel in these structures. Emergency relief of high-oxygen atmospheres within the cabin is also desirable. The emergency shutdown of all electrical and combustion systems not necessary for landing also helps. Emergency circuits required for cabin escape should be well protected from potential crash damage and be isolated in areas of low fire probability.

FIRE-HAZARD DETECTION

The prediction and detection of conditions predisposing to fire or representing incipient flame conditions in flight vehicles have been studied by Cary et al. at the Battelle Institute.³³ The engineering aspects of this problem have been reviewed by Lockheed-California

Co.¹³⁶ In general, it is felt that detectors should be employed only when proper action can be taken either to reduce or eliminate the hazard or to save the crew by immediate abortion of the mission. In space missions the last possibility is, except for limited periods in the flight plan, quite remote. Detectable hazards within the cabin will probably lead to either automated mechanical action or human effort to eliminate the hazard.

One should consider as detectable harbingers of impending fire hazard high temperatures, ignitable or toxic vapors, and the highly dangerous open flame. High temperatures, if recognized in time, may be reduced by "throttling" the heat source. Ignitable and toxic vapors may be evacuated and the source closed. The open flame, however, requires immediate quenching action on the ignition source, activation of fire-extinguishing apparatus, or abortion of mission.

TABLE 21.—*Fire-Control Provisions for Various Types of Baggage and Cargo Compartments*
[AFTER ASADOURIAN⁷]

| Class* | Characteristic | Means of fire protection |
|--------|--|---|
| A | Fire is easily discernible and is accessible in flight. | Hand fire extinguisher for each baggage and cargo compartment. |
| B | Sufficient access to baggage and cargo compartment in flight to move contents and to extinguish. | Separate system of smoke or fire detectors and hand fire extinguishers for each baggage and cargo compartment. No hazardous quantities of smoke, flames, or extinguishing agent should enter crew or passenger compartments when access to the baggage and cargo compartment is opened. The compartment should be lined with fire-resistant material. |
| C | Fire is not easily discernible and is not accessible in flight. | Separate systems of smoke or fire detectors for each baggage and cargo compartment with built-in fire extinguishing system. No hazardous quantities of smoke, flames, or extinguishing agent should enter crew or passenger compartments. Control of ventilation and draft within each baggage and cargo compartment so agent can control fire. Baggage and cargo compartment should be lined with fire-resistant material. |
| D | A fire occurring will be completely confined without endangering the vehicle or the occupants. | Neither flames nor smoke or other noxious gases should enter crew or passenger compartments in hazardous quantities. Ventilation and draft within compartments should be controlled.** Compartments should be lined with fire-resistant material. No critical effects should be caused by heat on adjacent parts. |

*The classification is adopted from paragraph 44.383 of the Civil Aeronautics Manual 4b.

**For compartments in class D having a volume not in excess of 500 cu ft, an airflow of not more than 1,500 cu ft per hour is considered acceptable. For larger compartments lesser airflow may be applicable. For measuring baggage compartment leakage rates, see CAA TDR No. 146.

The following types of detectors have been used in flight vehicles or have been projected for future use:

- (a) Flame detectors—visual or automatic
- (b) Heat detectors—unit and continuous
- (c) Smoke detectors—photoelectric
- (d) Carbon monoxide—infrared absorption
- (e) Vapor detectors—time-of-flight mass spectrometers, nondisperse infrared spectrophotometers, and column chromatographs
- (f) Pressure detectors

The choice of detector system for any application should be determined by the ability of a system to give a reliable indication of a real hazard condition and to give no false alarms under any environmental condition of application. The indication should be such that it is easily observed and/or heard by the crew members responsible for action. The following discussion is from the reviews of Ciccotti,³⁵ Lockheed-California,¹³⁶ and Cary et al.³³

Flame Detectors

Flame detectors are recommended where natural or forced heat convection is low, such as in some compartments of space vehicles, and only if the detector system complies with other requirements outlined below.

Flame detectors which operate on the flicker characteristic of a flame should not be used when flicker triggering may be caused by cycling phenomena such as light shining through rotating or vibrating equipment or when exhaust gases may trigger the detector. Flame detectors with low heat resistance or flame detectors that may lose their ability to indicate start of a fire, termination of a fire, or reignition of a fire, due to contamination of the sensor by soot, leaking oil, and so forth, should not be used. Visual-type radiation-sensitive detectors, if used, should be insensitive to the normally expected cosmic or solar radiation.

Most flame detectors are of the infrared or ultraviolet type. A suitable infrared fire detector has lead sulfide photoconductive cells with omnidimensional viewing. It readily distinguishes between the pulsating infrared emission pattern characteristic of a flame and the smoother infrared emission pattern caused by

other radiation sources. Detection and warning are almost instantaneous with the outbreak of an actual flame. The fact that flames may not flicker in convection-free zero gravity may confound this approach.

There are several types of adequate ultraviolet detectors. An ultraviolet-type fire detector recently developed for aircraft use has a phototube that operates on the Geiger-Müller principle.³⁵ The tube uses a pulse-integrating network to distinguish between the ultraviolet radiation from a flame and random radiation such as that from the sun or cosmic rays. This system is reportedly sensitive to a match flame 6 feet away or to burning oil in a 1-foot-square area at a distance of 100 feet, yet can discriminate against direct sunlight. It does not respond to overheat conditions, nor is it affected by ambient temperature or residual radiation. It is insensitive to infrared and visible light, and relatively insensitive to X- and gamma-radiation.

In addition to having the same advantages as infrared fire detectors, namely, omnidimensional viewing and nearly instantaneous, positive response to a flame, this particular ultraviolet unit can be adapted to perform a number of associated functions. For example, it can be used to detect smoke if an ultraviolet source is mounted beside it with the beam directed into the monitored area; smoke will scatter the ultraviolet energy and reflect some of it back to the detector. Another possible use for this unit is as a combustible gas detector. If a "Davy screen" equipped with a hot-wire element is added, air can be directed through the screen across the glowing wire. The wire will ignite any combustible vapors that may be present, and the phototube will detect the resulting ultraviolet radiation.

Optical fiber surveillance detectors, which transmit light from a fire to a remote viewing point through a bundle of thin glass fibers, may be used as a reliable means for checking the validity of fire warning-light signals, in cases where 100 percent reliability is desirable.

Heat Detectors

Heat detectors require contact with heat or flame. Unit-type heat detectors should, there-

fore, be used only in small compartments; or in large compartments with few confined hazard areas; or in large compartments with uniform, unidirectional airflow, without stagnant areas, and with few well-defined air exit areas. In all other applications continuous-type detectors should be used. These are useful only in areas where hot spots are constantly present and detection of critical overheat limit is required.

Fire and overheat alarm setting should generally be 100° F to 200° F above the maximum expected ambient temperatures at the location of the sensors. The setting should be high enough, however, to prevent harmless leakage of hot gases from causing an alarm.

Smoke and Carbon Monoxide Detectors

Smoke and carbon monoxide detectors should be used in ventilation outlets in compartments where low air supply permits only smoldering rather than an open flame. Smoke and carbon monoxide detectors should be used in inaccessible compartments with fire-extinguishing provisions only if fire extinguishing is effective on the kind of smoldering fire which may be expected in these compartments. If the smoldering fire is confined, for instance, in a clothing case or paper box it may smoke for a long period of time without penetrating the surface. The extinguishing agent would be wasted if applied externally to the case before the fire broke through.

In small potential fire zones and inhabited areas of spacecraft which have a continuous unidirectional flow of atmosphere, carbon monoxide detectors may be used advantageously, since they tend to provide early warning of an incipient fire before open flames are in evidence. Smoke detectors pick up changes in optical density of the atmosphere produced by smoke particles. Carbon monoxide analyzers continuously sample the atmosphere, and activate warning signals when the carbon monoxide concentration exceeds a predetermined value. This value is usually many thousand times less than the concentration that results from combustion of materials in aircraft compartments. Such devices give rapid warning of even a smoldering fire in a

space vehicle so that control measures can be taken in time to prevent a major conflagration.

It should be pointed out that in space cabins with 100 percent oxygen environments, fires will probably involve complete oxidation of products. Smoldering with much telltale smoke or release of carbon monoxide due to incomplete oxidation should not be relied on as a trigger of fire warning systems.

Vapor Detectors

More sophisticated physicochemical devices known as vapor detectors may be set to detect one or more critical compounds in space cabins, including carbon monoxide. They have been used for years on submarines for similar purposes. Development of a comprehensive atmosphere-analyzer warning system would enable the crew to take corrective action against the buildup of an explosive or other undesirable condition in the internal air. These would have to be properly located in the ventilation system to be effective.

Pressure Detectors

Incipient explosions may be detected by pressure-sensitive devices. Failure of breathing-gas control systems may also produce sudden pressure rises.

Appropriate means must be devised to distinguish between the two types of pressure rise. Explosive pressure-rise rates are much greater than those for other contingencies except for possibly an explosive failure of the breathing-gas control systems. There are existing explosion detection and suppression systems that appear to be adaptable to operation in a space-vehicle environment, but each individual installation will require specific additional engineering design and development.

Determination of the actual feasibility of detector systems requires complex risk-cost-weight analysis. The study of Cary et al.³³ outlines several possible computer procedures for analyzing feasibility data. In these analyses, the presence of high oxygen, low pressure, and zero gravity environments of limited accessibility should be included. Adequate planning for overall fire detection and suppression requires a most sophisticated risk analysis.

The ultimate in the development sequence aimed at fire and explosion protection is a system that not only warns of a fire or explosive condition, but also marks its nature, location, and magnitude, determines the type and amount of agent that should be used to counteract it, and actually activates the appropriate action automatically. Such a system would, of course, have to be coupled with an extensive piping network and with a computer memory unit programmed with complete data on the whole gamut of possibilities: the effectiveness of each agent carried against each possible hazardous condition, acceptable alternate agents, a running inventory of agents, maximum safe concentrations of agent from the standpoints of toxicity or anesthesia, vehicle area to be treated, and a number of other factors. The development of an automatic fire and explosion protection system is technologically feasible; whether it is economically justifiable will have to be evaluated.

PROTECTIVE CLOTHING AND STRUCTURES

A final problem to be overcome is thermal hazard in meteorite flash oxidation. What protective clothing and modification of interior structural materials are required?

The high radiant energy of the flash presents a burning problem which must be faced by the designer of space suits. As was pointed out in Chapter 2, effectiveness of flameproofing techniques for fabrics is radically altered by the oxygen content of the gaseous environment. The use of aluminized surfaces for reflection of the radiant energy has been required to cover the hazards of reentry heating. The same general fabric and coating design will protect against flash fires and meteoroid flash radiation. A recent review of the means and materials for combating thermal-radiation flash burns has been presented by the Armour Research Foundation.⁶ Most of the principles are directed against nuclear-weapons effects but the same general rules should hold for meteoroid flash burns and other flash fires in the cabin. It is beyond the scope of the present report to discuss this problem in detail. It is suggested, however, that the principles outlined in the

Armour study be modified to include the presence of high-oxygen, low-density gaseous environments. The studies of Clarke et al.³⁸ and Berkley¹² on the protective qualities of fabrics and clothing against thermal radiation should also be reviewed for the effects of unusual atmospheric environments to be found in space cabins. Recent techniques of Chianta and Stoll³⁴ contribute much to the evaluation of thermal transfer properties of fabric materials.

It has been suggested that much weight can be saved by using plastic instead of metal for space-cabin interior structure. Because of the low probability of meteoroid penetration, it would appear that these materials are safe for most missions near the earth. High-oxygen environments, however, create a special hazard in zones of high meteoroid density and even where meteoroid penetration is not a danger. In Operation Teapot²³² the resistance of many plastic and fibrous materials to radiant thermal damage from nuclear weapons was studied. The outline of Kelble and Bernados¹²² is also pertinent. These studies should be reviewed for selection of those materials which will be safest for use in space cabins with the entire anticipated atmosphere spectrum.

FIRE EXTINGUISHMENT

Fire extinguishment and "explosion" (detonation) depression in space-cabin environments is a fascinating problem. High oxygen concentration, low gas density, zero-gravity conditions, and limited removal of toxic products are the major factors compounding the task.

The physical methods of flame control were outlined in Chapter 1. They will be reviewed in greater detail below.

Isolation of Combustible from Oxidant (Dilution and Blanketing)

Presence of an infinite vacuum "sink" about a spacecraft lightens considerably the isolation approach to flame extinguishment. By dumping the cabin atmosphere into this sink one can decrease the concentrations of both gaseous combustible and oxygen below the limits of flammability. This single step will probably be of greatest value in fighting space-cabin fires. Of course, the procedure must be delayed

until pressure suits are donned and the replacement of the environment must be delayed until all ignition sources and/or combustibles are removed. If the cabin is compartmentalized with adequate pressure seals, only the area involved in the fire need be decompressed. To reduce propagation of flames to a minimum within a sealed compartment, the air-conditioning system should be turned off as soon as possible. As was discussed in Chapter 1, in the absence of gravity, forced convection and not natural convection is the prime source of oxidant-combustible mixing in heterogeneous systems. This elimination of forced convection may well be a critical factor during the time lost in donning pressure suits.

There is one paradox in the decompression routine. The actual act of decompression will create a forced-convection condition which may tip the balance in a borderline conflagration. It would seem that a slow decompression would be more hazardous than an explosive decompression. The former approach retains

oxygen for longer periods of time and may allow damage to critical structures. It must also be remembered that provision for cutting off the oxygen supply to the cabin must be included in the emergency procedure. Calculations for adequate oxygen supply should include consideration of the loss of gas during fire procedures.

The blanketing of a fire area with a gas denser than the ambient atmosphere is a standard extinguishment procedure. It is usually accomplished by the use of carbon dioxide or chemical foams and essentially prevents adequate oxygen from reaching the flame zone. In the absence of gravity, however, the density factor no longer comes into play and blanketing agents will probably be quite ineffective. The actual blast of gas or foam in the direction of the fire may set up a forced convection which will augment the transport of oxidant to a fire that might otherwise be kept in check by the effects of reduced gravity. Low nozzle-exit speeds, therefore, would improve the effi-

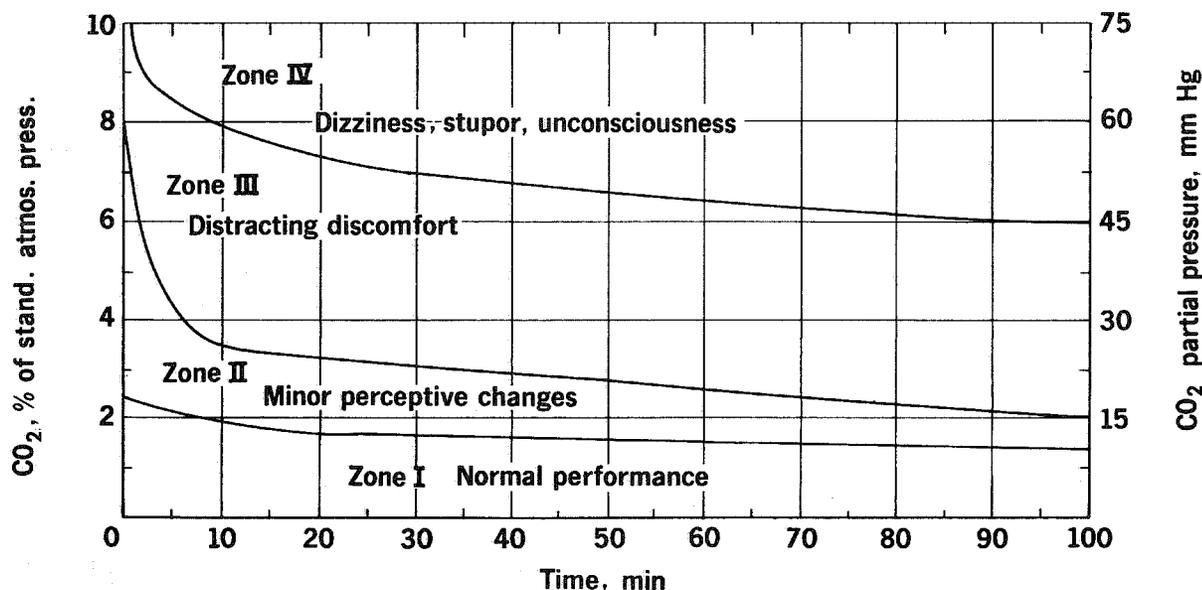


FIGURE 52.—Toxicity of carbon dioxide. Curves are adapted from the study of King¹²³ and the review of Nevison.¹⁶⁴ Zones fade into one another less clearly than shown and include symptoms common to most but not all subjects. In zone I no psychophysiological performance degradation is noted. In zone II small threshold hearing losses have been found and a perceptible doubling in depth of respiration. In zone III are found mental depression, headache, dizziness, nausea, "air hunger," and decrease in visual discrimination. Zone IV represents marked deterioration with inability to take steps for self-preservation.

ciency of the carbon dioxide approach. The blanketing of "overhead" fires by these agents would probably be more effective than in normal gravity environments. It must also be remembered that venting a cabin to reduce oxygen will remove carbon dioxide or foams as well. It is apparent, however, that either venting or carbon dioxide alone will be used, but never both simultaneously.

It should be kept in mind that carbon dioxide must be removed from the cabin before toxic levels are reached. There have been fatal accidents from excessive concentrations of carbon dioxide in aircraft cabins after the use of carbon dioxide extinguishers in baggage compartments.²³¹ Figure 52 demonstrates the time-concentration tolerance curves for carbon dioxide.¹⁶⁴ The excess carbon dioxide may be removed by venting to the outside or by the chemical absorption system within the air-conditioning system. Care must be taken not to overload the capacity of the carbon dioxide absorption system.

The use of blankets, towels, or similar materials for "snuffing" out small fires is to be discouraged. As will be mentioned in Chapter 7, a serious fire accident has occurred in a 5-psi 100 percent oxygen environment as a result of this approach to the problem. The use of "fireproof" blanketing fabric materials in 100 percent oxygen environments should be discouraged unless the fireproofing has been tested in these atmospheres (see Chapter 2).

Cooling

The usual agent for extinguishing fires by cooling is water. Other chemical agents also involve cooling as part of their mechanism. High heat capacity, large heat vaporization, and ability to undergo endothermic decomposition reactions contribute to the cooling process. It must be remembered that in zero-gravity environments liquid will not settle on a flame area. A stream released from a nozzle will break up into globules and ricochet off the surface until the energy of motion is dissipated.

Blockage of Radiant Heat Transfer

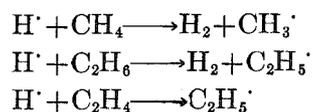
Many agents can interpose between the flame zone and unburned liquid of a hetero-

geneous unmixed system and decrease the radiant heat transfer to the fuel source. This decreases vaporization and reduces the concentration of vapor at the flame zone to a level below the lower (lean) limit.

Chemical Inhibition

Recent reviews of the voluminous literature on chemical extinguishing agents have been quite thorough.^{81,203} It appears worthwhile to review only the general mode of action of these agents in extinguishing flames and suppressing detonations. The mode of action very often determines the optimum use of each agent under any specific condition.

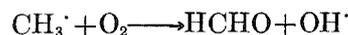
Hydrocarbons. Additions of hydrocarbons such as methane, ethane, and propane can inhibit hydrogen-oxygen flames and detonation. The use of these compounds is of only theoretical interest. The inhibition is probably brought about by the absorption of $H\cdot$. As was mentioned in Chapter 1, $H\cdot$ is the active free radical in propagating the oxidation of hydrogen. The hydrocarbons apparently react with the $H\cdot$ and substitute a less reactive $R\cdot$ in its place.⁸



The $C_2H_5\cdot$ may react with oxygen to give the more stable (unreactive) radical $HO_2\cdot$ which diffuses to the wall and is converted into stable compounds.



Methyl radicals react with oxygen to give



The $OH\cdot$ is active but formaldehyde (HCHO) ties up more $H\cdot$ to give



The formyl radical diffuses to the wall. Thus, the hydrogen-oxygen reaction is inhibited by free-radical conversion and trapping.

TABLE 22.—*Advantages and Disadvantages of Various Extinguishing Methods* [AFTER LOCKHEED-CALIFORNIA CO.¹³⁶]

| Method | Advantages | Disadvantages |
|---------------------------------|--|---|
| Manual extinguishing system. | Allows assessment of hazard by flight crew and may prevent waste of extinguishing agent. Avoids shock and hazard of unexpected shutdown. | May delay action beyond safe limits. Fires may run out of control 30 sec or less after ignition. |
| Automatic extinguishing system. | Superior to manual system only when fast action is vital. | Inadvertent operation can cause disastrous shutdown of vital systems. |
| Explosion suppression | Limits explosion peak pressures to levels safe for structure and equipment. Gives good explosion protection in small spaces. | Limited volume coverage of suppression units requires complex system for large volumes and odd compartment or tank shapes. Complex wiring system introduces ignition hazards. |
| Evacuation | Effective in space-vehicle compartments with oxygen atmosphere. | Requires donning of space suit when used in inhabited areas. Not effective for bipropellant and nonpropellant fires. |

Alkyl Halides. Carbon tetrachloride (CCl₄) and the other alkyl halides extinguish flames by blanketing, cooling, and chemically inhibiting combustion. Bromochloromethane (CH₂ClBr) is widely used. Recently other alkyl halides have been found to be superior in effectiveness against many different fire sources and are less toxic. These compounds studied by Engibous and Torkelson⁶⁷ are: dibromodifluoromethane (CF₂Br₂); bromochlorodifluoromethane (CBrClF₂); bromotrifluoromethane (CBrF₃); 1-2 dibromotetrafluoroethane (BrF₂C—CF₂Br). All these agents appear most effective in a 1 g environment when ejected forcefully so that they penetrate the flame.¹¹⁰ Friedrich^{82, 83, 84} has studied the mode of action of these compounds against a variety of vaporizing liquids. He concludes that these halides decompose in the flame to yield halogen atoms which are the active extinguishing agents. The more efficient alkyl halides are the ones which can penetrate the flames to the flame front without breaking down. At the flame front they become unstable, and they release the greatest number of halogen atoms at the front itself.

The chemical mechanism of action has been reviewed at the Seventh Combustion Symposium. In brief, Rosser et al.^{186, 187, 188} consider that hydrocarbon combustion proceeds by the diffusion and action of active species H[·], OH[·],

and O[·]. They hypothesize that the halogen atoms released at the flame front tie up these compounds. An example of the action is as follows:



and



The Br[·] is free to continue the chain-terminating steps until only the less reactive R[·] radicals are left. It has been generalized that all oxygen oxidations should be blocked by the halides except for NO₂ or NO₃⁻ oxidations which can tie up the HBr formed and prevent chain termination. There are still several fuels with unexplained anomalous responses to the alkyl halides.

It must be remembered that none of these agents are effective against burning alkyl borane fuels.²⁴⁷ They are effective to some degree against hydrogen-oxygen flames.^{204, 221, 222} Also, some alkyl halides intensify the combustion of some fuels such as hydrazine.^{155, 156}

A completely different theory from that of Rosser et al. has been suggested by Creitz.^{54, 55} He proposed that as one of the key steps in combustion, O₂⁻ ions are formed by capture of electrons produced from the ionization of the hydrocarbons. He suggests that halogens capture electrons rather than oxygen and thereby

inhibit the step. This hypothesis has never been ruled out in laboratory studies of reaction mechanisms and must still be considered as possible.

Halide Salts. A number of volatile inorganic halides have been found to be several times more effective than HBr, on an atom-for-atom basis, against hydrocarbon-air flames.¹⁸⁷ The molecules themselves appear to be the active inhibitors in a mechanism that differs from that of alkyl halides. Such compounds as BBr₃, POCl₃, PSCl₃, PBr₃, SbCl₃, SnCl₄, and TiCl₄ were most effective but were, unfortunately, corrosive and toxic.

Finely Divided Salts. Suppression of hydrocarbon,^{130, 131, 187} hydrogen,²¹¹ and even hydrazine^{155, 156} fires and detonations by finely divided alkali metal salts has been well studied in the past. Particles about 5 μ in diameter can evaporate on passage through the flame front. Those that evaporate most readily appear to be the most effective. The metal atoms of such salts as potassium bitartrate, sodium and potassium bicarbonate, and potassium oxalate have been used. The hydrated potassium and rubidium oxalates appear most effective. Presence of organic chlorides such as CH₃Cl appear to inhibit action of these salts, probably by tying up the metal ions with halogen ions.

How do these salts suppress combustion? The metal atom may act (a) as a third body in free-radical recombinations, (b) as an intermediate in recombinations, or (c) as a deactivating agent for excited species (see Chapter 1). The great advantage of these salt dusts is in the suppression of hydrogen-oxygen explosion. It must be remembered, however, that these salt dusts will not settle on a fire in zero gravity and will probably require forced propulsion through the flame front.

Choice of Extinguishing Methods

The choice of one extinguishing method over another in space vehicles is most difficult. In general, the whole hazard risk-detector-extinguishing sequence must be considered. Since the probabilities involved are still beyond the quantitative stage of assessment, it would seem best to review the basic principles on which the choice of agent may be based.

The advantages and disadvantages of the four basic approaches to the extinguishment problem are listed in table 22. It would seem that for each station in a vehicle, an optimum approach may be outlined. Evacuation, whenever possible, is the method of choice, but is hindered by the suit-donning time or time to flee from sealed compartments. The ineffectiveness of dilution against many propellant fires must also be kept in mind. The other suppression systems have their time and place as determined by vehicle and mission.

The choice of an extinguishing agent to back up the evacuation method is determined by the following factors:

- (1) Specific gravity
- (2) Corrosive tendency against vehicle structure
- (3) Physiological toxicity
- (4) Electrical conductivity
- (5) Swelling of elastomers
- (6) Effectiveness against unusual fires.

Specific Gravity and Corrosive Tendency. Table 23 presents the physical parameters of the most effective agents. It would appear that CO₂, CF₂Br₂, CF₃Br, CF₂BrCF₂Br, and CCl₄ are the most favorable (in decreasing order) as far as specific gravity and corrosive potential are concerned. In the absence of gravity, of course, the specific gravity is not much of a factor, but when the craft is at rest on earth or on a planet the specific gravity promptly resumes its importance.

Physiological Toxicity. The physiological toxicity of the cool and heated vapor against rats may be seen in table 24. It is clear that CO₂ is best, followed by CF₃Br. The group CH₃Br, CH₂BrCl, and CF₂ClBr is less favorable. Finally, CCl₄, CF₂BrCF₂Br, and CF₂Br₂ are the worst of all. The report of Engineer Research and Development Laboratories¹⁵⁰ has been backed up by numerous studies of many other groups. (See refs. 50, 66, 111, 126, and 160.) The time-concentration tolerance curves for CO₂ have recently been reviewed by Nevison¹⁶⁴ and are seen in figure 52.

It must be remembered that pressure suits, if donned, will protect against toxic vapors. Even when the crew is in a "shirtsleeve" en-

vironment, it may be possible to avoid toxicity by slowly venting the atmosphere and replacing it with fresh gas. The venting process itself, however, may create a gas current which can aggravate combustion under zero-gravity conditions.

Electrical Conductivity. The use of metal salts creates a hazard as far as electrical conductivity is concerned. Their use should probably be restricted to areas where hydrogen-oxygen explosions are a hazard. The alkyl halides and carbon dioxide are nonconducting.

Swelling of Elastomers. The swelling of elastomers by the halogenated alkyl compounds is not a serious problem, but should be considered in the design of extinguishing-system components. Table 25 is an outline of the swelling characteristics for the most favorable agents. Bromotrifluoromethane (CF_3Br) appears to be the most satisfactory in this respect.

Effectiveness Against Unusual Fires. Research studies of extinguishing agents for exotic propellants are still underway.^{161, 182, 189, 219} Laboratory tests have, in many cases, not

proven satisfactory in predicting flame and combustion problems in the field. Table 26 from Welch et al.²²⁷ outlines the effective percentage concentration for propellant-air fires in small-scale laboratory tests. The best agent against hydrocarbons, CF_3Br , was not studied. Full-scale fire tests showed these concentrations for ammonia fires to be inadequate. Combustion of materials like hydrazine is augmented by these agents.^{155, 156}

The meteoroid flash oxidation creates the problem of burning metals. As was discussed in Chapter 5, the use of magnesium inside cabins with high oxygen concentration is not recommended. If, however, other design criteria make magnesium imperative, it will probably be wise to think of the special problem of extinguishing magnesium fires. Greenstein and Richman⁹¹ have demonstrated that solutions of 50 percent diisodecyl phthalate in bromochloromethane are effective against magnesium fires. The phthalate solution acts as a coolant and bromochloromethane forms a protective coating (MgCl_2) upon reaction with the magnesium surface.

TABLE 23.—Physical Properties of Extinguishing Agents [AFTER LOCKHEED-CALIFORNIA CO.¹³⁶]

| Extinguishing agent | Mol. wt. | Sp. gr. of liquid at 70° F | Boiling point, °F | Freezing point, °F | Liq. density at 70° F, lb/gal | Corrosion resistance* of— | | |
|--|----------|----------------------------|-------------------|--------------------|-------------------------------|------------------------------|-------|----------|
| | | | | | | Steel | Brass | Aluminum |
| Carbon dioxide, CO_2 ----- | 44 | 0.76 | -109.0 | -110.0 | 6.3 | Corrosion resistance is high | | |
| Methyl bromide, CH_3Br ----- | 94.94 | 1.67 | 40.0 | -135.4 | 14.0 | 42.0 | 310 | >1,500 |
| Bromochloromethane, CH_2BrCl .. | 129.4 | 1.93 | 156.0 | -123.7 | 16.1 | 650.0 | 250 | >1,500 |
| | | | | | | 27 | 200 | >1,500 |
| Dibromodifluoromethane, CF_2Br_2 - | 209.8 | 2.27 | 76.1 | -222.9 | 19.0 | 280 | 1,620 | >1,500 |
| | | | | | | 0.8 | 0.7 | 0.7 |
| Bromotrifluoromethane, CF_3Br --- | 148.9 | 1.57 | -57.9 | -270.4 | 13.1 | 62 | 375 | 55 |
| | | | | | | 0.9 | 1.5 | 0.7 |
| 1,2-dibromotetrafluoroethane, $\text{CF}_2\text{BrCF}_2\text{Br}$ ----- | 259.8 | 2.15 | 117.5 | -166.8 | 18.0 | b-91 | b-35 | 59 |
| | | | | | | 1.5 | 5.7 | 0.4 |
| Carbon tetrachloride, CCl_4 ----- | 153.8 | 1.59 | 170.1 | -9.4 | 13.3 | 140 | 385 | 50 |
| | | | | | | 1.5 | 8.7 | >1,500 |
| | | | | | | 93 | 213 | 54 |

* Average penetration, (Inch/Month) $\times 10^{-6}$, upper figures dry, lower figures wet. These data are from tests by Jackson Lab., E. I. du Pont de Nemours & Co., Inc.

^b The minus sign indicates tightly bound scale forming in layers on a metal test strip rather than corrosion or penetration.

Application Engineering of Extinguishing Agents

Current military practice has determined bromochloromethane, CH₂BrCl (Mil B-4394), and bromotrifluoromethane, CF₃Br (Mil B-12218), to be the most suitable agents as far as maximum effectiveness and minimal detrimental side effects are concerned. The quantity of agent to be used in any situation is rather difficult to determine. The minimum quantity required depends on airflow and volume of compartment. Table 27 outlines the recommended values for aircraft.

It has been recommended for aircraft that in automatic systems the halogenated compounds should be discharged within a maximum duration of 1 second and carbon dioxide within 1.25 to 1.35 seconds from 400 to 600 psi cylinders to attain the concentrations in table 28. It has also been recommended that these concentrations be maintained for at least 0.5 second simultaneously throughout the cabin.¹³⁶

How well do these application recommendations apply to fires in spacecraft cabins? It appears that, in the past, fire-extinguishing systems have been specified on the basis of reaching or exceeding a given agent concentration for a given period of time. Presumably, these specifications are related to the fire-extinguishing ability of a known concentration of agents against known fuel concentrations, as well as to the engineer's knowledge of past performance of detector-extinguishment systems. To justify the use of a given space cabin fire-extinguishing system through a risk study, it will be necessary to obtain performance data of a more quantitative nature than has been available in the past. The three necessary pieces of information are: The probability that in a given fire the system will be activated; the probability that a given extinguishing system will operate when activated; and the probability that its operation will successfully extinguish

TABLE 24.—*Physiological Properties of Extinguishing Agents* [AFTER LOCKHEED-CALIFORNIA CO.¹³⁶]

| Extinguishing agent | Approx. lethal concentration for 15 min exposure of rats (from ref. 150) | | Warning of presence of toxic vapors by smell, irritation, coughing, and lachrymation | |
|---|--|------------------------------------|--|---|
| | Natural vapor, ppm vol. | Vapor heated to 1,470° F, ppm vol. | Natural vapor | Heated vapor |
| Carbon dioxide, CO ₂ ----- | 658, 000 | 658, 000 | Odorless at low concentration; acrid at high concentration. | Odorless at low concentration; acrid at high concentration. |
| Methyl bromide, CH ₃ Br | 5, 900 | 9, 600 | Odorless, poisoning not immediately apparent, odorant added by U.S.A. mfr.* | Decomposition products are moderately irritating. |
| Bromochloromethane, CH ₂ BrCl. | 29, 000 | 4, 000 | Sweet odor----- | Decomposition products are exceedingly irritating. |
| Dibromodifluoromethane, CF ₂ Br ₂ . | 54, 000 | 1, 850 | Heavy, ethereal----- | Decomposition products are extremely painful to inhale. |
| Bromotrifluoromethane, CF ₃ Br. | 800, 000 | 14, 000 | Slight, ethereal----- | Acrid, irritating. |
| 1,2-dibromotetrafluoroethane, CF ₂ BrCF ₂ Br. | 126, 000 | 1, 600 | Slight, ethereal----- | Acrid, irritating. |
| Carbon tetrachloride, CCl ₄ . | 28, 000 | 300 | Solventlike----- | Decomposition products are extremely painful to inhale. |
| Bromochlorodifluoromethane, CF ₂ ClBr. | 324, 000 | 7, 650 | Slight, ethereal----- | Acrid, irritating. |

*Addition of odorant required by Government specification.

TABLE 25.—Swelling of Elastomers in Fire-Extinguishing Agents (Maximum Percent Increase in Length at Room Temperature) [AFTER LOCKHEED-CALIFORNIA CO.¹³⁶]

| Extinguishing agent | Elastomer* | Percent swell |
|---|---------------------------------------|---------------|
| Carbon dioxide, CO ₂ | No swelling caused by CO ₂ | |
| Bromochloromethane, CH ₂ BrCl. | Viton A..... | 4 |
| | Silicone 23..... | 10 |
| | Butyl..... | 15 |
| Dibromodifluoromethane, CF ₂ Br. | Polysulfide..... | 8 |
| | Thiokol FA..... | 8 |
| | Hycar OR-15..... | 11 |
| | Buna N..... | 11 |
| | Perbunan 26..... | 23 |
| Bromotrifluoromethane, CF ₃ Br. | Perbunan 26..... | 0 |
| | Neoprene Type GN-A. | 0 |
| | Hycar OR-15..... | 1 |
| | GR-S..... | 1 |
| 1,2-dibromotetrafluoroethane, CF ₂ BrCF ₂ Br. | Thiokol FA..... | 4 |
| | Neoprene Type GN-A. | 6 |
| | Hycar OR-15..... | 7 |
| | | |
| Carbon tetrachloride, CCl ₄ . | Viton A..... | 1 |
| | Polysulfide..... | 12 |
| | Hycar OR-15..... | 13 |
| Bromochlorodifluoromethane, CF ₂ ClBr. | Butyl..... | 2 |
| | Thiokol FA..... | 4 |
| | Hycar OR-15..... | 5 |

*Materials for each extinguishing agent which exhibited the lowest linear swelling in tests with a number of materials. Tests were conducted by E. I. du Pont de Nemours & Co. by storing test strips in sealed glass tubes with the liquid agent for 2 weeks.

TABLE 26.—Extinguishing-Agent Concentrations for Some Propellant-Air Fires (Laboratory Testing) [AFTER LOCKHEED-CALIFORNIA CO.¹³⁶ FROM THE DATA OF WELCH ET AL.²²⁷]

| Propellant | Agent | Concentration, % vol. |
|-------------------|--|-----------------------|
| Ammonia..... | CF ₂ BrCF ₂ Br..... | <0.25 |
| | CF ₂ Br ₂ | <0.25 |
| | CH ₂ BrCl..... | <0.25 |
| | CH ₃ Br..... | 0.3 |
| Aniline..... | CO ₂ | 4.7 |
| | CH ₂ BrCl..... | 1.8 |
| | CH ₃ Br..... | 1.9 |
| | CO ₂ | 2.1 |
| | CF ₂ BrCF ₂ Br..... | 2.2 |
| Ethanol..... | CF ₂ Br ₂ | 3.2 |
| | CF ₂ BrCF ₂ Br..... | 5.3 |
| | CF ₂ Br ₂ | 5.8 |
| | CH ₂ BrCl..... | 8.7 |
| Hydrogen..... | CH ₃ Br..... | 11.4 |
| | CO ₂ | 14.1 |
| | CH ₃ Br..... | 15.5 |
| | CF ₂ BrCF ₂ Br..... | 17.3 |
| | CH ₂ BrCl..... | 31.0 |
| Methanol..... | CF ₂ Br ₂ | 34.4 |
| | CO ₂ | 52.5 |
| | CF ₂ BrCF ₂ Br..... | 16.8 |
| | CH ₂ BrCl..... | 17.9 |
| | CF ₂ Br ₂ | 20.6 |
| Nitromethane..... | CH ₃ Br..... | 21.0 |
| | CO ₂ | 27.5 |
| | CF ₂ BrCF ₂ Br..... | 4.2 |
| | CF ₂ Br ₂ | 8.6 |
| Fluorine..... | CH ₂ BrCl..... | 12.4 |
| | CH ₃ Br..... | 18.9 |
| | CO ₂ | 21.7 |
| | All agents except CO ₂ reacted with fluorine. | |

the fire or, at least, increase the salvage value of the spacecraft system. Justification will be further influenced by the probability of detecting the fire in time for the extinguishing system to have value.

One type of study which is of value in assessing the overall problem is outlined in figure 53. For those agents which are applied in, or are primarily effective in, gaseous form,

extinguishment effectiveness can be represented by such a graph. Here the concentration of agent necessary to extinguish a hypothetical fire is plotted as a function of various conditions such as fuel concentration, initial (T_1) and final (T_2) reactant temperatures, and partial pressures of oxygen and inert diluent gases in the atmosphere. As has been discussed, the oxygen and diluent gas pressures in the space cabin

TABLE 27.—Quantity of Extinguishing Agents [AFTER LOCKHEED-CALIFORNIA CO.¹³⁶]

| Agent | Flow | Compartment configuration | Agent quantity, lb* |
|---|------|---------------------------|-----------------------------|
| Bromotrifluoromethane, CF ₃ Br | High | Smooth | 0.25 W _a + 0.02V |
| | High | Rough | 0.75 W _a + 0.02V |
| | High | Very rough | 1.25 W _a + 0.02V |
| | Low | Smooth or rough | 0.05V |
| | No | Smooth or rough | 0.02V |
| Bromochloromethane, CH ₂ BrCl | High | Smooth | 0.4 W _a + 0.025V |
| | High | Rough | 1.2 W _a + 0.025V |
| | High | Very rough | 2.0 W _a + 0.025V |
| | Low | Smooth or rough | 0.06V |
| | No | Smooth or rough | 0.025V |
| Carbon dioxide, CO ₂ | High | Smooth | 0.5 W _a + 0.03V |
| | High | Rough | 1.5 W _a + 0.03V |
| | High | Very rough | 2.5 W _a + 0.03V |
| | Low | Smooth or rough | 0.07V |
| | No | Smooth or rough | 0.03V |

*W_a=Pounds of air per sec passing through zone at cruising speed. V=Net volume of zone in cubic feet.

are very critical in determining burning rates and temperatures. The effects of zero gravity, as they are more clearly defined, should be added to the other variables contributing to the design envelope.

The weight-volume tradeoffs of extinguishing agents are of great importance in space operations. Agents are often rated by the minimum volume or weight percentage of agent that completely suppresses the flammability under the worst possible conditions. For example, in air at room temperature about 29 volume percentage of carbon dioxide is required under the most unfavorable conditions, while only 11 to 15 percent of the alkyl halides is required.³³ On a total weight basis, however, the advantage of the halides is much less apparent.

It is also possible to save weight and space by programing the application rate of extinguishing agents so as to account for the stage of development of the fire. To extinguish the flame with a minimum quantity of agent in a ventilated compartment or exposed location, the application rate should be high, so that the agent concentration is high. However, to prevent reignition the agent must be supplied continuously for a period of time sufficient to

allow possible ignition sources to cool or otherwise be deactivated. It seems likely that the minimum agent concentration to prevent reignition may be lower than that required for extinguishment. If this is true, it has not been recognized in the literature, and no known fire extinguishment system has employed a staged discharge flow to take advantage of such a situation.

It must be remembered that in the final full-scale fire protection tests, the space condition should be most closely simulated. Zero-gravity conditions, of course, can be studied only in model systems set up in operational spacecraft or in an aircraft in zero-gravity

TABLE 28.—Extinguishing-Agent Concentration [AFTER LOCKHEED-CALIFORNIA CO.¹³⁶]

| Agent | Minimum concentration | |
|----------------------|-----------------------|--------------|
| | Percent wt. | Percent vol. |
| CF ₃ Br | 22 | 6 |
| CH ₂ BrCl | 36 | 11 |
| CO ₂ | 49 | 37 |

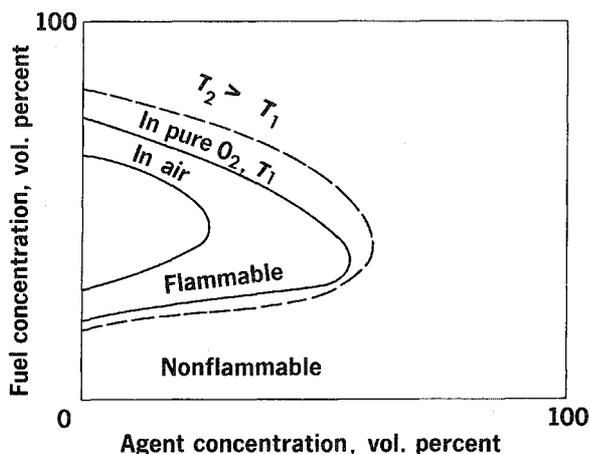


FIGURE 53.—*Flammability limits of a fuel as affected by an extinguishing agent.* (AFTER CARY ET AL.³³)

parabolas. It may be possible to obtain enough gravitational coefficients from experimental data to simulate this factor in full-scale ground tests by modifying the appropriate combustion parameters. It must also be remembered that

because of the probable scattering effect at zero gravity, optimum nozzle velocity should be used to obtain the maximum blanketing effect for each agent. The appropriate nozzle velocity, ejection duration, and final concentration parameters for each agent needs to be simulated in mock cabins with complete interior configuration. The "fire pockets" between instruments and structures are a major factor in determining the design envelopes of the fire-extinguishing system.

For oxygen-supported fires of hydrocarbon-type fuels, a substantial background of experience is available which may be applied, at least empirically, to the fire-extinguishment problem. However, for fires supported by other types of oxidants or involving radically different types of fuels, there is little experience. Experimental studies of the extinguishment of such fires should be started as soon as such oxidants or fuels are incorporated into planned future vehicles; otherwise, logical evaluation of extinguishment systems will be impossible.

Role of Fire and Blast Hazard in Selection of Space-Cabin Atmosphere

REVIEW OF FIRE ACCIDENTS IN SPACE-CABIN EXPERIMENTS

Those interested in the design of space cabins have been concerned recently by the occurrence of several fire accidents in high-oxygen environments. The first occurred in the space-cabin simulator at the USAF School of Aerospace Medicine, Brooks Air Force Base, Texas.^{37, 226} The data were obtained by oral communication with Drs. H. G. Clamann and B. Welch. Any errors of fact are the fault of the author.

Several years ago during a space-cabin experiment performed at an altitude of 33,000 feet with 100 percent oxygen, a power tube in the TV cabin monitor overheated. The "resin" base of the tube ignited and hot plastic dripped out of the chassis onto coolant lines passing beneath. These coolant lines were covered with a Ruberoid insulation of an as yet undetermined composition. The lines did not catch on fire. Fumes from the hot resin alerted the cabin crew. The mission was aborted without further damage to cabin or crew. Instead of focusing attention on the hazards of fire, the accident gave a "false sense of security." The fact that the molten resins or the Ruberoid insulation did not flame violently in 100 percent oxygen gave the investigators more confidence in the safety of this potentially hazardous environment than they had prior to the experience.

In 1962, the two-man space-cabin simulator was being used to study temperature control factors in pressure suits and cabins. Two sub-

jects were dressed in pressure suits with closed helmet visors. One subject had both inlet and outlet of his suit connected to the heat exchanger. The other subject had only the inlet side of the suit connected to the heat exchanger and was actually asleep when the fire broke out. The fire was not detected by the sight or smell of smoke. This is a very important point. The crewman saw a glow behind the instrument panel. Within several seconds the rear of the panel was ablaze. The crewman who was asleep awoke when the fire alarm went off and for some reason opened the visor of his helmet. He inhaled the fumes issuing from the blazing panel. The other crewman, who had his visor closed and both inlet and outlet air hoses attached to the heat exchanger, inhaled none of the cabin fumes directly. Both subjects reportedly "passed out." The one with the open visor suffered "respiratory tract damage," probably from the direct inhalation of fumes. His laboratory pulmonary-function tests have returned to normal. The subject with closed visor suffered no apparent respiratory tract damage even though he remained in the chamber longer (2 to 3 minutes after he discovered the glow) than the other man with the open visor. Neither subject experienced clothing or body burns. The fire was extinguished with difficulty by means of a carbon dioxide device.

The exact cause of the fire was not determined. The glow appeared at the back of the instrument panel where the wiring passed be-

hind an access panel. The panel was not hinged (as first reported by rumor) but was opened by a "Dzus fastener." The flexion of wires "at a hinged edge of the panel" was evidently not, as previously reported to the author, responsible for the fire. The wires were in a 24 to 26 volt circuit. The circuit breaker or fuse system was operative when checked after the fire. There were apparently no obvious sites of defective circuitry. Damage by the fire, however, probably obscured any subtle defect that may have been responsible. The wire insulation was of polyvinyl plastic and was probably the major source of fuel. The Ruberoid insulation covering the coolant pipes also caught fire. The electrical insulation behind the instrument panel was totally burned.

During the experiment the vapors in the cabin were being sampled in a cryogenic trap. The vapors and fumes generated during the fire were thus studied by both gas chromatography and infrared spectrophotography. The following compounds were new or had levels above those ordinarily present in the cabin: benzene, diazomethane, ethyl ether, formaldehyde, inorganic isocyanates, acetylene, methyl chloride, and ethyl chloride. The isocyanates were thought to come from the Ruberoid insulation on the coolant pipes. No polyurethane diisocyanate foams were reported to have been on fire, though the Ruberoid may well have contained this plastic as a component. It is of interest that no hydrogen chloride or phosgene was reported, since pyrolysis of polyvinyl chloride has been shown to produce these materials.⁴⁸ It is possible, of course, that the screening tests were not able to detect these materials. It is not known how sophisticated a fire safety analysis was performed on the materials which were used in the cabin.

The other fire occurred in 1962 at the Aircrew Equipment Laboratory of the Naval Air Center, Philadelphia, Pa.¹⁵² The accident occurred in a chamber with an internal atmosphere of 100 percent oxygen at 5 psi. Four men in the chamber were taking part in experiments under the acceleration-atelectasis-oxygen toxicity study reviewed in Part I of this report.

A light bulb in the ceiling fixture burned out. One man climbed up to replace the bulb. After

the bulb was replaced, he heard a "sound like the arcing of a short circuit." A small flame (about ½ inch long) was seen coming from an insulated wire in the fixture. The composition of this insulation is still not known. The subject requested water but was told to snuff the fire out with a towel. The towel caught on fire and blazed so vigorously that it set the man's clothing afire. An "asbestos fire blanket" was used to snuff out the clothing fire, but it too burst into flames. The asbestos blanket reportedly had an organic filler or coating which "kept the asbestos from flaking off." The clothing of the other subjects who were using the blanket also caught on fire. Altogether four men received second-degree burns. It was not reported by what means the fire was finally brought under control. It was felt that the blanket and towel had been "saturated with oxygen for 17 days and burned much more vigorously than would be expected under sea level conditions."

An interesting aspect of this case is the fact that burning insulation dripped from the light fixture onto a bunk. One crewman tried to snuff out the resulting fire, and "his skin caught on fire." The burns on his hands were "severe" and necessitated treatment for 11 or 12 days in the hospital. The cabin was being continuously vented and no analysis of the vapors was being performed at the time of the accident. No "unusual chemical extinguishers" were used on the fire. No symptoms of lung damage were reported. No formal report of this accident has as yet been published.

Future experiments in this chamber are being planned. More thought has been given to details of the fire hazard. Showers or sprinklers will be installed in the cabin in case another fire accident occurs.

These accidents illustrate in concrete fashion the potential dangers of 100 percent oxygen atmospheres. It can be argued that the lack of professional fire-safety engineering may have been a major factor in these accidents. The cabin fire at the USAF School of Aerospace Medicine does not appear to be a result of obvious human error. The prime factor in initiating the fire is still unknown. From the previous discussion of burning of electrical

insulation, it would appear that the choice of polyvinyl chloride was probably not optimum. One might also question the positioning of a Ruberoid insulated coolant pipe beneath or close to the electrical system. The design tradeoffs which determined these factors are not known. In an operational space vehicle such factors could possibly be avoided.

In the Aircrew Equipment Laboratory fire, the basic defect of flaming insulation might not have been a serious event if the human errors in fighting the fire had not complicated the situation. Had asbestos or possibly silicone-glass fiber insulation been used, the original flame might never have been initiated. Use of a flammable fabric to snuff out a fire in 100 percent oxygen was certainly not the optimum approach, but in an acute emergency situation, such action is not entirely unexpected. Testing of the effectiveness of the asbestos fire blanket in 100 percent oxygen environments prior to the experiment would probably have averted some of the difficulties.

ROLE OF OXYGEN AND INERT GASES IN THE FIRE HAZARD

In both situations, either safety design or fire discipline might have prevented entirely the accidental fires. Nevertheless, it must be admitted that a 100 percent oxygen environment does present an unusual hazard in space cabins. How serious is the fire hazard produced by this environment? Will the addition of inert gases at rather low concentrations decrease the hazard to any degree? Let us review the theoretical and empirical data presented in Chapters 1 to 6 and pick out those combustion parameters in which the atmospheric constituents play a major role.

Ignition parameters will be discussed first. The electrostatic spark ignition of flammable gases is markedly affected by the presence of an inert diluent. As seen in figure 4, the addition of nitrogen to a mixture of propane and oxygen will increase minimum ignition energies by almost 2 orders of magnitude on going from 100 percent oxygen to 21 percent oxygen. At any given percentage of inert gas in the propane-oxygen mixture, halving the total pressure in the system will increase the

minimum ignition temperature by a factor of 5. A change from 21 percent oxygen at sea level to 100 percent oxygen at 5 psi should decrease the minimum ignition energy by a factor of 10.

The relative effects of other inert gases were seen in tables 2 and 8. As will be discussed in Part III of this report, only helium, neon, and nitrogen will be contenders for the inert gas in sealed cabins. In table 2, it is seen that for increasing the minimum spark-ignition pressure, helium was more effective than nitrogen. This was also true for increasing the minimum spark-ignition energy and increasing the quenching distance for both hydrogen-oxygen and methane-oxygen systems. Table 8 showed how helium is more effective by a factor of 2 to 3 for both of these parameters in both combustion systems. It was pointed out that the electrostatic charge which can build up on a human body, if discharged, is capable of igniting a great many hydrocarbon-air mixtures. Most mixtures of hydrocarbon and pure oxygen within the limits of flammability would certainly be ignited by such a discharge.

The ignition of gases or liquids by hot surfaces is dependent on the percentage of oxygen in the gaseous mixture as well as on the total pressure of oxygen in the system. The minimum spontaneous-ignition temperatures of some hydraulic fluids can be reduced by almost a factor of 2 when the volume percentage of oxygen in an air mixture is increased from 20 to 100 (fig. 26). Some fluids are hardly affected by this change. The plate-ignition temperatures of many fluids and fuels are reduced by the decrease in percentage of inert diluent or the increase of oxygen tension in air mixtures. Table 9 and figures 29 to 33 indicate the magnitude of change expected from these variations in atmospheric constituents. Figure 31, for instance, demonstrates that as the partial pressure of pure oxygen is increased from 4 in. Hg (2 psi) to 10 in. Hg (5 psi) the plate-ignition temperature of the hydraulic fluid MLO-8200 decreases from 1,100° F to 560° F. The rate and temperature of burning of these fluids is markedly increased by increases in oxygen partial pressure or by decreases in percentage of diluent gas. The explosion potential in-

creases accordingly. It should be remembered that the physical parameters of the test vessel are subtly critical in modifying the specific determination of ignition temperature for any gaseous system.

The ignition temperature or minimum burning current of insulated electrical wire is markedly affected by the partial pressure of oxygen and percentage of inert diluent. Figure 34 and tables 10 to 12 indicate the magnitude of this effect with different insulating materials. The variation in response to these atmospheric parameters by different plastic insulations is marked. Optimum selection of insulation in space cabins requires review of such data.

Ignition of flammable materials by heated gases such as those produced by pilot flames, adiabatic compression, shock waves, and meteoroid penetration is also dependent on oxygen concentration. It would appear that only in the case of hypergolic ignition is the atmospheric oxygen or diluent not a major factor.

The limits of flammability of almost all combustible gases or vapors are determined by the partial pressure of oxygen and by the percentage concentration of diluent gas. In general, the upper (rich) limit is greatly elevated by increasing the oxygen pressure or decreasing the percentage of diluent gas. This is seen in figure 4 for the propane-oxygen-nitrogen system. The range of limits of flammability is changed from 2-10 percent to 2-40 percent propane by increasing the percentage of oxygen from a sea-level environment to a 100 percent oxygen environment. The range of explosion limits is also widened by increasing the partial pressure of oxygen and decreasing the percentage concentration of diluent.

Inert gases affect the range of flammability limits in a way which is greatly modified by the physical environment other than the atmosphere itself. In table 2 it can be seen that for wide tubes, nitrogen is more effective in decreasing the flammability range of hydrocarbon-oxygen systems than is helium, while in narrow tubes helium is more effective. The direction of propagation is also critical. Table 7 indicates that the relative effects of nitrogen, helium, and argon vary from fuel to fuel and

with direction of propagation. The complexities generated by the experimental variables make a clear-cut evaluation of the relative "safety" of the inert diluents most difficult for these gaseous combustion systems.

Once ignition occurs in a system that lies within the limits of flammability, both the rate and the temperature of burning are markedly affected by the oxygen and inert-gas parameters. Figures 14 to 18 indicate the magnitude of these effects for burning fabrics. A very important quantitative point is brought out in figure 18. The rate of burning of cotton fabric in a 5 psi, 100 percent oxygen environment is 3.7 times the rate in the 8,000-foot-altitude air cabin maintained in current pressurized high-altitude aircraft. Comparative rates for other oxygen-nitrogen mixtures may be determined from this graph.

Tables 3 to 5 and figures 20 to 23 indicate how slight increases in the percentage of oxygen in air markedly affect the burning rates of many different fabrics. These tables and figures also indicate that fireproofing techniques which are adequate for sea-level air conditions fall quite short of adequately protecting fabrics in atmospheres with elevated percentages of oxygen. The modification of fireproofing capacity by reduction in total pressure along with elevation in partial pressure of oxygen has not yet been adequately studied. This area deserves further work.

The effect of inert gases on the rate of burning of premixed gaseous hydrocarbons and hydrogen flames has received much study. These combustion systems have much less relevance to space-cabin environments than do nonhomogeneous solid, liquid, and vapor systems. The magnitude of inert-gas effects cannot be directly extrapolated from the well-mixed gaseous systems to the nonhomogeneous vapor, solid, and liquid systems.

In figures 13 and 24, it can be seen that for the gaseous hydrocarbon or hydrogen combustion systems, nitrogen is far more effective than argon or helium in retarding the flame speed in burner experiments. From figures 17 and 19 it can be seen that nitrogen is only slightly more effective than helium in retarding the rate of burning of fabrics. In both the

gaseous and fabric combustion systems, however, the percentage of diluent does have a marked effect on flame speed or burning rate regardless of what diluent is used. For example, in figure 24(b), increasing the percentage of helium, argon, and nitrogen gas from 0 to 80 percent will decrease the flame speed of a propane-oxygen burner system from 11 ft/sec to about 1 to 3 ft/sec.

It is important to realize that the temperature of the combustion system is also reduced by addition of inert diluent gases. Figure 25 indicates that for several hydrocarbon and hydrogen systems, increasing the diluent gas from 50 volume percent to 80 volume percent will decrease burning temperatures from about 2,600° K to 1,600° K. This is also true in the burning of liquids and solids. Reduction of rate and temperature of burning by inert gases has a great effect on the fire and detonation hazard. As the time scale of combustion phenomena is reduced, deflagration or flame phenomena are, in specific systems, converted to detonation phenomena. As the rate and temperature of combustion are reduced, the chances of secondary detonation are reduced, as are the chances of secondary fires in materials with higher ignition temperatures.

In the overall deflagration hazard it is, therefore, difficult to assess the exact safety factor which an inert gas contributes. This is also true in the case of the meteoroid blast and flash hazard. In the studies of simulated meteoroid penetration it was clear that the intensity of the light flash and subsequent burning of animals was markedly affected by the presence of nitrogen in the environment. In the Ling-Temco-Vought studies, penetration into a 5 psi, 100 percent oxygen environment resulted in a light flash 7 times as intense as in a sea-level environment. Interestingly enough, the light flash appeared more intense in a 5 psi 100 percent oxygen environment than in a 14.7 psi 100 percent oxygen environment. The blast overpressures, however, appeared little affected by the oxygen concentration in the cabin. The revised penetration-probability figures suggest a minimal weighting of the meteoroid blast factor in a choice of cabin atmospheres for current cislunar missions.

FIRE RISK OF HIGH-OXYGEN LOW-INERT-GAS ENVIRONMENTS

After reviewing these data, is there actual justification for eliminating 100 percent oxygen environments in space cabins as an excessive risk? The argument against this step may be mustered as follows.

All the data presented in this report are of an idealized nature. The probability of having fires of the well-mixed homogeneous gaseous variety is extremely low. Hydraulic systems, machinery requiring lubricants, propellants, and all of the hazardous equipment and conditions outlined in Chapter 6 can be eliminated from the cabin. Only electrical insulation, clothing and other fabrics, mattress or padding materials, and paper are the fuels which cannot be eliminated. Proper fireproofing and choice of these materials and adequate fire discipline in the crew as outlined in Chapter 6 will reduce the hazard in even these combustion systems to a negligible minimum.

The problem of meteoroid penetration and resultant flash and blast hazard is significant only for missions in the asteroid belt. About the earth and in cislunar space the probability of being penetrated by a meteoroid is extremely small. The latest calculations presented in Chapter 5 of this report indicate that for spacecraft with 28 square meters of surface area, an aluminum skin 0.03cm thick, and no meteoroid shield system, the chances of being penetrated by meteoroids in the vicinity of the earth is once every 2.3 years. Addition of a bumper and absorption core, with possibly little addition in overall weight, will reduce this probability by a factor of 10. These probabilities are for minimal penetrating masses. What if the craft is penetrated by such a small particle? From the studies of the Ling-Temco-Vought group, it would appear that the flash and blast from minimal penetrating particles would not excessively endanger a crewman at the center of a typical space cabin. It would take an extremely rare particle of large mass to be a significant factor as a space-cabin hazard. As justification for the addition of inert gases to space-cabin systems, the meteoroid hazard should be relegated to the bottom of the list.

What about protective systems? If automatic fire detection and extinguishing devices are considered for large space-cabin systems where remoteness of crew from trouble spots becomes a factor, the fire risk is further reduced. The vacuum of space and the potential for rapidly eliminating oxygen from the cabin environment by venting the atmosphere is a tremendous safety factor. It is true that in the "shirtsleeve" environment projected for long-range space missions, this safety factor will be limited by the time required for donning suits or exiting to an emergency compartment. However, in "current missions" where lack of experience weighs heavily in the fire risk, crews will probably be in pressure suits throughout the entire flight profile. The venting mechanism will, therefore, be available when it is needed the most.

What about gravity? From the discussion in Chapter 1, zero gravity will most probably reduce the fire hazard rather than increase it. Therefore, should not elimination of forced convection allow zero gravity to "put out fires"? As was pointed out, the degree of hazard reduction is open to question and cannot be determined from theoretical considerations. Empirical data are obviously required to answer this question. The only zero-gravity factors that augment combustion are the creation of ignition hot spots and the reduction of heat transfer from the flame front due to lack of convection. Since potential hot spots can be predetermined, this unfavorable zero-gravity interaction can be eliminated by good safety design. It appears, therefore, that one may rely, but not too heavily, on zero gravity to reduce the fire risk.

After considering all the above arguments, is not the concern about fire and blast risk resulting from 100 percent oxygen environments only academic? At first sight, the arguments presented do seemingly reduce the concern. It is easy to say that sophisticated safety design will eliminate ignition sources and fuels and that training will eliminate human errors. It is also easy to rely on the dumping of cabin pressure, zero-gravity fire attenuation, and detector-extinguisher systems as backup for potential design failures. It is difficult, how-

ever, to assign to many of these factors a probability of success or failure. The ultimate question, of course, is this: Is the increase in overall probability of mission failure brought about by the fire risk of 100 percent oxygen environments greater than the overall probability of failure brought about by the added weight and complexity of a multigas cabin system? The fire risk of 100 percent oxygen is one aspect of the problem. The risk of oxygen toxicity discussed in Part I of this report is another. The two must be added together to assess the overall risk of 100 percent oxygen environments. Can the risk attributable to a 100 percent oxygen environment as opposed to inert-gas systems be determined in a more quantitative fashion with regard to fire hazard than it could be with regard to physiological oxygen toxicity? The answer is probably "not at this stage of the game." There are not enough quantitative data on the non-

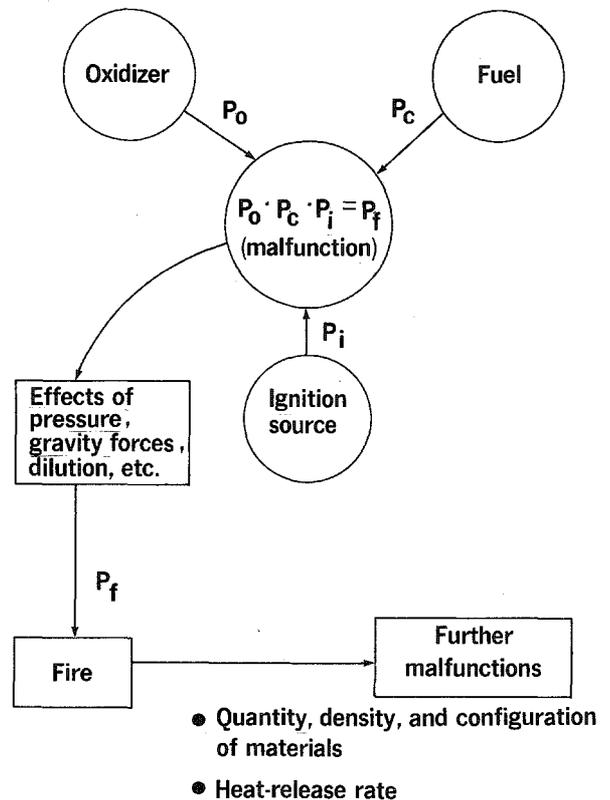


FIGURE 54.—The fire situation. (AFTER CARY ET AL.³³)

homogeneous, multifactored fuel-oxidant interactions that represent the space-cabin fire hazards to assign valid probabilities. How does one approach the problem of estimating these probabilities?

ESTIMATION OF OVERALL FIRE HAZARD IN ENGINEERING DESIGN

In their recent review of the reliability of flight-vehicle fire protective equipment, Cary et al.³³ have presented a framework for a possible approach to the quantitative evaluation of fire risk. Let us briefly review some of these basic concepts, with emphasis on the gaseous atmosphere.

The probability of fire is only one component of the overall mission hazard. Thus, the probability of the overall mission hazard P_H may be represented by the relation

$$P_H = 1 - (1 - P_1) \times (1 - P_2) \dots (1 - P_i)$$

where the probability of fire P_f is one component. The event of fire depends on the coincidence of a combustible fuel, an oxidizer (not necessarily in stoichiometric quantities), and an ignition source. An expression for the probability of fire may be written as follows:

$$P_f = P_i \cdot P_c \cdot P_o$$

where

- P_f probability of fire associated with each class of materials in cabin
- P_i probability of malfunction causing a suitable ignition source (equal to 1.0 if fuel and oxidant spontaneously inflame) in the normal environment
- P_c probability of available combustible fuel (taken as 1.0 if fuel material is present, or some value from 0 to 1.0 if fuel availability depends on malfunction or other circumstance)
- P_o probability of available oxidizer (taken as 1.0 if oxidizer is present, or some value from 0 to 1.0 if oxidizer availability depends on malfunction or other circumstance)

Figure 54 is a schematic representation of these probability relationships. The growth and propagation of a fire will depend on the

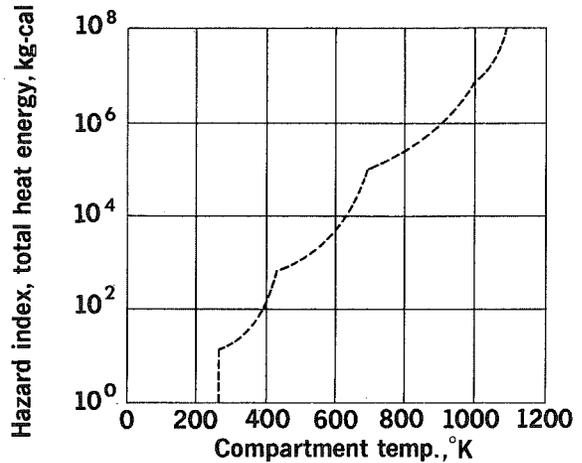


FIGURE 55.—Variation in hazard index during fire in a hypothetical compartment. (AFTER CAREY ET AL.³³)

type and amount of fuel and oxidizer available and the geometry or arrangement. Obviously, when an excess of fuel is present, the burning rate is proportional to the rate of introduction of the oxidizer. When an excess of oxidizer is present, the burning rate is proportional to the rate of supply of the fuel. Reduced pressure and addition of inert diluents tend to slow down the reaction. As the fire grows in intensity, greater amounts of fuel may become available, and further malfunctions caused by the fire may lead to fire situations in other areas.

For each compartment it seems possible, in concept at least, to determine a hazard index. An index would express the total heat energy that would be present as a function of temperature (with time implicit) when the fuel materials available were burned. The total high-energy index for a hypothetical compartment might take the form shown in figure 55. The calculation of the index itself will be discussed below. The sequence illustrated assumes that the most easily ignited material has been ignited by a minimum ignition source. As the total thermal energy within the compartment increases and the average compartment temperature increases, more fuels or oxidants become available to the fire, and the heat released increases in discontinuous steps corresponding to the ignition temperature or flash point of these secondary fuel sources. At some point,

the detonation hazard appears to complicate the picture.

It is quite clear that the actual degree of hazard depends upon a large number of specific characteristics which have already been reviewed:

- (1) Flammability limits (variation with temperature, pressure, and fuel-oxidant combinations)
- (2) Chemical reactivity
- (3) Heat of combustion
- (4) Ignition temperature and minimum ignition energy and quenching distance
- (5) Character of products (toxic, corrosive, noxious)
- (6) Rate of pressure rise and pressure ratio
- (7) Flame speeds
- (8) Vapor pressures
- (9) Range of hypergolicity of fuel-oxidant combinations
- (10) Heats of vaporization
- (11) Detonation characteristics

It is obvious from our review that the role of inert gases in each of these characteristics is quite complex in itself and dependent on the physical parameters of the specific combustion hazard in question. It would require an extraordinary amount of full-scale in situ experimentation to define these parameters adequately.

In view of the obvious difficulties of attempting a rigorous definition and calculation of a hazard index, the simplified concept in figure 55 may be used as a very rough approximation. The index could be determined as follows:

$$H = \frac{h_c}{MC_p}$$

where

H hazard index

h_c maximum total heat-energy release from all possible combustion reactions within the compartment

\bar{C}_p average heat capacity of all materials within the compartment

M total mass of all materials within the compartment

Given sufficient information, values of the hazard index could be determined for each

increment of time after initiation of combustion as indicated in figure 55. It would be necessary to determine what kind of fire is most likely to initiate the fire sequence. For a given compartment configuration, different ignition sources can initiate the fire sequence as the temperature rises. This is illustrated conceptually in figure 56. At the lowest temperature, powerful ignition sources would be required. As the temperature rises, weaker ignition sources may become effective, until finally spontaneous ignition occurs.

It has been assumed in this discussion that the design configuration would make use of compartmentation. The importance of effective thermal barriers between compartments is evident. The full scale of compartmentation can be achieved only if the barriers can shield adjacent units from the heat released by burning fuels inside the compartment. Such arrangements could serve to isolate the high-fire-hazard units that could not otherwise be eliminated. Further reduction in the probability of fire may be gained if the compartments or packages can be positioned so that high-fire-hazard compartments are surrounded by low-fire-hazard compartments. As the size and content of each compartment is reduced, perhaps to the level of individual compartments (i.e., packages), probability of fire would be likely to decrease also.

The probabilities of reducing the overall fire risk by inclusion of semi- or fully-automatic fire detecting and extinguishing systems can be determined. As outlined in Chapter 6, these probabilities must be calculated in the light of the unusual gaseous components of the atmosphere and zero-gravity conditions. The review of Cary et al.³³ outlines in detail the research work which is still required to allow complete reliability analysis of detection-extinguishment systems.

How helpful is the historical approach? Can the experience with fires in operational aircraft be used to obtain empirical probability factors for such an overall fire-hazard analysis? The answer is probably no. In operational aircraft cabins one is dealing with air atmospheres at reduced pressures. Experience with aircraft fires is, therefore, limited to only one possible

parameter in the space-cabin atmosphere. It should also be remembered that the necessity for fire risk analysis in aircraft is based on a different requirement than is the risk analysis in space cabins. In aircraft cabins, the design of the cabin and the atmospheric constituents are basically fixed. The risk-regret analysis of the fire hazard-detection-extinguishment profile is required for a decision relative to the necessity for and design of a supplementary fire protection system. In the space cabin, such an analysis is required for the actual cabin design and choice of atmosphere. This actually puts the cart before the horse and thereby complicates the whole picture.

AN INTUITIVE APPROACH TO THE CHOICE OF ATMOSPHERE

It appears that the ultimate decision relative to the weighting of the fire hazard in the total

selection of a space-cabin atmosphere will be made on a semiquantitative level with intuition playing a major role. The time needed for more quantitative appraisal of the fire problem appears to run well beyond the maximum time available for engineering decisions regarding single- versus multi-gas systems.

This general appraisal of the situation may be started by recognizing that the safest cabin atmosphere is air at reduced pressure. The 8,000-foot atmosphere used in current high-altitude aircraft cabins is about as safe as can be in the tradeoff between fire hazard and physiological hazard. Lower air pressure would decrease the cabin fire hazard. If an 11 psi cabin pressure were beyond engineering capabilities, or if a lower pressure were deemed desirable to reduce the decompression hazard (Part III of this report), a decrease in pressure and concomitant increase in partial pressure of

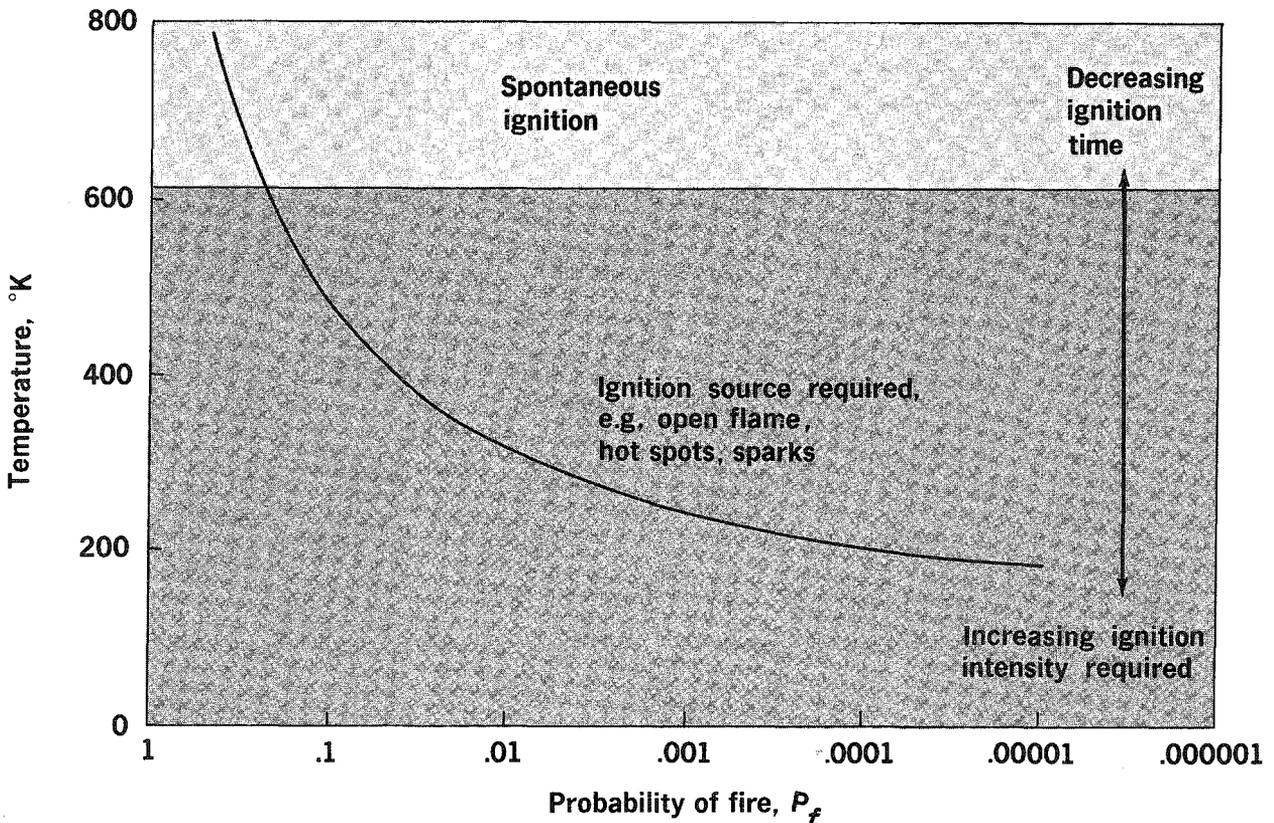


FIGURE 56.—Concept of probability of initiation of fire for hypothetical compartment. (AFTER CARY ET AL.³³)

oxygen would be required. There appears to be no clear-cut threshold in the fire hazard as the percentage of oxygen is increased. Increasing the oxygen generally affects all the combustion parameters in the direction of increasing the hazard. However, as Wolfhard²⁴³ points out, it is probably the first moderate increase of oxygen index that changes the fire hazard most severely.

The sensitivity of response of each combustion parameter to elevation in percentage of oxygen is different. Minimum ignition energy for electrostatic sparks is probably the most sensitive. Other parameters follow behind at varying degrees of sensitivity. It is difficult to arbitrarily set a given limit for tolerable hazard even in such clear-cut factors as minimum spark-ignition energies or rates of burning of fabrics.

As far as the choice of inert gas is concerned, the decision is again too complex for an approach other than the intuitive. Helium appears to be safer than nitrogen as far as spark-ignition parameters are concerned, but is a much poorer choice in the case of the rate of burning of premixed gaseous systems.

Nitrogen is also very slightly safer in terms of the rate of burning of fabric materials. Wolfhard²⁴³ feels that, overall, nitrogen is the safer of the two gases.

Neon lies between helium and nitrogen in narrowing the limits of flammability in hydrogen-oxygen systems. No other data were obtained for neon. This gas may well be a good compromise in the overall reduction of fire hazards. The choice of inert gas will probably be determined by factors other than combustion parameters (to be discussed in Parts III and IV of this report).

In conclusion, it cannot be stated with certainty on the basis of present data that, as regards fire hazard alone, 100 percent oxygen should be eliminated as an atmospheric environment in space cabins. The closer to the 8,000-foot air atmosphere one can get, the safer the choice. Any compromise of this "ideal" should be in favor of more inert diluent and lower total pressure. The more closely the ideal fire-prevention design and the ideal detection and extinguishing systems outlined in Chapter 6 are approximated, the less significant becomes the choice of atmosphere.

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