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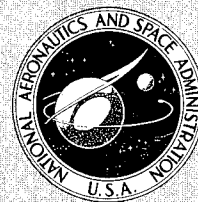
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CONFERENCE ON MATERIALS FOR IMPROVED FIRE SAFETY

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

MAY 6-7, 1970



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FOREWORD

The Manned Spacecraft Center was pleased to host the NASA Conference on Materials for Improved Fire Safety which was held May 6-7, 1970. This document is a compilation of papers presented at the conference and represents the culmination of several years of effort by NASA and industry which was directed toward the common objective of minimizing the fire hazard in manned spacecraft and in some other related areas. One of the more serious problem areas in the Apollo program was the flammability of nonmetallic materials. The effective and timely solution of this problem area resulted from much of the effort reported herein and contributed greatly toward the successful achievement of landing men on the Moon and returning them safely to Earth.

Each year on Earth the loss in property and human lives resulting from fire is enormous. The materials developed for improved fire safety and the many lessons and knowledge gained in the course of conducting this research and development are quite extensive and should find many direct and useful applications in industrial, commercial, and domestic areas. With the judicious and proper application of such information it should be possible to make a large step toward minimizing this age-old hazard to mankind.

ROBERT R. GILRUTH
Director
Manned Spacecraft Center

PREFACE

Leaders in an impressive variety of industries and Government agencies were briefed for two days in May 1970 at the Manned Spacecraft Center near Houston on studies of combustion, tests of materials, and methods of curbing fires. The research and development work described was done as part of the National Aeronautics and Space Administration's Apollo program to land men on the Moon. The hazards were extraordinary, and both new procedures and new materials were developed to protect the astronauts in the spacecraft. This Special Publication was compiled from technical papers prepared for that Conference on Materials for Improved Fire Safety.

Congressman Jerry L. Pettis of the 33d District of California sounded the conference keynote in an address entitled: "What Earthly Good Is Space?" Many persons unaware of the many ways in which innovations in technology can now serve mankind have asked this question. The answer became increasingly clear throughout the four sessions of this conference, and will be apparent to those who examine the 163 illustrations, the dozens of tables, and the related reports in this publication closely.

The technology developed to provide a safe environment for men in spacecraft can be adapted to many other modes of transportation. It can be used to reduce the possibilities of fires and toxic gases in vehicles built to travel on and under air, land, and water as well as in the vacuum beyond our atmosphere. The testing procedures used in the space program can also be adapted to meet challenges in manufacturing goods for consumers. The danger of fires in refineries, factories, mines, and woodlands can be further reduced. By the proper selection and placement of materials now available, our homes, hospitals, farms, and cities can be made more secure.

"A breakthrough in fireproofing technology has been achieved," as Congressman Pettis said. "The successful R and D program conducted by NASA in the field of non-metallic fireproof materials has produced a 'quantum jump' that can greatly affect many major industries and has profound life-preserving implications."

Some applications of the newly available knowledge of combustion and materials to age-old problems have already begun. More will be discovered as men and women with imagination, Yankee ingenuity, and a desire to serve their fellow men, become acquainted with technical findings such as this publication reports. The authors of the papers that follow could only partially foresee the use which others might make of their data. They have striven, therefore, to present the results of their work in a manner helpful to all researchers on the frontiers of science and engineering.

"Ours is an open society," Congressman Pettis pointed out. "That policy pays off. This conference was conceived, design, and engineered to make known—and to make available to the public—a vital area of new technology developed by NASA that can have a revolutionary impact on society. Much of this technology was paid for out of public funds. It is appropriate that it be made available for the public good as soon as possible.

"The national space program and the impetus that it provides for advanced research, experimentation, and development affords us a unique opportunity to transfer technology into social benefits. When a man's life is involved, we in America have always tried harder, worked better, and produced more reliably. For manned space systems, 99 percent reliability wasn't good enough. Our motive was to save the lives of the astronauts—and other lives are saved as a result.

"The acceleration of scientific and technical progress, propelled by the space exploration mission, has touched every field of science, every body of knowledge, all aspects of civilization, and every human life will ultimately feel its impact."

The Technology Utilization Program of NASA is an effort to accelerate the dissemination and widespread industrial use of technology applicable to tasks outside as well as within the aerospace community. This is being done in part by holding conferences for leaders in particular industries and professions, and in part by the issuance of Special Publications.

This particular conference was concerned wholly with safeguarding lives and property from fire. This can be done in a great variety of ways: by the choice of materials for clothing, paints for compartments, electrical packaging, by the use of intumescent and other coatings to prevent fires from spreading, by the testing and isolation of flammable materials, and by the establishment of criteria and management systems that minimize the possibilities of hazardous combustion. All of these techniques were considered and explored as part of the Apollo program.

At the first session of the Houston conference, Manned Spacecraft Center spokesmen described how nonmetallic materials were screened, the flammability of components was measured, and the fire safety of the Apollo command and lunar modules finally assured. At the next session, the development and use of special materials such as elastomers, polymers, potting compounds, and light plastic foams was reviewed in more detail. At the third session, configuration control, the clothing of the astronauts, the effects of gravity on flames, and fire extinguishment were among the topics discussed. At the final session, the speakers reviewed their experience with special tests devised to prevent electrical fires from spreading, to evaluate materials, to make certain that toxic gases would not fill the spacecraft, and to assure control of the oxygen environment of the spacecraft in which the astronauts were confined.

This publication has been issued to disseminate the information to a wider audience. A glossary has been included to assist readers who may find some of the terminology strange. As more men and women examine these reports, other further potential uses for the technical data and information will result, and more dividends will accrue to all mankind from our national investment in space flight.

PHILIP H. BOLGER
*Assistant NASA Security Director
Conference Chairman*

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Session I

FLAMMABILITY REQUIREMENTS AND TEST TECHNIQUES

ALECK C. BOND, *Chairman*
Manned Spacecraft Center

The Combustion Process

W. R. DOWNS

Manned Spacecraft Center

Fire and combustion have contributed immensely to the sciences of chemistry and metallurgy, to power production and utilization, to man's physical comfort, and to the development of spacecraft systems and modern rocketry. The most commonly observed form of combustion is that of ordinary objects burning in air. This appears to be a simple process; but, in reality, it is a most complex action. The objective of this paper is to describe the basic processes of combustion.

DESCRIPTION OF THE COMBUSTION PROCESS

Combustion is defined as any relatively fast, heat-producing reaction of a fuel with an oxidizer. The term "relatively fast" indicates times in seconds or fractions of seconds. The essential ingredients required for combustion are fuel, oxygen or other oxidizers and an ignition source. The fuel must be a material that will unite with oxygen to produce a significant amount of heat. For most materials, the initiating energy must be supplied by an ignitor, for example, a match, a hot wire, or heat produced by friction. For most solid fuels, this energy must be sufficient to raise the temperature of a small region of the fuel to a point at which decomposition or pyrolysis will occur. However, for carbon and metal solids, the oxidizer reacts directly with the solid surface of these materials to form combustion products (oxides). The temperature must be raised sufficiently to make possible a self-sustaining, rapid chemical reaction. This condition constitutes incipient combustion, which is a critical stage in that excessively rapid conduction of

heat away from the area will tend to stop combustion, whereas appropriate heat-transfer rates in the fuel and the oxygen-fuel gas mixture at the fuel surface will enhance combustion. Once ignition has been achieved, the combustion process for most solid fuels becomes dependent on the rate at which pyrolysis of the fuel can occur, the rates at which the gases react, the availability of oxygen, the specific heats of the gaseous mixtures, and the heat losses from the system. In the ignition and ensuing combustion processes, much depends on the availability of oxygen. The ability of the ignitor to initiate combustion, the speeds at which pyrolysis products of the fuel are produced, and the rates of the gas-phase reactions all depend on the availability of oxygen.

In any gaseous mixture, the availability of a gas is a direct function of the gas concentration, which is measured normally by the partial pressure of that gas in the mixture. For example, oxygen in air exists at a partial pressure of 0.2 atmosphere and, thus, is only one-fifth as available in air as it would be in a 100-percent-oxygen atmosphere. Therefore, a severalfold increase in combustion rates in 100 percent oxygen compared to that in air at the same pressure is expected. Furthermore, as combustion products are formed, the relative oxygen concentration can be decreased from the initial concentration in the absence of sufficient convection or in a restricted volume.

CHEMICAL AND PHYSICAL MECHANISMS

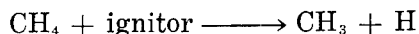
Until approximately 170 years ago, flame

was thought to be an imponderable substance that flowed into and out of materials and consumed them. A study of the candle flame by Sir Humphrey Davy led to the basis for understanding fire and combustion; similarly, in this paper, the candle flame will form the basis of a discussion of chemical and physical mechanisms that occur in the combustion process.

The fuel in the candle is paraffin, a solid straight-chain hydrocarbon. Methane is the simplest member of the hydrocarbon (paraffin) series, and is a fundamental building block of such hydrocarbons. To keep the chemistry as simple as possible, methane will be considered as the fuel in the following explanation. The reactions of methane as a fuel are more or less typical of those of the higher members of the paraffins. The reaction of methane with oxygen yields carbon dioxide, water and heat



For this reaction to begin, an outside ignition source must be used. Introduction of the ignitor is shown by the expression



The energy from the ignitor breaks a chemical bond in the methane molecule, and the result is the formation of two chemical species, CH_3 and H . The CH_3 and the H are called "chemical free radicals." A chemical free radical is an electrically neutral fragment that possesses unpaired and unshared electrons and, therefore, is readily reactive. This is the first step in a complex series of events that comprise the total combustion reaction. The making and breaking of chemical bonds involve energy changes that may result in the production or absorption of heat and light. If the combustion process were explicable completely by this action, then a specific color of light or radiant spectrum for any given burning fuel could be observed. However, other complicating factors occur. These factors may be classified into two kinds: (1) the chemical reactions of the free radicals with each other, with surfaces with which they come into contact, and with mo-

lecular species that may be present; and (2) a coupling of the chemical reaction rates with convective effects induced by gravity or by ventilation gas flow. Each of these two factors will be discussed.

EFFECTS OF FREE-RADICAL REACTIONS

The H free radical produced from rupturing the bond of the methane molecule combines immediately with an oxygen molecule to produce the hydroxyl free radical (OH) and an oxygen atom (O). The OH also is readily reactive, and it attacks another methane molecule to yield water and another CH_3 radical. This process (fig. 1) continues in rapid sequence until all of the methane is consumed or until the oxygen is exhausted. This sequence of chemical reactions is called the chemical-chain mechanism for combustion of methane, and it should be noted that the net result is the union of oxygen with methane to produce water, carbon dioxide, and heat. More complicated but similar chain-reaction mechanisms take place when fuels such as plastics, wood, or fabrics are burned.

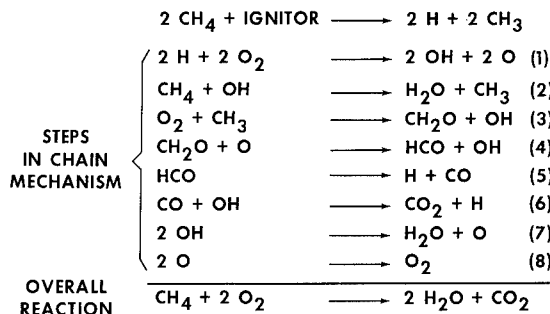


FIGURE 1.—Chain mechanism for methane combustion.

CONVECTION AND GRAVITATIONAL EFFECTS ON COMBUSTION RATES

By definition, combustion is an exothermic reaction—that is, heat is produced. In a gravity field, the locally heated gases experience convective forces that couple with the chemical-chain mechanism. The convection brings into the combustion zone additional oxygen for reaction with the free radicals.

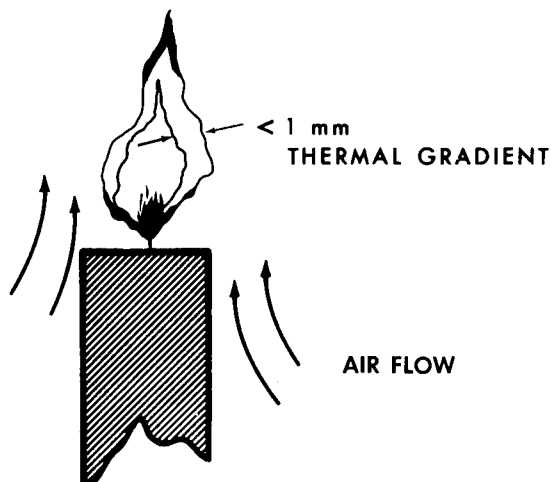


FIGURE 2.—Candle flame on earth.

This coupling of convection and combustion is illustrated in figure 2. Here, all of the chemical-chain-mechanism reactions represented in figure 1 are taking place in a very thin zone, called the reaction zone, around the flame. This reaction zone is the region where the chemical free radicals encounter oxygen from convection currents.

The reaction rate for a mechanism in which convective coupling exists can be represented by the Arrhenius equation (ref. 1):

$$K = A_e^{-E/RT}$$

where K is the reaction rate, A is a constant, e is the Naperian log base, E is activation energy, R is the universal gas constant, and T is absolute temperature (average) of the flame. As the gravitational field is increased and convective mass transfer increases, the burning rate first increases rapidly and then levels off. This leveling off occurs at different values of acceleration for different materials, but it generally occurs at an acceleration of greater than $3g$. This is to be expected from the molecular model previously considered if examination is made of the thin reaction zone where most of the chemical reactions occur and if it is considered that, as gravitational forces increase and convection becomes an ever-increasing driving force, the

reaction zone becomes thinner and the reaction becomes fuel-limited.

In addition to convection, other factors are involved in the reaction zone in a flame: diffusion, conduction, viscosity, and radiation. The interrelationships of the most important of these factors are shown in figure 3, which illustrates the energy/spatial relationships that exist in any flame. In this illustration, factors which tend to contribute to the energy of the flame are assigned positive values and those the net effect of which is to remove energy from the flame are negative. Thus, diffusion and convection, by providing oxygen for combustion, have a net effect of contributing to the energy of the flame.

In a zero-gravity environment and with no convective coupling, any burning would be expected to be significantly different from that of a gravity environment (ref. 2). Without the coupling of convection, the flame initiated by an ignitor is influenced subsequently primarily by diffusion of the gaseous products away from the fuel and of oxygen toward the fuel. The reaction rate for such a process can be given by the following equation (ref. 1):

$$K = AT^{-n}$$

where K is the reaction rate, A is a constant dependent on fuel composition, T is the absolute temperature (average) of the flame, and

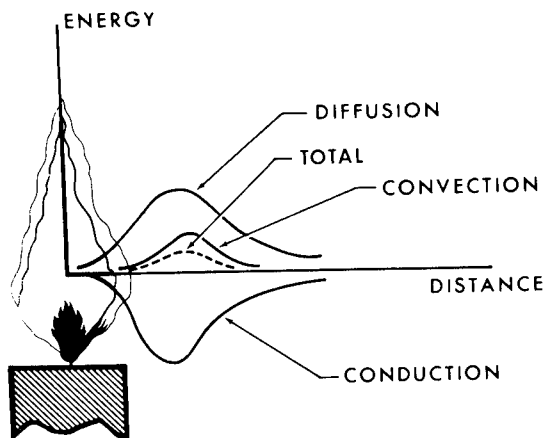


FIGURE 3.—Energy transport from a candle on earth.

n ranges in value from 0 to 1.5 for most fuels. Under a reduced convection environment, diffusion broadens the flame front and thickens the reaction zone. The reaction becomes oxygen-limited as convection is reduced. The thinning of the reaction zone under increasing convective conditions indicates a trend toward fuel limiting of the effects of coupling, and a subsequent limitation of the convective effects because of eventual limitation of flame temperature. These combustion conditions are illustrated in figure 4; the flame thickness is that region in which the radiant energy is visible. The reaction zone is that part of the flame in which the oxygen combines with the fuel.

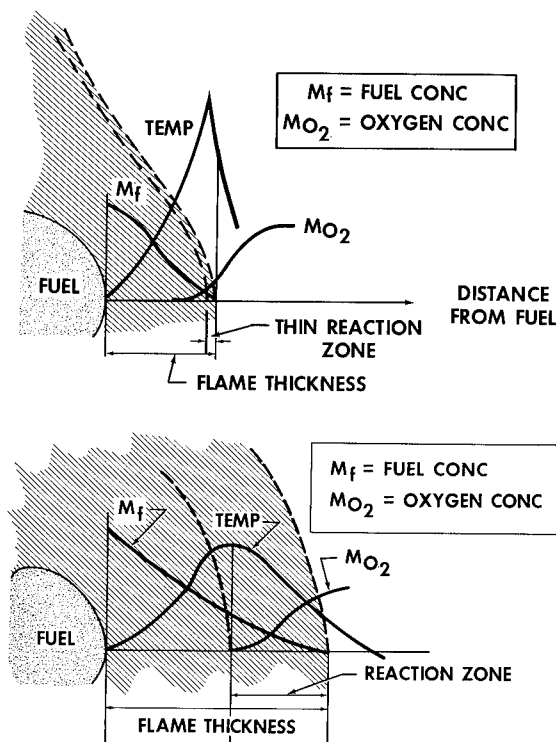


FIGURE 4.—Comparison of combustion under convective conditions (top) and nonconvective (zero gravity) conditions (bottom).

FEEDBACK

The heat generated by active free-radical species accelerates chemical reactions; heat lost by radiation, conduction, and convection

reduces the rate of reaction; and the availability of fuels provides an upper limit to the reaction rates. Combustion chemistry, therefore, is seen as a chemical "feedback" system (fig. 5). Steady-state burning is carried out only when an exact balance is achieved or when the fuel is made available at a constant limited rate, as in a burner or a candle. If the feedback exceeds some critical factor, the system becomes self-sustaining and combustion increases.

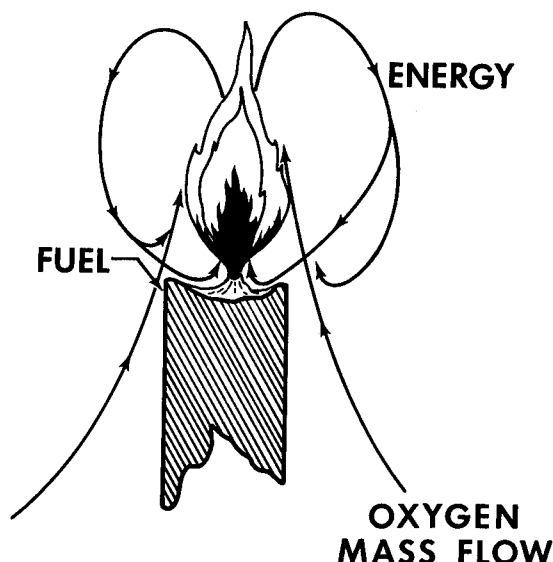


FIGURE 5.—Feedback mechanism of burning candle.

ADDITIONAL FACTORS IN THE COMBUSTION PROCESS

On the basis of the preceding chemical and thermodynamic considerations, it now is possible to explain some of the principal additional effects involved in combustion. Parameters such as fuel compositions, exposed area and density, geometry, and diffusion effects involving oxygen transport will be discussed.

Fuel composition has a tremendous effect on flammability and combustion. Some materials simply will not burn, even in pure oxygen. Most carbon-containing and silicon-containing materials, such as most of the polymers, will burn in 100 percent oxygen at a pressure of 1 atmosphere; those that are

pyrolyzed easily will sustain combustion at oxygen pressures much lower than 1 atmosphere. In such fuels, the reactive chemical species are formed with relative ease. Fuel composition, therefore, determines the combustion susceptibility and the ease of pyrolysis and affects the reaction rates over a wide range of oxygen pressures and a wide range of ignition temperatures. Carbon and metal solids do not so burn. For these materials, the oxidizer reacts directly with the surface of the solid.

Exposed area and density affect combustion rates. Samples having high thermal conductivity and high heat capacity act as heat sinks to inhibit the onset of the reaction-chain mechanism. On the other hand, materials with large surface area and low density, such as nylon or cotton fabrics, exhibit low thermal conductivity and heat capacity and ignite with ease.

The overall orientation of the specimen as it relates to the convective environment governs whether combustion will progress in the direction of the convective mass flow or in some other direction. This orientation is important in determining the extent of the transport coupling and the ultimate combustion rate attainable for a given material. The transport coupling is greatest where convective mass flow is toward new, unburned combustibles. Here, the fastest rates are attained; the highest temperatures are reached; and, because of convection, the greatest difficulty is encountered in achieving extinguishment.

CONCLUDING REMARKS

Combustion has been defined as any relatively fast, heat-producing reaction between a fuel and an oxidizer. The ingredients for combustion are normally oxygen, fuel, and an ignition source, and the efficiency of the process is dependent on the availability of oxygen. The combustion process for most fuel materials is a reaction chain mechanism for the fuel oxidation involving the formation and destruction of chemical free radicals. However, for carbon and metal solids, the oxidizer reacts directly with the surface to form combustion products. The chain-reaction mechanism couples to the energy and material transport factors in which a portion of the energy produced is fed back to drive the reactions. In addition to the chemical feedback mechanism, factors such as the fuel composition; exposed surface area of the fuel; the density, geometry, and convective environment of the fuel; and diffusion effects play an important part in the combustion process by governing the rates at which combustion takes place. Convection and diffusion forces promote the rate of combustion and generation of heat, whereas thermal conduction and reactant starvation diminish these rates.

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Manned Spacecraft Nonmetallic-Materials Flammability Selection Criteria and Requirements

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ABSTRACT

In this report, the criteria and requirements governing the selection of nonmetallic materials for use in manned spacecraft to control potential fire hazards are reviewed. To illustrate how the criteria were met, the development of the NASA Manned Spacecraft Center flammability requirements are discussed and traced through their historical evolution. Also, the events that dictated the changes that have taken place are discussed. The current nonmetallic-material requirements include the following areas.

1. A new approach, nonmetallic-materials usage categories, emphasizes acceptance based on the location and amount of the nonmetallic materials used in the spacecraft, as well as the fire-resistant performance characteristics of the materials.

2. The importance of the test ignitor is presented, and the current standard ignitor and several special-usage ignitors are described.

3. The flammability screening and application tests are presented, and the importance of these tests in the final verification and acceptance of nonmetallic materials is emphasized.

Significant features of a nonmetallic materials handbook are discussed. This handbook includes materials-selection guidelines, test requirements, and materials control programs. Also, the handbook includes an extensive compilation of materials test results

and performance characteristics obtained from tests conducted during the past several years. Finally, a brief discussion of the applications of the Manned Spacecraft Center criteria and requirements to nonaerospace areas is included.

INTRODUCTION

The selection of nonmetallic materials is controlled by established criteria, guidelines, and requirements to eliminate the flammability hazard. Discussions in this report are limited to those nonmetallic materials intended for use in manned spacecraft. The overall system constraints must be considered during the materials-selection process. They include—among other parameters—weight, location, volume, performance, and the oxygen environment to which the material will be exposed.

A brief discussion is given here of (1) the historical evolution of the nonmetallic-materials flammability requirements and criteria, (2) materials usage categories, (3) test-ignition-system choice, (4) nonmetallic-materials screening-test requirements, (5) application-test requirements, and (6) potential nonaerospace applications. Other reports presented during the symposium treat specific areas in more detail. In this report the evolution of nonmetallic-materials requirements and present Manned Spacecraft Center (MSC) nonmetallic-materials control requirements are reviewed.

HISTORICAL EVOLUTION OF NONMETALLIC-MATERIALS FLAMMABILITY CRITERIA

Before 1963, flammability controls in the field of nonmetallic materials were sparse and depended primarily upon materials specialists acting only on a consultant basis. In 1964, the conclusion was reached that additional requirements were needed if the flammability aspects of nonmetallic materials were to be controlled. Working groups were formed with the Apollo spacecraft contractors to attempt to define the need and extent of the necessary controls. Several conclusions were reached during these sessions, including the need for (1) a nonmetallic-materials flammability screening-test specification, (2) suitable accept/reject criteria, (3) an acceptable / nonacceptable nonmetallic-materials flammability list, and (4) additional work in the use of nonmetallic materials in an enriched oxygen atmosphere.

During May 1966, two specifications were prepared, and several nonmetallic materials were tested to one of the specifications. However, it was soon discovered that this specification was too permissive. Also, because the initial ignitor that was used was not representative of credible spacecraft ignition sources, a number of materials that were noted as acceptable were later found to be unacceptable using the more severe and more representative ignitor system discussed in this report.

A shortcoming of the earlier specifications was that the applications of the materials were not considered in the development of the acceptable/unacceptable nonmetallic-materials list. No consideration was given to the geometry, thickness, or usage of the various materials being tested. It was noted that the requirements of manned spacecraft associated with enriched oxygen atmosphere, operation in a hostile environment, high-density requirements in crew-bay area, and capabilities of fire-extinguishing systems required more restrictive methods of control. For this reason, a new specification was published during 1967 to encompass the important element of evaluating materials based

on usage in the spacecraft. This document specified that screening tests must take into account such items as material quantity, location, area exposed to oxygen, positive ignition sources, possible propagation paths, and the most severe environment the materials are expected to encounter.

Material categories that specify the material usage are defined in table I. These specific material categories were chosen because they accurately define all the major usages within and outside the crew-bay area of the spacecraft. The categories are defined further by the level of flammability hazard that is associated with each material usage and aid in developing realistic criteria and tests. For example, a small nonmetallic ink marking does not require the same degree of flammability testing as do large quantities of nonmetallic materials exposed within the crew-bay area.

During 1968, a specification was prepared to support a major redesign activity in the Apollo Program. At approximately the same time, a proposed Center-level document was published. This document was prepared to support all MSC programs with special emphasis on future programs. There are no major differences in the basic goals and testing methods of either document. The specific

TABLE I.—*Nonmetallic-Materials Usage Categories*

Category	Material usage	Primary acceptance criteria
A	Major exposed	Self-extinguishing
B	Minor exposed	No propagation
C	Suit loop	Self-extinguishing
D	High-pressure oxygen systems	No reaction
E	Sealed containers	Do not burst container. No flame
F	Vented containers	Do not burst container. No flame
G	Nonflight equipment	Depend on usage
H	In and around spacecraft outside crew bay	Depend on usage

differences that do exist between the two documents are given in table II.

Further refinement of the Center-level document is in process to define better the accept/reject criteria, configuration analyses, and nonmetallic-materials configuration management. The scope of this report relative to criteria will be confined to that document.

The evolution of the nonmetallic-material specifications from 1963 to the present is summarized in table III.

TEST-IGNITION SYSTEM

The purpose of the test ignition system is

TABLE II.—*Differences Between Specifications MSC-PA-D-67-13 and D-NA-0002*

Test	MSC-PA-D-67-13	D-NA-0002
Configuration and systems-level tests	Not required for category A materials if the materials pass screening test 1, "Upward Propagation."	Required for final verification and acceptance for all category A and B materials whether passing screening tests or not.
Analyses in lieu of configuration and vehicle verification tests	No allowance in basic document. Revision A (Addendum I, Oct. 1969) permits contractors to outline requirements in their materials control program plans.	No allowance for analyses in place of tests. New revision will allow analyses requirements.
Nonmetallic-materials configuration management	No specific requirements in basic document. Revision allows for contractor to include the requirements in his materials control program.	Elements of a plan present. New revision will provide details of plan requirements.

TABLE III.—*Chronological Historical Evaluation Summary of MSC Nonmetallic Materials Flammability-Requirement Specification*

Specification title and date	Major objective	Document limitation
Before 1963	Advisory function on nonmetallic materials from flammability standpoint	No real closed-loop system control or specific criteria
Procedures and Requirements for Evaluation of Apollo Crew-Bay Materials (May 1966)	Standardization of testing of nonmetallics in an enriched oxygen atmosphere	Did not consider application of materials
Crew-Bay Non-metallic Materials Status Report of Unacceptable/Acceptable Materials (June 1966)	Development of acceptable/unacceptable material usage list	Did not consider application of materials
Nonmetallic Materials Selection Guidelines (May 1967)	Categorization of materials based upon application	Insufficient attention to configuration control and testing procedures
Procedures and Requirements for the Evaluation of Spacecraft Non-metallic Materials (June 1967)	Configuration testing required as the final acceptance mode for non-metallic materials	Lack of configuration management and quality assurance provisions
Apollo Spacecraft Non-metallic Materials Requirements (Feb. 1968)	Provide configuration testing of nonmetallic materials and provide for configuration as the primary means for acceptability	None
Procedures and Requirements for the Flam-	Update and define current test procedures	Definition of nonmetallic-materials

TABLE III.—*Chronological Historical Evaluation Summary of MSC Nonmetallic Materials Flammability-Requirement Specification—Concluded.*

Specification title and date	Major objective	Document limitation
mability and Offgassing Evaluation of Manned Spacecraft Nonmetallic Materials	and add additional tests and criteria; proposed as a Center-level document	configuration testing or analyses and configuration management required

to provide a realistic, positive source of energy to ignite materials samples. The choice is critical in the credibility of nonmetallic-materials flammability testing, and, thus, it becomes extremely important in the evaluation of flammability test results.

Before 1966, materials were ignited by placing a Nichrome wire in contact with the material. The disadvantage of this ignitor was that the energy input to the material was insufficient and nonuniform. Consequently, many materials did not ignite, which led to the incorrect assumption that these materials were nonflammable.

During 1966, a new ignition system was developed that featured a Nichrome wire to ignite a length of tissue paper that was wrapped around the Nichrome wire and placed at the edge of the test sample. Although this system appeared to have overcome the disadvantage of the point-energy input to the sample and the nonuniformity problem of the Nichrome wire alone, the energy input was insufficient and again led to incorrect assumptions as to the actual nonmetallic-material flammability properties.

A review of ignition systems was conducted during 1968 and 1969 to attempt to develop one that would be comparable to credible spacecraft ignition sources, that could provide repeatable results, and that would provide relatively good heat distribution and time characteristics. This review resulted in the choice of a length of a silicone rod wrapped with the Nichrome wire and

placed close to the end of the sample. This system satisfied all of the requirements mentioned previously. Unfortunately, during the ignition process, the system does exhibit some properties associated with dripping and smoking. However, this handicap does not appear to have caused loss of repeatability of results and it is the best ignition system available at the present time.

An example of the erroneous results that can be obtained by the use of unrealistic ignition systems is as follows. During a randomly selected data sampling at MSC, 23 nonmetallic materials self-extinguished with the Nichrome/paper system. When these materials were retested with the silicone ignitor, 11 ignited and burned, four ignited but self-extinguished, and eight did not ignite. Similarly, when 12 configurations were tested with the Nichrome/paper wire, none ignited. However, when similar retests were made with the silicone ignitor, all items ignited and burned. Improved test-ignition systems are being developed, including double base propellants, treated compressed cellulose materials, and elastomeric-type polymers.

Other nonstandard ignitors also are used at MSC and at the contractor facilities to provide supplemental flammability information. These ignitors, used in experimental, developmental, and special configuration tests, are.

1. Polycarbonate and Kynar drip ignitor systems that simulate special cases in which a material ignites and burning mass drips on other areas of the spacecraft.

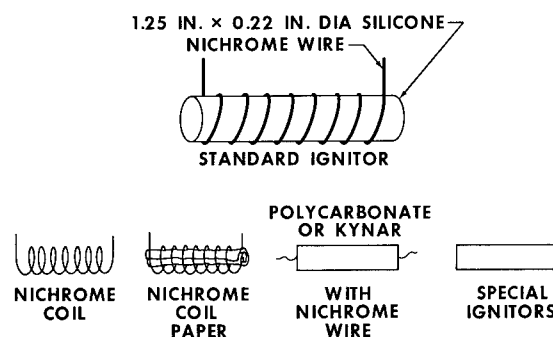


FIGURE 6.—Ignitors.

2. Flame-impingement Bunsen burner ignitors that help a person determine how space suits and other special material applications behave under an open flame.

3. Special nonstandard ignitors, which are constructed of materials contained in a particular assembly. These materials represent worst-case ignition sources.

The MSC standard ignitor and the other ignitors mentioned previously are shown in figure 6.

MATERIALS USAGE CATEGORIES

A major consideration in the development of the MSC criteria has been the actual usage of materials in the spacecraft. This is important because different usages dictate the specific test and acceptance criteria to be applied. For example, a large amount of material in a critical area of the crew bay requires more flammability tests and a more restrictive acceptance criteria than a minor exposed nonmetallic material. For this reason, material usages were divided into different categories. The following is a description of each category used to identify where materials are used in the spacecraft.

1. Category A—Major exposed materials in the crew-bay atmosphere: This category includes material applications that are essentially unlimited with respect to quantity, proximity to ignition sources, or exposure to cabin atmosphere and are used extensively throughout the spacecraft. As a minimum, these materials are included in this category:

- a. Debris traps or nets
- b. Outer layers of space-suit materials
- c. Couch cushions
- d. Webbing and harness
- e. Spacecraft electrical wire bundles and accessories, such as wire-bundle ties, cable clamps, wire-bundle chafe guards, shrink tubing, sleeving, and any other nonmetallic materials used in contact with electrical wiring
- f. Connector potting compounds
- g. Coating materials
- h. Paints

- i. Oxygen umbilical hoses
- j. Any component/assembly that must function to effect a safe crew abort
- k. Nonmetallic panel surfaces

Representative category A materials, such as the couch materials made of Teflon-impregnated fiber glass cloth and restraining harnesses fabricated from polyimide fibers, are shown in figure 7.

2. Category B—Special applications and minor exposed materials in the crew-bay atmosphere: This category includes those materials used in discrete locations of the crew bay. The specific amount and arrangement of materials at discrete locations are chosen to prevent propagation. This type of material arrangement is such that the fire cannot spread to any other nonmetallic materials in the habitable compartment and render non-functional any spacecraft system essential for the safe recovery of the crew. As a minimum, these materials are included:

- a. Isolated electrical components including terminal boards, conformal coatings, and potting compounds
- b. Isolated instrument panels including control knobs, dial faces, luminescent panels, panel fronts, paints and coatings, and potting compounds
- c. Batteries and associated equipment
- d. Limited quantities of miscellaneous materials, such as:

- (1) Discretely isolated shock-absorber materials

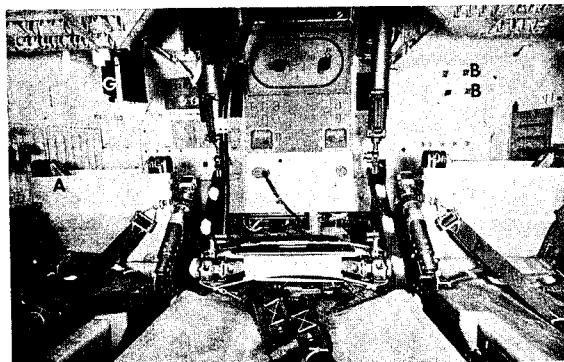


FIGURE 7.—Command module interior.

(2) Discretely isolated thermal-insulation materials

- (3) Plastic sheets
- (4) Nonmetallic films and containers
- (5) Tapes
- (6) Seals and/or sealants
- (7) Adhesives
- (8) Lubricants

e. Other material applications—All material applications not included in other categories are considered subject to the category B guidelines and requirements. The placement of patches of Velcro, which, in this case, is a category B application, is shown in figure 7.

3. Category C—Suit-loop materials in the crew-bay atmosphere: This category includes the materials in the suit loop at less than 20 psia of oxygen. As a minimum, the materials that fulfill the following functions are included in this category:

a. Materials within the environmental-control-system loop integral to the space suits, such as hoses, helmets, flex joints, valve seats and seals, if nonmetallic, and inner garment materials.

b. Suit-loop wiring and electrical components, such as biomedical harnesses, communications, signal conditioners, connectors, transducers, wetness sensors, and thermocouples.

An oxygen umbilical hose, the inside of which is a category C application, is shown in figure 8. The outside of the hose is a category A application. The glass-cloth overwrap was used to make the outside part of the umbilical hose acceptable as a category A material.

4. Category D—Materials in high-pressure oxygen system: This category includes those materials used in greater than 20-psia oxygen-pressure applications. As a minimum, the materials that fulfill the following functions are included in this category:

- a. Filters
- b. Seals
- c. Valve seats
- d. Pressure bladders
- e. Lubricants

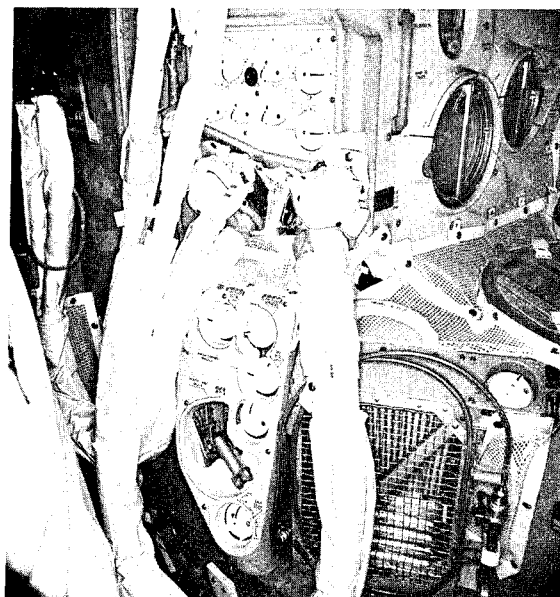


FIGURE 8.—Lunar module suit loop (category C).

5. Category E—Material applications in sealed containers for the crew compartment: This category includes those materials used inside sealed containers that contain an internal ignition source, are filled with inert gas, air, or potting compounds, and have no means of receiving or backfilling with a supply of oxygen. The materials that fulfill the following functions are included in this category:

- a. Electrical wiring
- b. Spot ties
- c. Potting compounds
- d. Coating materials
- e. Electronic components

An example of a category E application is shown in figure 9. The sealed container is shown at the top of the figure. The tape recorder, at the bottom of the figure, is the item completely enclosed within this particular container. The tape recorder is a potential electrical ignition source.

6. Category F—Materials in containers vented in the crew compartment: This category includes those materials used inside unsealed containers with or without an internal ignition source. Removal of materials from containers is permitted for operational use only. As a minimum, the materials that fulfill

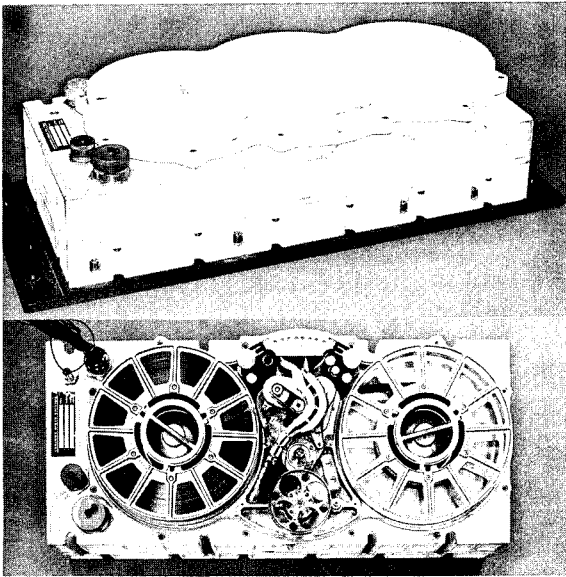


FIGURE 9.—Sealed container data-recording system (category E).

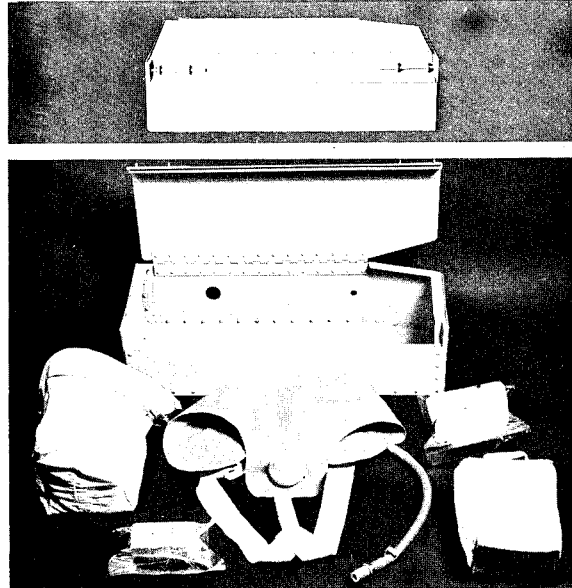


FIGURE 10.—Command module vented container (category F).

the following functions are included in this category:

a. Where an internal ignition source is present

- (1) Foams
- (2) Printed circuit boards
- (3) Wiring
- (4) Potting compounds
- (5) Conformal coatings
- (6) Electronic components

b. In containers with no internal ignition source

- (1) Survival gear
- (2) Personal equipment
- (3) Food bags
- (4) Flight data books

Category F applications are shown in figure 10. At the top of the figure is the container as used in flight and at the bottom are some of the contents, such as food packages and personal effects.

7. Category G—Materials applications in nonflight equipment: This category includes those materials used in nonflight equipment during closed-hatch power-on tests in atmospheres with various oxygen concentrations. These are included in this category:

a. "Remove before flight" bags

b. Plastic dust caps

c. Plastic bags

d. Plastic tape

e. Carry-on ground support equipment (GSE) and associated cables

Representative category G materials are shown in figure 7. All such items are removed before flight.

8. Category H—Materials in uninhabited portions of the spacecraft: This application includes materials in the uninhabited portions of the spacecraft that are exposed to an atmosphere that will support combustion. The test outlined for this category is typical of the tests required for qualification of materials used in manned test chambers and GSE used in conjunction with vehicle test and checkout. The materials that fulfill the following functions are included in this category:

a. Insulation blankets

b. Protective covers

c. Wire bundles and harnesses

d. Tape

e. Conformal coatings

f. Encapsulants

NONMETALLIC-MATERIALS TEST REQUIREMENTS

Two types of tests are required to evaluate nonmetallic materials: the nonmetallic-materials screening tests and the application tests. The specific requirements for each category are as follows:

1. Screening tests
 - a. Characteristics
 - (1) Flash point and fire point
 - (2) Upward and downward propagation rates
 - (3) Carbon monoxide
 - (4) Total organics
 - (5) Odor
 - b. Use as guide
2. Application tests
 - a. Configuration
 - b. Systems
 - c. Use as final acceptance of nonmetallic materials

Screening tests are used during the early stages of a given program (preliminary design) to eliminate obvious hazards and to as-

sist the designer in selecting nonmetallic materials with a degree of confidence that they will be acceptable. This process ensures the best material for a particular application. Application tests (taking into account configuration and system tests) are used as the final verification and acceptance of nonmetallic materials for manned spacecraft. Although offgassing is not specifically discussed in this paper, offgassing results are used as an input to toxicity studies.

Material Screening Tests

The usage of a given material in the spacecraft determines the level of test severity required for that material. The type of test required for each category is listed in table IV. As shown in this table, the three types of screening tests are upward propagation, downward propagation, and flash point and fire point tests.

Upward propagation, the most severe screening test, is used extensively to screen materials that have potential usage in the

TABLE IV.—Screening Test Requirements by Category

Category	Title	Test 1 (upward propagation)	Test 2 (downward propagation)	Test 3 (flash point and fire point)
A	Major exposed materials	X		X
B	Minor exposed materials		X	X
C	Materials in suit loop	X		
D	Materials in high-pressure oxygen systems	(^a)	(^a)	(^a)
E	Materials in sealed containers		X	
F	Materials in vented containers		X	
G	Materials in nonflight equipment	X	X	X
H	Materials in and around spacecraft outside crew bay	X	X	X

^a Acceptance is based on no reaction of the material with oxygen when mechanically impacted at a given energy level.

spacecraft crew bay in large unrestricted quantities. The material to be tested is held vertically and ignited from the bottom.

The downward-propagation-rate test is less severe and uses an ignition source at the top of the vertically held material to be tested. This test is used to evaluate the non-metallic materials that are used in small quantities and locations in the crew-bay area. These materials are evaluated further in application tests for final acceptance.

The flash point and fire point test is for the purpose of quickly screening out the most flammable materials.

Typical test results obtained from the material screening tests are shown in figure 11. For a given oxygen enrichment and material, a significant variation of results is noted. This variation in results is indicative of the accuracy associated with screening tests. The data in the figure show that cotton fabric is the most sensitive to a flammability environment and shows the greatest variation in the test data. Polycarbonate, Fluorel, and Teflon have extremely low propagation rates with the lowest variation in the test results.

The behavior of nonmetallic materials at different oxygen concentrations is shown in figure 12. A linearity is exhibited within each material for the particular range of environmental conditions shown, but each material behaves differently with respect to oxygen enrichment. The difference in the slope of the curve noted for different materials can

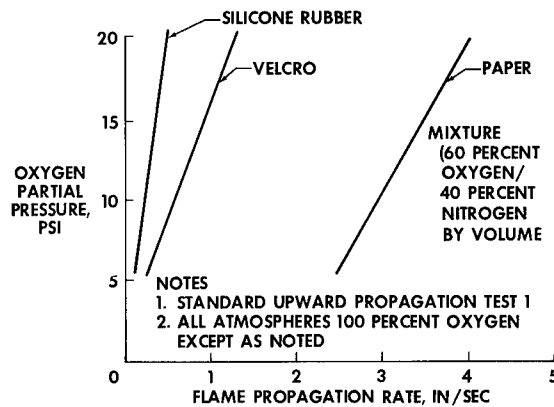


FIGURE 12—Flame-propagation rate as a function of oxygen concentration.

be attributed in part to the thickness and the porosity or density of the material. However, no extrapolation should be attempted because linearity does not necessarily continue throughout all environments. The data shown are arithmetic average values.

The results of screening tests are obtained from MSC contractors, MSC laboratories, and other NASA Centers and are processed into a data system. Materials information and test data then are disseminated by MSC through a periodically updated document. It gives the following types of data for nonmetallic materials:

1. Flammability rate
2. Test environment
3. Material identification
4. Manufacturer and designation
5. Flash points and fire points
6. Carbon monoxide offgassing
7. Total organics offgassing and other related data

In addition, the document includes other important subjects such as:

1. Criteria for materials selection, test, and control for manned spacecraft
2. Combustion
3. Offgassing and contaminants
4. Ignition considerations
5. Fire prevention, detection, and extinguishment
6. Special spacecraft material development

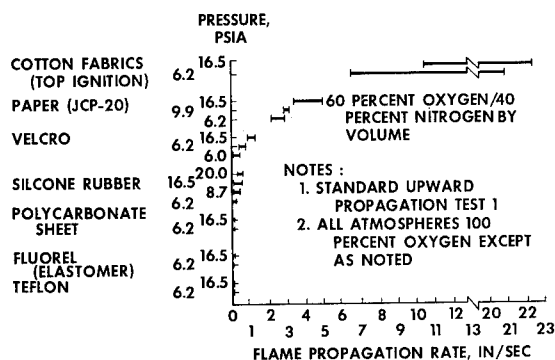


FIGURE 11—Relative flame-propagation rates for selected nonmetallic materials.

and special instruction on how to use the data.

Application Tests

The final verification and acceptance of nonmetallic materials is based on data from application tests. These tests are performed on a worst-case material configuration and environment usage, that is, the most hazardous environment to be encountered during the mission. The MSC general fire-control criteria used to establish the specific design and test requirements are:

1. Evaluation and control of potential (credible) ignition sources must be maintained by design measures.

2. Any accidental fire that may start must be restricted to a definable area, such as a length of wire between two barriers within a covered cable.

3. The rate and magnitude of pressure rise resulting from an accidental fire must not be capable of causing damage to the structure or pressure shell of the space vehicle.

4. Any accidental fire that might occur shall not be such that the lives of the crew-

men will be jeopardized or their well-being impaired.

5. Design features shall be incorporated to restrict and control any accidental fire.

The requirements of the fire-control criteria have been met by establishing application tests as shown in table V. Both the simulated panel/assembly (configuration) and crew-bay (system) tests are required. In these tests, internal and external ignition sources are used. The internal ignition source simulates the sources within electrical equipment, terminal boards, circuit breakers, and so forth. External ignition sources can result from fires started in other areas that can propagate to the test material. The simulated panel and assembly tests are performed either in actual or simulated configurations to ensure that these assemblies (such as main-display and circuit-breaker panels) are nonflammable. These tests are simpler than simulated crew-bay tests and permit the evaluation of problem areas quickly for early isolation of proper corrective action.

In figure 13, a lunar module (LM) circuit-breaker panel is shown before and after a

TABLE V.—*Summary of Nonmetallic-Materials Application Flammability Tests*

Nonmetallic- materials usage category	Title	Simulated panel and assembly flammability tests (configuration)			Simulated crew-bay configuration flammability verification test (system)		
		Yes	No	Ignition ^a	Yes	No	Ignition ^a
A	Major exposed materials in the crew-bay atmosphere		X		X		Internal and external
B	Special applications and minor exposed materials in the crew-bay atmosphere	X		Internal and external	X		Internal and external
E	Material applications in sealed containers	X		Internal	X		Internal
F	Material applications in vented containers	X		Internal and external	X		Internal and external

^a Internal ignition as a result of faulty internal electrical components; external ignition as a result of fire started in another compartment, but propagated.

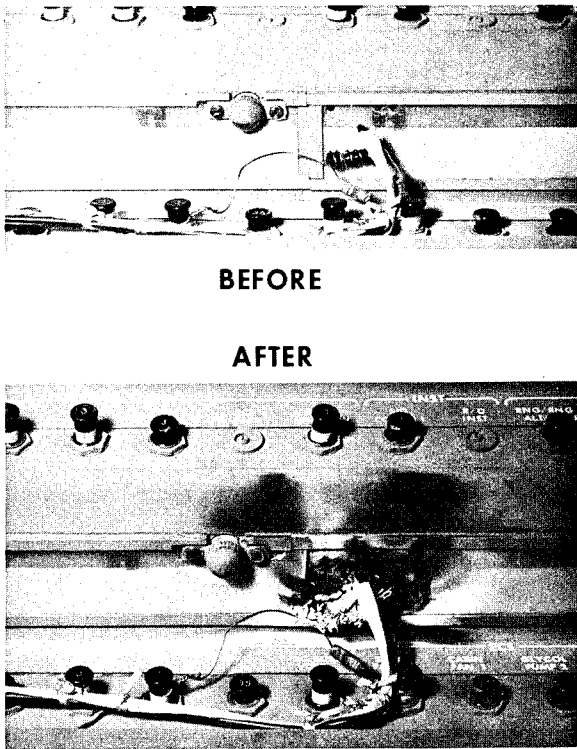


FIGURE 13—Configuration-test lunar module circuit-breaker panel.

configuration test that was performed to determine if a fire, once started, would propagate throughout the panel. The fire was self-extinguishing in the 6.2-psia pure-oxygen atmosphere, and therefore, the panel was acceptable for use in the LM.

The final verification and acceptance of non-metallic materials is based on the simulated crew-bay test. This system test is performed using the spatial and geometric configurations of a selected number of worst-case assemblies. The purpose of the test is to define all the worst-case potential ignition sources to ensure that fires are restricted to well-defined (discrete) areas. This is the only type of test that ensures that no propagation path exists between assemblies and that the entire spacecraft is safe from the flammability hazards of nonmetallic materials.

A part of a multi-unit systems test performed inside the LM mockup vehicle is shown in figure 14. In this case, the geometric and spatial distribution of nonmetallic

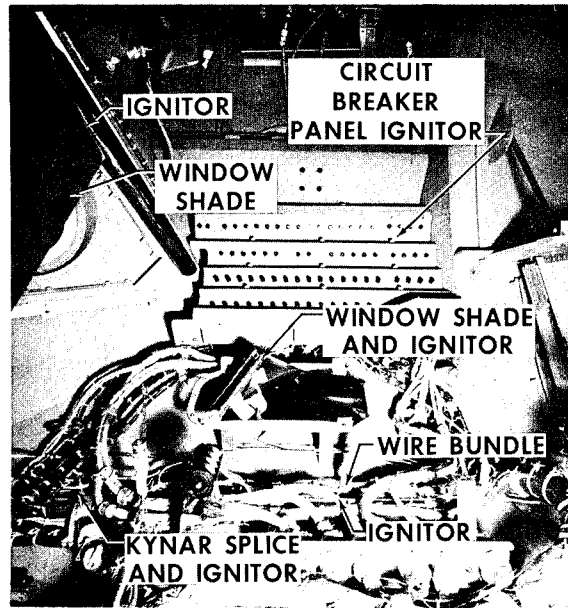


FIGURE 14—Lunar module system test.

materials in their final usage configurations are being studied for propagation paths among the subsystems. It can be noted that the ignitors have been placed strategically in wire bundles, circuit-breaker panels, and window shades that are considered potential ignition sources.

The objectives and acceptance criteria for various application categories discussed previously for the system tests are summarized in table VI. Major and minor materials (categories A and B) used in panels, assemblies, and other areas of the spacecraft crew bay, when tested in their application category, must be self-extinguishing. Also, they must not propagate to adjacent equipment, and the fire must be restricted to discrete areas. Materials used in sealed and vented containers (categories E and F), when tested, must not rupture these containers or allow flames to be emitted outside.

In table VII, we give the results of the flammability test on the heat exchanger used to cool the water-glycol fluid, which in turn is used to maintain acceptable temperature levels on electronic components. Major damage occurred to the heat exchanger as a result of this test, which was attributed to the

TABLE VI.—*Summary of Flammability Acceptance Requirements for System Tests*

Nonmetallic- materials applied configuration usage category	Title	Objectives	Acceptance criteria
A	Major exposed materials in the crew-bay atmosphere	Test panels and assemblies of worst-case materials configured in a mockup vehicle.	Self-extinguishing and no propagation of a fire to adjacent equipment by radiation, conduction, or mass transfer.
B	Special applications and minor exposed materials in the crew-bay atmosphere.	Same as above except for special assembly tests.	Demonstrate that there can be no fire propagation using ignitions from internal and external sources. The effects of burning of the assembly must be analyzed.
E	Materials application in sealed containers.	Test nonmetallic materials in sealed containers for combustion characteristics.	The container shall not rupture and emit flame, smoke, and gas.
F	Materials application in vented containers.	Evaluate the combustion characteristics of non-metallic materials in vented containers.	The container shall not rupture nor otherwise emit burning particles, gases, and excessive heat into the crew bay.

TABLE VII.—*Summary of Configuration and System Flammability Test Results at 6.2 psia Oxygen*

Configuration	Worst-case materials	Highest rate, in/sec (screening test)	Application-test results	Required modifications
Ignition of nonmetallic materials in the heat-exchanger compartment	Silicone foam Fluorel foam	0.167	Major damage occurred as a result of this fire, because of the high burn rate of the Fluorel and silicone materials	Remove the Fluorel foam; cover silicone with fiber glass (Beta).

high burn rates of the silicone and Fluorel foams used in this system. As a result of this testing, the Fluorel foam was removed and the silicone materials were covered with fiber glass (Beta). This action reduced the flammability hazard to an acceptable level.

In many instances, a hazardous material

can be flameproofed by some simple but effective method. Applying nonflammable tapes, wrapping with nonflammable fiber glass (Beta), treating with nonflammable coatings (such as Ladcote), using heat-sink devices, and other techniques have been used effectively to eliminate flammability hazards.

NONAEROSPACE APPLICATIONS

A detailed treatment of the application of spacecraft nonmetallic-materials requirements and criteria to commercial uses is not possible within the scope of this report. However, the criteria and requirements have resulted in the development and tests of nonmetallic materials that proved applicable to manned spacecraft and should be applicable to the less hazardous earth atmospheres. Teflon wire insulation, as used in the spacecraft, is being considered for use in commercial aircraft, ships, and public buildings. Fluorel coating and encapsulating materials that are used throughout the spacecraft are available commercially and are being considered for use in the interiors of commercial aircraft because of their fire-resistant properties. The polyimide and the Teflon fiber-based fabrics likewise are being evaluated as seat materials in airplanes, trains, and public buildings. The paints used inside the crew-bay areas met the flammability requirements of the Apollo specification, and the vendor has put them on the commercial market. Used as interior paints in residential housing, the paints would decrease or eliminate rapid flame spread. The requirements and criteria discussed in this report could be imposed on construction contractors, ship-

builders, aircraft manufacturers, and so forth and, thereby, could result in the fabrication of structures with fewer fire hazards than the structures presently built.

An important consideration is that "tailoring" is required for various applications. For example, in ground test chambers that have a capability of rapid egress and water deluge, more liberal use of flammable materials may be permitted.

CONCLUDING REMARKS

In this report the historical development of the nonmetallic-materials flammability requirements has been described. Additional improvements are planned to support advanced programs.

More effort is required to develop better ignition systems, analytical techniques for predicting application behavior of materials, and materials with better nonflammability properties. New materials must be capable of satisfying mechanical, electrical, and related application requirements, as well as the requirement for nonflammability.

Nonaerospace applications of the nonmetallic-materials data and requirements certainly are possible, but caution must be exercised to ensure that tailoring of requirements is based upon application.

Development of Materials Screening Tests for Oxygen-Enriched Environments

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Flammability testing before the Apollo Program was not widely standardized. Although significant flammability test programs were carried out during Project Mercury and the Gemini Program, and although attempts were made to rate materials with respect to ease of ignition and flame-propagation rate in oxygen environments, general agreement concerning the type of testing required did not exist. For example, in at least some of the materials testing for Project Mercury, air was used as a test environment. Many of the materials listed as acceptable under earlier test programs are no longer so considered in light of currently used test methods. The development of material-usage categories and criteria, discussed in reference 1, led to the logical development of tests to determine whether specific materials would meet these criteria. Although the specific categories and criteria were developed after initiation of the Apollo Program, the overall test development was well under way during the Gemini Program.

EARLY TEST DEVELOPMENT

At the conclusion of Project Mercury, and with the establishment of laboratory facilities at the Manned Spacecraft Center (MSC), additional emphasis began to be placed on development and standardization of flammability test methods. Investigations into the flammability characteristics of irradiated polyolefins had established clearly

that, in spite of the heat sinks provided by large wire bundles, this commonly used spacecraft wire insulation would burn vigorously in a 5-psia pure-oxygen environment, the nominal Apollo spacecraft-cabin flight environment. Replacement of the polyolefin-insulated wire with polytetrafluoroethylene insulation resulted in the formation of a NASA Ad Hoc Committee to establish and formulate a test and development program for Apollo wire insulation. This program, which was conducted by General Electric Corp., resulted in the selection of Teflon and Teflon-bonded H-film wire insulation for the Apollo Program (ref. 2). It also resulted in the preliminary development of the present Apollo wire-insulation flammability test definition.

At approximately the same time, the Apollo prime contractors were invited to present test procedures and ideas on flammability testing to NASA. North American-Rockwell Corp., aided by the Minneapolis Honeywell AiResearch Corp. and Collins Radio Co., began an evaluation of test techniques. This study established a test for ignition point based upon sparking the ambient atmosphere close to a heated specimen; this procedure is quite similar to the test proposed by Bolstad (ref. 3) in 1963. The test was a forerunner of the currently specified combined thermogravimetric analysis and spark-ignition test to be discussed later. The study also established that standard American Society for Testing Materials (ASTM) and Federal-

specification tests were of little value in rating materials for use in high-oxygen-concentration environments.

Shortly after this period, NASA began development of materials to be used in oxygen-enriched environments. Several test chambers for testing at high partial pressures of oxygen were obtained. It soon became apparent that so many tests of a highly varied nature were being run at different locations that it was not possible to correlate the results of these tests, and it was decided that it would be necessary to establish a standard set of test methods and criteria and to impose these on all contractors. This set of specifications was published subsequently by NASA (ref. 4.). The document established nine types of tests and an applied-configuration test philosophy. The tests required to be conducted on material samples were related to the usage of the material.

PRESENT TESTS

The nine tests currently required to screen materials for use in the Apollo Program are:

1. Upward propagation
2. Downward propagation
3. Combined thermogravimetric analysis and spark ignition (flash and fire point)
4. Electrical wire insulation and accessory flammability
5. Electrical potting and coating flammability.
6. Odor
7. Determination of carbon monoxide and total organics
8. Friction and impact ignition
9. Flash-point and fire-point determination

Tests 1 to 5 are discussed in the following sections; tests 6 to 9 are discussed in other papers in this symposium.

Upward-Propagation Test

This is the basic flammability test used today and is the most severe screening one currently being conducted. The specimen is mounted in a steel holder with clamps along the edges (fig. 15) in a test chamber of suffi-

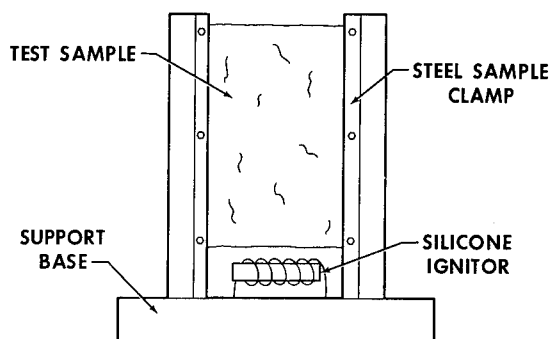


FIGURE 15—Test fixture for upward- and downward-propagation tests.

cient volume to permit complete combustion of the specimen without significant oxygen depletion. An ignition source is provided at the bottom of the specimen. The ignition source now used is a Nichrome-wire-wound piece of silicone rubber 7/32 in. in diameter by 1 1/4 in. long. In oxygen the silicone ignitor provides a flame temperature of approximately 2200° F and burns for approximately 25 sec. Early in the test program, tissue paper was used in conjunction with a Nichrome wire to provide an ignition source. This source did not provide a reproducible flame duration and, furthermore, had a flame temperature of only 800° to 1000° F. Adoption of the silicone ignitor provided a significant improvement in the reproducibility of both flame duration and flame temperature. The environment used depends upon the intended use of the material. For example, if the material is to go into the crew compartment area of the Apollo command module, the test environment would provide a 95 percent or higher oxygen concentration at 16.2 psia. If, however, the material is to be used in the lunar module, the test environment would be 95 percent or higher oxygen concentration at 6.2 psia. The difference in these two environments arises because the command module is launched with a viable environment, while the lunar module is inert at launch with a nitrogen environment, and the oxygen in the lunar module is not supplied until the vehicle is in orbit. At this point, the cabin pressure is 4.8 ± 0.2 psia, but the maxi-

imum relief-valve setting is 6.2 psia. Materials are acceptable for use in design provided they do not ignite under the conditions of the test or that they self-extinguish before propagating more than 3 in. along the 5-in. total sample length. Materials that do not self-extinguish are considered to have failed the test. Rate of flame propagation is not a criterion because of the nonreproducibility of data.

Downward-Propagation Test

This test, which uses the same test chamber and fixtures as the upward-propagation test, is essentially a measure of the flame propagation rate under the best possible conditions and is considered to be a measure of the in-orbit, zero-convection propagation rate. In this test, the silicone ignitor is positioned at the top of the test article and, upon ignition, flame propagation is measured either by high-speed motion-picture photography or by a thermocouple rake that measures the passage of the flame front down the specimen. As in the upward-propagation test, the test is conducted for most materials without the use of any heat sink behind the specimen. Where this is not possible (as, for example, with paints), the material is placed in a typical as-used configuration by putting a layer of paint on an aluminum plate and conducting propagation tests to determine if the paint permits a flame to propagate in spite of the heat sink associated with the aluminum plate. Materials with downward-propagation rates greater than 0.3 in/sec cannot be used, even in discrete, limited applications, unless these materials can pass a component-level configuration flammability test in the as-used configuration testing (ref. 5). As for the upward-propagation test, the test environment for the downward-propagation test is specified by the intended use of the material. Unlike the upward-propagation test, materials that are considered to have passed the downward-propagation test must be controlled very carefully and used in small quantities in situations where they do not provide a significant flame-propagation path.

Combined Thermogravimetric Analysis and Spark-Ignition Test

The currently specified flash- and fire-point tests involve the use of two separate types of test equipment, a thermogravimetric analyzer (TGA) and a small heating-rate chamber (flash and fire point). The TGA is used to determine the flash and fire points of the test specimen. This test is an extension of an earlier test method that combined the spark ignitor directly with the TGA (ref. 6). The TGA data give a measure of the weight loss of the materials as a function of time as the temperature is increased at a linear rate from ambient to approximately 600° F. It is possible to observe the evolution of offgassed products in an oxygen environment as the test-specimen temperature is raised and, in this way, characterize the material. The flash- and-fire-point apparatus provides a spark discharge (50 ± 20 millijoules) of a duration of approximately 2 milliseconds at each $4^\circ \pm 1^\circ$ F temperature rise. This spark, which is located immediately above the specimen, is intended to ignite any flammable vapors being evolved. A fiber-optics/photoelectric-cell arrangement is used to convert the spark/flash/fire information to a storage oscilloscope presentation. An X-Y recorder is used to record the flash and fire occurrences with respect to temperature and time. A typical test result is shown in figure 16. As this

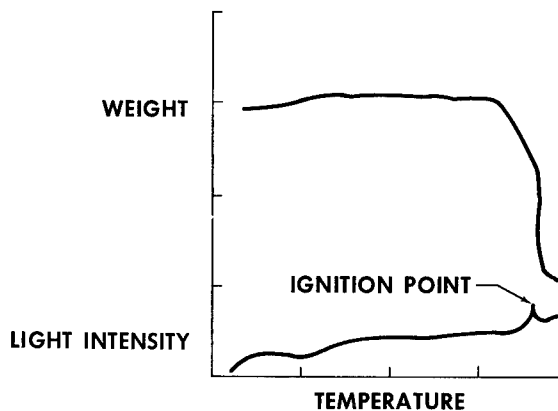


FIGURE 16—Typical thermogravimetric spark-ignition test result.

figure indicates, the information from the TGA and flash- and fire-point test can be correlated; that is, if a combustible volatile is emitted, then the flash and fire data will indicate a flash or fire (or both). With a noncombustible volatile no flash or fire will occur. This test, although useful to materials technologists in the relative ranking of materials, has not been of primary importance in determining the acceptability of materials for use in manned spacecraft. For example, it was not very difficult to establish that materials that will pass the flash- and fire-point test with the spark above the specimen ignite rather easily if the spark is directed into the specimen. Hence, this test in no way measures whether a material can or cannot be ignited by an electric spark. Much work has been done in the development of flash- and fire-point tests, and there has been a steady improvement. Materials that have a flash point of less than 400° F or exhibit charring or pyrolysis at less than 450° F are considered to be unacceptable.

Electrical Wire-Insulation and Accessory Flammability Test

This test is essentially a propagation test conducted on a standard wire bundle. The test chamber may be the same type of chamber used in the upward- and downward-propagation tests. The test bundle consists of seven insulated wires, six of which are 12 in. long and one of which is 13 in. long. The wires are bound tightly together and horizontally mounted in a chamber (fig. 17). The long center wire is overloaded electrically to

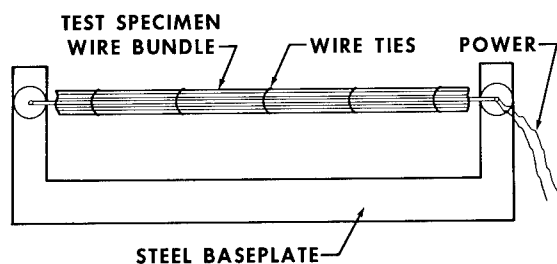


FIGURE 17—Electrical wire-overload test figure

the point of fusion or ignition of the insulation. At the time of ignition, current to the current-carrying wire is removed, and the specimen is observed to determine whether the fire propagates or self-extinguishes. If the test bundle cannot be ignited at the temperature associated with fusion of the conductor or if the insulation ignites but self-extinguishes, the wire is considered acceptable for use.

Electrical Potting and Coating Flammability Test

This test is quite similar to the wire-insulation test in that a standard potted connector is used; the test criterion is met if the fire will not propagate along the potting compound. Ignition is provided by electrical overload and fusion of an 18-gage Teflon-insulated wire. Potting compounds and coatings are considered acceptable if they do not sustain combustion after removal of the ignition source.

Determination of Carbon Monoxide and Total Organics and Odor Tests

In addition to the flammability tests, two tests determine whether the materials are suitable from the standpoint of evolution of potentially toxic products in the low-pressure environment of manned spacecraft. One of these tests is the determination of carbon monoxide and total organics, and the other is an odor test. The determination of carbon monoxide and total organics test involves loading a preselected specimen into a container of oxygen at a pressure of 5 psia and then heating this container to 200° F for a period of 24 hours. The oxygen in the container is then sampled, and mass spectroscopy, infrared spectrometry, and gas chromatography are utilized to evaluate, identify, and quantify the amount of total organics and carbon monoxide liberated during this period of time. In the odor test, the samples of materials are prepared in essentially the same way, except that they are heated at 155° F for at least 72 hours. For odor evaluations, a panel of pretested and preselected

odor consultants sniff the oxygen environment taken from the test specimen and rate this according to a standard subjective scale (ref. 7).

Other Flammability Tests

A number of supplementary screening tests also have been devised. These tests are designed to provide backup data for use in materials qualification and to provide flammability information to design engineers. They include a differential-scanning-calorimeter test with spark ignition, which is quite similar to the standard TGA flash- and fire-point test; an autogenous ignition-point determination; a heat-of-combustion test; a conformal-coating flammability test; a short-circuit ignition test; a molten-ignitor drip test; and a flame-impingement test for fabrics, suits, and container materials. The autogenous ignition-point determination and the heat-of-combustion test are no longer used because they do not provide an adequate method of ranking materials for screening. Several of these nonstandard test methods are discussed in reference 8.

CONCLUDING REMARKS

In summary, there now exists a series of standard tests that have been used for a considerable period of time to evaluate the characteristics of material combustion in oxygen-enriched environments. Development is not considered to be complete, but the tests in the current form are sufficiently reproducible to provide a strong foundation for selection of materials for use in the design of

manned spacecraft and, with minor modifications, for direct application to other programs. The proof of the use of any material still is, and must be, passing a verification test in the configuration of intended use.

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Flammability Testing of Components

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The selection of safe materials for use in the Apollo spacecraft required a thorough nonmetallic-materials test program that was conducted in three phases. After the preliminary screening tests (ref. 1) and before any full-scale mockup testing began (ref. 2), a series of tests classified as component flammability tests was performed. These tests were conducted on components identical to those used in the spacecraft or on realistic simulations that incorporated all nonmetallic materials in the proper locations, quantities, and geometries. The purpose of component-flammability testing was to determine the flammability characteristics of a variety of different sizes, shapes, and configurations of nonmetallic materials of similar or different types that make up a functional assembly, subsystem, or system in the spacecraft.

TEST CRITERIA AND REQUIREMENTS

The initial selection and design of nonmetallic materials comprised the necessary base line from which controls were used to minimize the flammability characteristics of an end-item component. However, for the purpose of this report, the assumption was made that the component design was already established and that testing was required to verify the nonmetallic-materials acceptability.

Component-Configuration Control

A component for flammability testing was either a fully controlled piece of flight-qualified hardware or a simulation. In many instances, especially when a component was very expensive to manufacture, an accurate

simulation of the component was fabricated for testing. Although the test unit was not required to be completely representative of the flight configuration, and although known nonflammable parts may have been simulated, the nonmetallic (possibly flammable) materials represented the exact flight article with respect to quantity, geometry, and location.

The Apollo component flammability testing was conducted to determine only the combustion characteristics. No attempt was made to establish the operational capability of a component after flammability testing, because, in most cases, critical component functions were duplicated by redundant systems. For spacecraft use, the items represented by the test articles would be required to meet all other requirements associated with crew safety and mission success.

Test Conditions

Worst-Case Analysis—In all instances, the general test criteria for a component verification of materials for use in manned spacecraft were based on an analysis and subsequent testing of the worst-case configuration of potentially flammable materials. To determine and analyze the worst-case conditions, a thorough understanding of the spacecraft systems was required. The following parameters were the minimum considered during the selection of the worst-case conditions of a particular component:

1. The amount of flammable material in a given location
2. The propagation paths provided by surrounding materials

3. The most severe atmosphere in terms of oxygen content and pressure

4. The location, number, and type of possible ignition sites

Ignition types—Two basic types of ignition techniques (internal and external) were selected for flammability testing. Internal ignition simulated wire or electrical-component overload caused by a short circuit. A representative piece of spacecraft wiring or other electrical component could be used as the ignition source, or a length of Nichrome wire could be used as an ignitor by placing the wire in the area of the assembly being tested. The electric power supply necessary to overload the electrical component or wire had to provide a large, controlled current so that extremely high temperatures could be achieved. Power-supply requirements varied for the particular components undergoing test. However, the power source generally could supply power in excess of that necessary to produce fusion of the wire or component.

External ignition, used to simulate flame impingement from a nearby source, was accomplished by using a Nichrome wire wrapped around a standard silicone ignitor or, in some cases, a flammable material representative of materials found in the component undergoing test. To provide the flame source, materials such as potting compounds, shrink tubing, and solder splices were placed in contact with the Nichrome wire. Determination of the exact ignitor specifications was based on a worst-case analysis. The quantity of flammable material, the total energy input, and the location of the ignitor within the test article were factors considered during the selection of the ignitor specifications.

General test requirements—The following guidelines were used for the determination of the specific test requirements for a particular component:

1. The configuration and nonmetallic materials of the test article must duplicate the flight article.

2. The test article must be oriented in the test chamber to duplicate the position of the test article during normal operation.

3. The test-chamber volume with the test article installed must be large enough to contain sufficient oxygen to allow complete combustion. Adequate space around the test article must be available to observe the extent of projection of burning pieces caused by the sputtering and expansion of gases internal to the burning mass.

4. All thermal interfaces of the test article must be simulated. These interfaces include:

a. Cold plates

b. Mounting structure

c. Convection caused by forced-air circulation

d. Surrounding-structure radiation characteristics

5. Test-article atmospheric conditions must meet specific criteria. First, the test-chamber ambient temperature must be the same as that anticipated for actual use. Second, the atmospheric gaseous content and pressure must represent actual use conditions.

Additional details and test guidelines may be found in reference 3.

Test Equipment

Component tests were performed in 18-in.-diam cylindrical chambers and in an Apollo boilerplate command module. In the 18-in. test chambers (fig 18) and supporting equipment several tests could be conducted simultaneously. Each test chamber had a volume of approximately 5 ft³ and a pumping capability of 50 ft³/min. The chambers incorporated instrumentation that provided a controlled ignition source, continuous temperature and pressure monitoring, test-gas sampling, and motion picture coverage.

The command module boilerplate (fig. 19) had a volume of 400 ft³, a high-capacity pumping system, and a data-acquisition system. The boilerplate, a single-wall steel test chamber, had the geometrical shape of the Apollo command module. The interior of this boilerplate chamber could be configured to accommodate a wide variety of component-flammability test requirements. The pumping system for the boilerplate chamber consisted

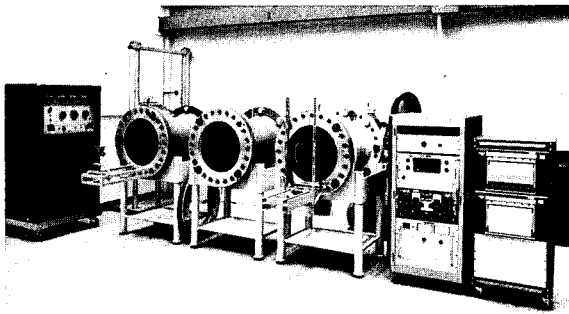


FIGURE 18—Eighteen-in. diam cylindrical test chambers.

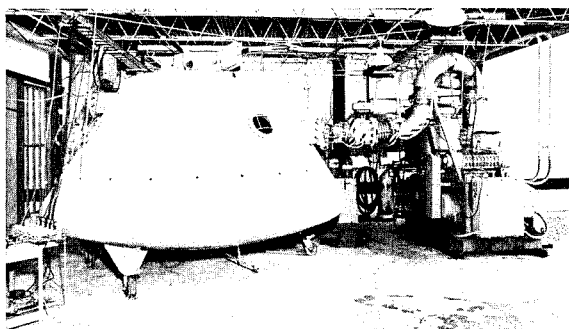


FIGURE 19—Command module boilerplate test chamber.

of a 1100 ft³/min mechanical vacuum pump, which was in series with a 2700 ft³/min centrifugal-type booster pump. The pumping system was used to obtain the atmospheric pressure and gas concentrations required for each test.

Before each test, the boilerplate chamber was evacuated and backfilled with the test atmosphere to the specified pressure and gas concentrations. Gas-chromatograph readings were made to verify the specified oxygen content. The large pumping capacity was required so that, if a component started to burn vigorously during a test, the fire could be extinguished by rapid evacuation of the chamber atmosphere. The test chamber could be evacuated from an atmospheric pressure of 14.7 to 0.1 psia in less than 1 min.

The facility control consoles (fig. 20) were remote from the boilerplate test chamber, and the instrumentation and data accommodated by the consoles were:

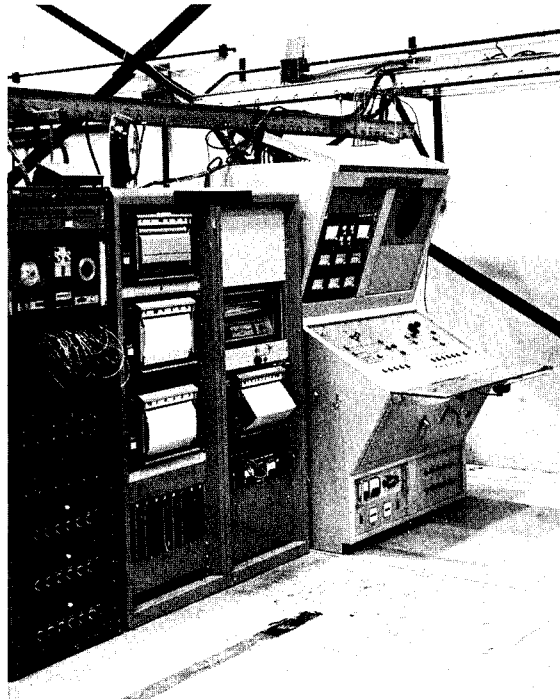


FIGURE 20—Boilerplate test chamber console.

1. Thirty-two channels for thermocouple (temperature) readings
2. Twelve 60-A ac or dc ignition circuits.
3. One 250-A dc ignition circuit
4. Six camera-light circuits
5. Four ac or dc circuits for cameras (inside or outside the test chamber).
6. Two closed-circuit-television-camera circuits (inside or outside the test chamber)
7. Six gas-sampling stations
8. One direct-read-out oxygen-gas-sampling station
9. Two 12-in. flanged feedthroughs that could be modified for any test requirements

Test-chamber selection for a particular component was governed by the test requirements, the size of the article, and the support equipment that was needed to provide the required degree of fidelity in the simulation of the nominal component environment.

Data Requirements

Photographic data supplemented temperature, pressure, and combustion-product

measurements in these tests. The requirements and specific instrumentation for proper evaluation of each test were determined on an individual basis. Additional information on the data requirements is contained in appendix A.

COMPONENT-CONFIGURATION CATEGORIES AND TEST EXAMPLES

For the Apollo flammability program, approximately 500 tests were conducted on command module components, and approximately 300 tests on lunar module components. The tests were divided into five general categories.

Category 1—Electrical Wire Insulation and Accessories: Tests were designed to determine the flammability characteristics of wire insulation and accessory materials that are used in the habitable areas of manned spacecraft. Examples of electrical accessories tested are wire-bundle sleeving, heat-shrinkable tubing, bundle ties, and cable clamps. Ignition of the test article required forced-current overloads up to the melting or fusion point of the wire or electrical component. The general criterion of acceptability in this category required that the test assembly not sustain combustion after the removal of the ignition source. General test guidelines for testing components in this category are provided in reference 3. A description of a specific test performed on a typical component is provided in appendix B.

Category 2—Electrical Component Potting and Coatings: Tests were devised to simulate short circuits, dielectric breakdown of conductors, or terminal-block failures in an operational environment. To provide a realistic ignition source, the test articles were subjected to current-overload heating up to the melting or fusion point of the metallic elements. The acceptability criterion required that potting materials or coatings not sustain combustion after removal of the ignition source. Components such as circuit breakers, terminal blocks, and bus bars were tested. General guidelines for testing components in this category are provided in refer-

ence 3. A typical component-configuration test of this category is discussed in appendix C.

Category 3—Nonmetallic Components in Vented Containers: The purpose of flammability testing of nonmetallic components in vented containers was to determine the characteristics of combustion within the container and the effects on adjacent objects. The ignition source was provided by external-type Nichrome ignitors installed inside the container. Stowage containers, electrical junction boxes, food warmers, and cameras are typical examples of test subjects. The acceptability criterion was that the container would not emit flame or burning materials through ruptures or vents. General guidelines are presented in reference 3. A typical component-configuration flammability test for nonmetallic materials in vented containers is discussed in appendix D.

Category 4—Nonmetallic Components in Sealed Containers: Nonmetallic components packaged in sealed containers were tested to verify the ability of the containers to withstand internal combustion without rupturing and to evaluate the effects of fire within the containers. Positive ignition sources were simulated to produce heating to the fusion or melting points of metallic components. The acceptability criteria required that the container self-extinguish after removal of the ignition source and that the container remain sealed. Typical examples were lighting-control assemblies, guidance and navigation components, the attitude-indicator assembly, and the thrust-to-weight indicator assembly. General guidelines for performing tests of this category are given in reference 3. A typical example of flammability testing of a component in a sealed container is discussed in appendix E.

Category 5—Electrical Assemblies, Subsystems, and Systems: Electrical assemblies, subsystems, and systems were tested to determine the combustion characteristics of nonmetallic materials of similar or dissimilar types in various shapes, sizes, and configurations. Examples are electrical-control-panel assemblies and power-distribution panels.

The acceptability criteria required that (1) the flame generated within electrical panels not penetrate the back cover to the extent that other components outside the panel would be ignited and that (2) the flame not propagate beyond the general vicinity of the ignition source. The extent of acceptable flame propagation within the test article was determined on an individual basis and depended on the configuration and location of the test article. General guidelines for tests of this category are given in reference 3. A typical example of component-configuration flammability for an electrical subsystem is discussed in appendix F.

CONCLUDING REMARKS

Design development, design verification, and end-product qualification for the Apollo spacecraft were accelerated significantly by component-flammability testing. The test program provided data quickly and economically for the analysis of a broad expanse of nonmetallic materials used in a wide variety of applications and combinations. By simulation of worst-case conditions, preliminary designs were advanced to near-firm status and, often, like components were verified or qualified by similarity.

The test data reported herein were directed toward the design development and verification of the Apollo spacecraft. However, the general knowledge gained from these tests indicates that this type of testing may be applicable to other situations for which the fire hazard is severe and for which fire protection is mandatory. Component-con-

figuration testing also may be used for verification tests of systems in which minor design changes have been made or for systems that are located in less severe atmospheres (lower oxygen content) and for which sufficient materials-flammability data are available.

During testing in support of the Apollo spacecraft, the operational characteristics of test systems were not determined because of the inherent randomness of damage that might be caused by a fire. However, the possible loss of vehicle functions as a result of a fire was lessened by the redundant systems designed in the spacecraft. Although component testing provides much data, the value of final verification by full-scale mockup tests, especially for manned vehicles, cannot be overlooked. No matter how carefully a component test is configured and conducted, the results cannot always be taken as conclusive when applied to an entire system. The many variables such as location, heat-sink characteristics, airflow patterns, and so forth can be simulated only by full-scale mockup testing (ref. 2).

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APPENDIX A

Data Requirements

PHOTOGRAPHIC COVERAGE

Still photographs were obtained to provide adequate pretest and post-test documentation. Instrumentation motion picture cameras were provided to record all real-time events for the duration of the tests. Motion picture coverage was set up to provide a record of the flame-propagation rate, flame-propagation path, material-dripping, sputtering, and sparking characteristics.

TEMPERATURE MEASUREMENT

Temperatures were recorded continuously during testing. Temperature-measuring and temperature-recording equipment had response times equal to or greater than the predicted rate of temperature change at the location being measured. Temperature-measuring devices and the location of these devices were varied depending on the assembly configuration being tested. The following in-

formation was available from the devices:

1. An internal and external temperature profile of the assembly
2. The temperature of the ambient gas atmosphere
3. The temperature of the test-assembly supporting structure and the test-chamber wall

PRESSURE MEASUREMENT

Equipment was available to record and provide continuous measurement of the test-chamber gas pressure for the duration of the test.

COMBUSTION-PRODUCTS DETERMINATION

The quantity and composition of all stable combustion products were determined. Mass-spectrometry methods were used for the determination of the products of combustion.

APPENDIX B

Electrical-Wire-Insulation and Accessory-Flammability Testing of Lunar Test Article 8-Kynar Sleeving

TEST OBJECTIVES

This test was designed to screen flammable wire insulation and electrical-accessory materials that were proposed for use in habitable areas of the lunar module. In addition, the test was designed to establish that electrical wire insulation and accessories could not sustain combustion in the designated test atmosphere after removal of the ignition power source, which provided current over-

loads up to the melting point of the electrical wire.

COMPONENT DESCRIPTION

The test bundle of seven H-film-insulated wires, of which six were 12 in. long and one was 13 in. long, was inserted into a length of lunar test article 8 (LTA-8) Kynar sleeving. One-half inch of insulation was stripped from each end of the 13-in. wire. A crimp spade lug terminal was used at each end to

terminate the overloaded 13-in. wire and to provide a heat sink.

The sample holder consisted of two horizontally mounted electrical connections (knurled bolts spaced 12 in. apart). Three nonflammable supports were provided to support the center and ends of the sample wire bundle. The electrical terminals were connected to the ignition power source (fig. B-1).



FIGURE B-1.—H-film-insulated wire bundle.

IGNITION LOCATION

The external electric power supply was connected to the electrical terminals on the 13-in. wire in the sample bundle. The power source provided a large, steady current through the 13-in. wire so that a high temperature was achieved quickly. In addition, the power source could supply a current 10 percent greater than the nominal fusion current of the wire.

TEST DESCRIPTION

The sample was mounted in the holder and installed in the test chamber, which was set up to provide an atmosphere of 30 percent oxygen/70 percent nitrogen at a pressure of 14.7 psia. A 40-A current was applied to the

wire; the current was increased in 5-A increments at 1-min intervals.

Smoke was observed 90 sec after test initiation, at which time the current was 45 A. At 100 sec, the Kynar melted and the H-film bundle was exposed. At 140 sec, when a current of 50 A was applied, the Kynar sleeving ignited and burned vigorously, and the wire failed at 143 sec. The material continued to burn even after the igniter power had been removed.

POST-TEST RESULTS

From the post-test inspection, it was determined that the Kynar sleeving had burned away from the wire bundle almost completely. Only a small portion of the sleeving remained at the ends of the wire bundle near the electrical connections. The wire had failed and was severed in several places (fig. B-2). The material was not self-extinguish-

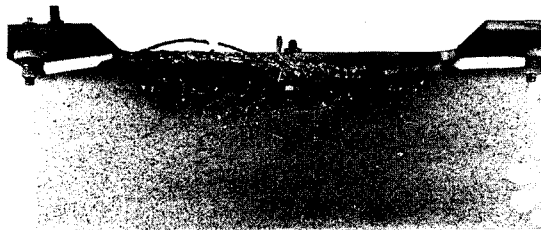


FIGURE B-2.—Post-test photograph of the H-film-insulated wire bundle.

ing in the test atmosphere. From this flammability test, it was determined that the sleeving was unacceptable for use in the prescribed environment.

APPENDIX C

Electrical-Component-Potting and Coating-Flammability Test: 10-Channel Fuse Module

TEST OBJECTIVES

This test was designed for the evaluation of the flammability characteristics of spacecraft potting compounds in a specific environment. It was required that connector potting material not be capable of sustaining combustion in the designated test atmosphere after the ignition source was removed.

COMPONENT DESCRIPTION

A 10-channel fuse module was built into the nonmetallic portion of an electrical connector. The test was designed to simulate the breakdown of connector contacts within the potting that was used to seal the connectors environmentally (fig. C-1).

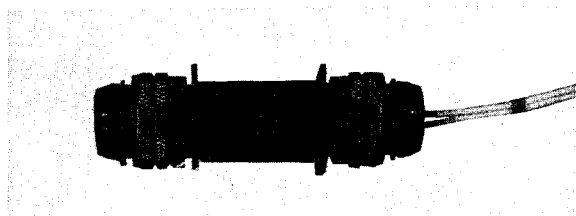


FIGURE C-1.—Electrical connector 10-channel fuse module.

IGNITION LOCATION

Ignition of the sample was accomplished by the use of a regulated energy input. The ignition source, a heated 20-gage Nichrome wire, was wrapped around the body of the sample. The power supply to the Nichrome wire provided sufficient voltage (controlled by means of a variable transformer) to ignite the test specimen.

TEST DESCRIPTION

The test specimen was mounted in the sample holder so that a center section of the

connector (2 in. wide by 5 in. long) was exposed. The Nichrome wire was wrapped around the body of the sample in contact with the midpoint of the sample, and the unit was installed inside the test chamber. The test-chamber environment was 100 percent oxygen at a pressure of 16.5 psia.

Within 5 sec after the current was applied to the Nichrome wire, the sample began burning vigorously. Propagation of the bright yellow flame was observed for 3 to 4 min. The flame was accompanied by spewing and dripping of the potting compound and the pressure inside the test chamber increased rapidly. The test was terminated by chamber pumpdown, which was required to extinguish the flame.

POST-TEST RESULTS

From the post-test inspection, it was determined that the flame had propagated to, and completely burned, one of the end connectors. The center fuse section also had been destroyed completely (fig. C-2). Conse-

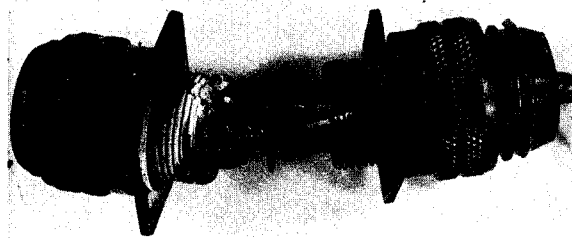


FIGURE C-2.—Post-test photograph of the 10-channel fuse module.

quently, the potting compound was considered unsuitable for use on unprotected components in an environment of 100 percent oxygen at a pressure of 16.5 psia.

APPENDIX D

Flammability Test of Nonmetallic Components in Vented Containers: Command Module Rotational Hand Controller

TEST OBJECTIVES

This test was designed to determine the flammability characteristics of the rotational hand controller (RHC) assembly in an environment of 60 percent oxygen/40 percent nitrogen at a pressure of 16.2 psia and with a fire initiated within the unit. In addition, the test was to demonstrate the containment characteristics of the container after the contents were ignited by simulating a short-circuit condition.

COMPONENT DESCRIPTION

The RHC assembly was enclosed in a vented metal case. A silicone-rubber boot was used over the handle opening to form a dust seal (fig. D-1). Components were primarily mechanical and metallic. A terminal board, located in the left side of the RHC assembly (fig. D-2), was probably the great-

est potential source of electric ignition in the RHC unit because of the relationship of the board to the boot and because the board was encased completely with polyurethane conformal coated epoxy.

IGNITION LOCATION

An external Nichrome ignitor was used for the RHC test. The ignitor was placed inside the metal case on the terminal board, which was encased in polyurethane.

TEST DESCRIPTION

The RHC was mounted on a command module couch-armrest assembly. Thermocouples were installed at various points on the RHC to monitor temperature variations during the test. A test-chamber environment of 60 percent oxygen/40 percent nitrogen was

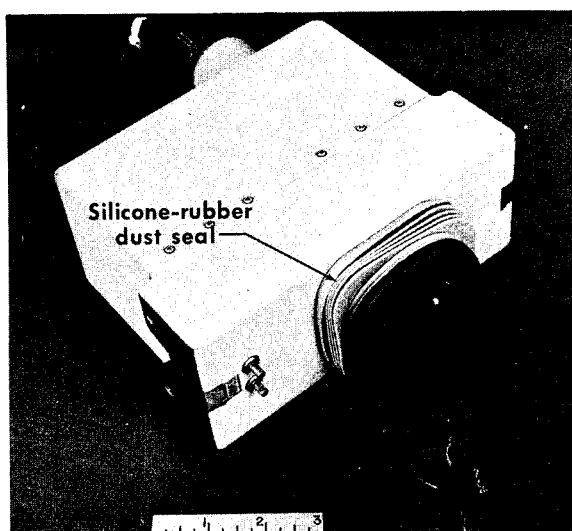


FIGURE D-1.—Rotational hand controller.

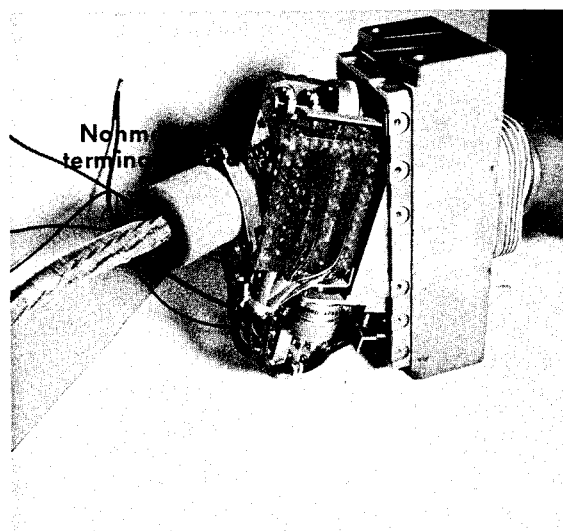


FIGURE D-2.—Interior of RHC.

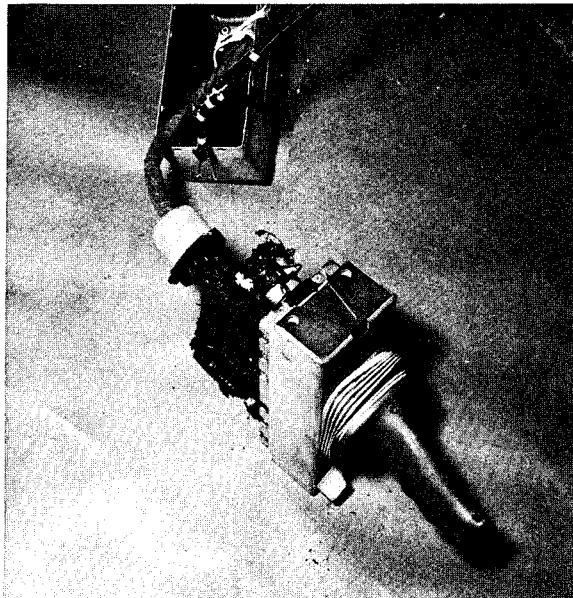


FIGURE D-3.—Post-test burn damage to RHC.

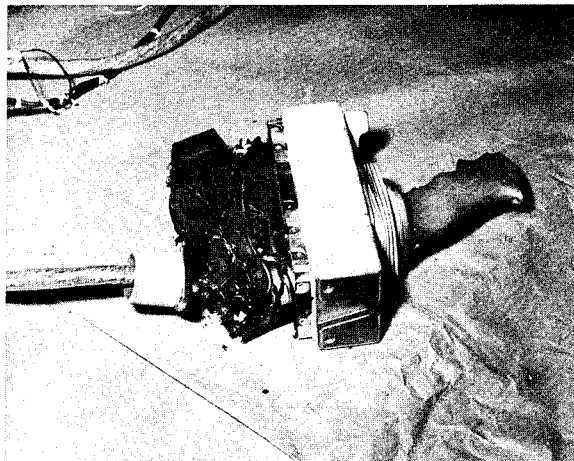


FIGURE D-4.—Post-test photograph of RHC.

provided. A 12-A dc was applied to the ignitor for approximately 15 sec; and ignition was verified by the thermocouple temperature readings. Smoke was observed 1 min 25 sec after initiation at which time the silicone bellows separated from the lower portion of the RHC. At 5 min after test initiation, a considerable amount of smoke was coming from the RHC, and a moderate haze was noticed throughout the cabin. At 24 min 20 sec after test initiation, a slight flame was observed inside the RHC. At this time, the test

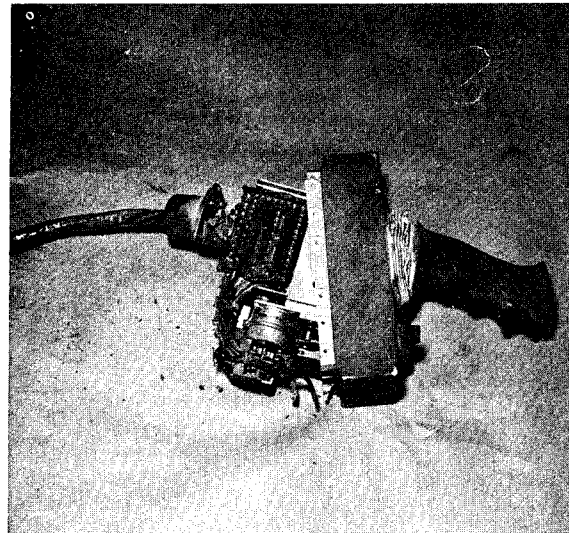


FIGURE D-5.—Damage to RHC after second test.

was concluded because of decreasing visibility and lack of flame propagation outside of the RHC assembly.

POST-TEST RESULTS

From the post-test inspection, it was determined that severe damage took place inside the metal case of the RHC. The polyurethane coating in the ignition area was badly damaged and had flowed over other internal components. Wire insulation in the bottom portion of the RHC also was burned off, and many of the resistors that were encapsulated in the polyurethane coating were exposed. Large deposits of soot and melted polyurethane were found throughout the RHC case (figs. D-3 and D-4).

From this flammability test on a vented container, it was determined that the fire was self-contained and that no flame was emitted from the RHC assembly. It was assumed that the silicone bellows separated from the RHC because of a pressure differential caused by the ignition. It was considered significant that, during a second test, the bellows remained in place, and the controller damage that resulted from ignition was much less severe and was restricted to the area of the ignitor (fig. D-5).

APPENDIX E

Flammability Test of Nonmetallic Components in a Sealed Container: Lunar Module Lighting-Control Assembly

TEST OBJECTIVE

This test was conducted to evaluate the effectiveness of the lighting-control-assembly case to contain a fire initiated by a positive ignition source located within the assembly.

COMPONENT DESCRIPTION

The lighting-control assembly was one of several lunar module components selected for special flame-containment testing. The lighting-control assembly, which was encased in a metal box, was composed primarily of electrical and electronic components that were covered by a silicone-potting compound. For this test, the lighting control assembly was modified to incorporate a Nichrome wire ignitor to provide a positive ignition source within the assembly.

IGNITION LOCATION

The Nichrome ignitor wire was placed inside the metal case on the silicone-potting compound that covers the electronic components (fig. E-1). The ignitor was connected electrically to a variable-voltage current-regulated direct-current power supply.

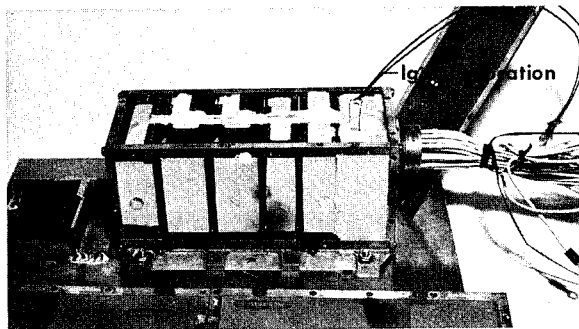


FIGURE E-1.—Pretest location of ignitor.

TEST DESCRIPTION

The lighting-control assembly was placed in the test chamber, and a thermocouple was attached to each of the six sides of the assembly. The test chamber environment was 100 percent oxygen at a pressure of 6.2 ± 0.1 psia. It had been determined empirically that a 9-A current would heat the 20-gage Nichrome wire to a red glow; therefore, an initial heating current of 9 A was used for the test. The current was increased in 1-A increments at 2-min intervals until fusion of the ignitor occurred.

No significant change in the assembly occurred when the 9-A current was applied to the ignitor. When a current of 21 A was applied, smoke was observed coming from the top plate of the lighting control assembly. The smoking continued until the ignitor fused (approximately 10 sec after a current of 23 A was applied). At this point, the test was concluded.

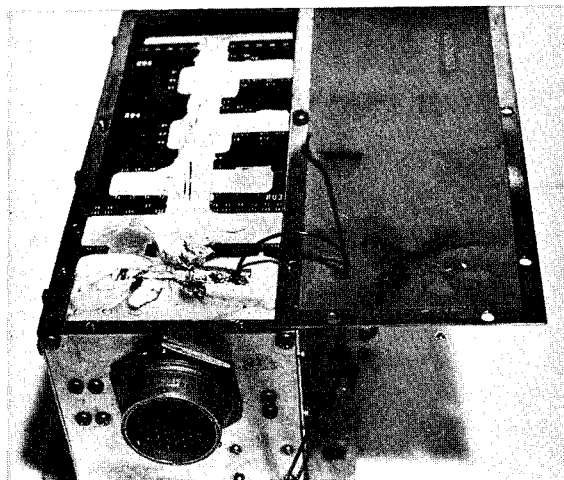


FIGURE E-2.—Post-test lighting-control assembly.

POST-TEST RESULTS

No external change in the appearance of the lighting-control assembly was noted when the assembly was examined visually. The covers were removed, and the assembly was examined and photographed. Discoloration of the silicone-potting compound in the vicinity of the ignitor was the only internal change observed. The top cover of the light-

ing control assembly also showed smoke discoloration near the location of the ignitor (fig. E-2). A slight rise in the temperature that was recorded during the test was attributed to the test-chamber floodlights. Because no external change in the appearance of the lighting control assembly was noted, it was concluded that the case was adequate to contain any fire produced by a positive ignition.

APPENDIX F

Electrical Assemblies, Subsystems, and Systems Flammability Tests: Lunar Module Panels 14 and 16

TEST OBJECTIVES

Flammability testing had indicated previously that the lunar module materials were safe in the normal flight atmosphere of 100 percent oxygen at 5.8 psia. The launch atmosphere was to be 100 percent nitrogen at a pressure of 14.7 psia. In an attempt to reduce consumption of onboard oxygen in the lunar module, it was decided to evaluate the possibility of launching the lunar module at 100 percent oxygen at 14.7 psia.

The purpose of this flammability test was to verify whether the fire-resistant capabilities designed into the panel components for an environment of 100 percent oxygen at 6 psia were adequate to prevent the fire-protected components from being ignited in a launch atmosphere of 100 percent oxygen at 14.7 psia. For this purpose, two tests were conducted.

COMPONENT DESCRIPTION

Panels 14 and 16 of the lunar module were selected as being typical of all circuit-breaker panels in the lunar module 3 configuration with respect to flammable-material quantity and distribution. The panels in-

cluded a full complement of circuit breakers, bus bars, instruments, and switches (fig. F-1). Both the effects of a fire internal to the

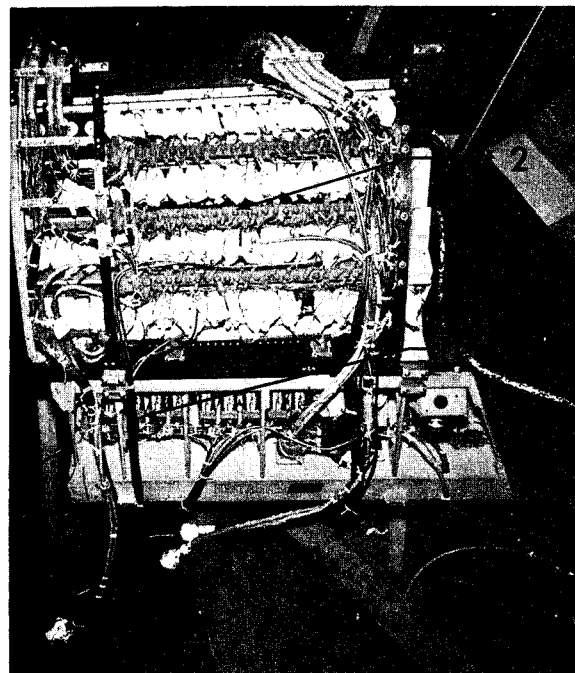


FIGURE F-1.—Pretest lunar module panels showing test locations.

assembly and the effects of a fire on the spacecraft external to the assembly were to be considered.

TEST 1

Ignition Location

The ignition source for test 1 consisted of an electrically overloaded length of 20-gage wire (lunar module specification) that was wrapped around the potted portion of a flag indicator at the bottom of the circuit-breaker panel (fig. F-1). This position had been determined by combustion-hazard analysis as an area vulnerable to a potential fire that could propagate both internally and externally to the panel.

Test Description

The panel was nonoperative. All panel controls and displays were in the OFF position, and all panel connectors were electrically disconnected and tied in place away from the back of the panel. Sections of the protective scuff cover in the rear of the panel were cut to allow visual observation of the ignition area. Pyrex glass was mounted at the rear of the panel at a distance equivalent to the distance between the pressure wall of the lunar module cabin and the panel. The test chamber environment was 100 percent oxygen at a pressure of 14.7 psia.

A current of 50 A was applied to the electrical ignitor. The potting material ignited and self-extinguished after approximately 1 min of burning. The test was terminated after 5 min, at which time it was verified that all temperatures were ambient or well below the nonmetallic-material ignition temperatures.

Post-Test Results

During the post-test inspection, it was determined that the fire had not propagated to adjacent components. Damage was noted at the site of the ignition only.

TEST 2

Ignition Location

The ignition source for test 2 consisted of an electrically over-loaded length of 20-gage wire (lunar module specification) that was placed in a wire bundle behind bus bar 4TB2. This bus bar is located approximately midway between the top and the bottom of the panel (fig. F-1).

Test Description

The panel was inoperative. Configuration of panel controls, displays, and connectors was the same as that for test 1. Atmosphere and pressure of the test chamber also were the same as for test 1.

A current of 50 A was applied to the electrical ignitor wire. This current was maintained for 30 sec. When no burning or current interruption occurred, the current was increased to 60 A. Forty-five sec after initia-



FIGURE F-2.—Post-test lunar module panels.

tion, the overloaded wire ignited, and the fire propagated along other wires to the fire-protective coating on the bus bar. At 1 min 35 sec after initiation, the row of circuit breakers immediately above the bus bar ignited. Dripping material ignited components along the lower part of the panel. The fire propagated to the front of the panel 6 min after initiation. In less than 1 additional min, the fire had engulfed the entire panel front. The test was terminated by evacuating the test chamber.

Post-Test Results

From the post-test inspection of the panels, it was determined that both panels and the components were almost completely destroyed. Damage was so extensive that it was impossible to obtain meaningful information

from the post-test inspection of individual components (fig. F-2).

SUMMARY

Fire-resistant capabilities designed into the panel components were determined to be adequate by previous testing for an environment of 100 percent oxygen at a pressure of 5.8 psia. However, when the panels were retested in an environment of 100 percent oxygen at 14.7 psia, it was demonstrated that the fire-resistant capabilities built into the panel were inadequate to prevent ignition and fire propagation caused by an electrically overloaded (ignition) wire. As a direct result of this component test, the decision was made to launch the lunar module with an inert atmosphere of 100 percent nitrogen at 14.7 psia.

Flammability Tests for Apollo Command Module and Lunar Module Mockup

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After extensive materials and component-level tests, a series of full-scale-spacecraft-mockup flammability tests provided the final verification that the Apollo command module and lunar module were safe. The flight atmosphere at reduced oxygen pressure and two possible spacecraft launch atmospheres were evaluated. The safer of the two launch atmospheres was defined. Interior mockups of Apollo command and lunar modules were used in a series of 173 flammability tests. They were conducted in oxygen at reduced pressures of 5.8 psia and 6.2 psia and in two possible launch atmospheres, 16.2 psia 100 percent oxygen and 16.2 psia 60 percent oxygen/40 percent nitrogen. Fires were started in the mockups at locations selected as representative of potential ignition hazards. For each test, data were recorded to determine possible propagation paths. Changes in materials and configuration were made in attempting to make the command and lunar modules fire-safe. The full-scale mockup tests were made in order to investigate several basic design approaches, including elimination of long propagation paths, addition of nonflammable coatings and containers, and use of firebreaks. Some of the tests conducted are discussed in this paper. The applicability of full-scale-mockup flammability-test techniques to areas outside the space program also is considered.

OBJECTIVE

The objective of the test program was to

verify the fire safety design of the Apollo command and lunar modules by performing deliberate ignitions at many locations while the interior atmosphere was controlled to simulate realistic flight conditions. For each ignition, data were acquired:

1. To determine whether the fire would propagate; and, if so, to determine the degree of propagation and the magnitude of the fire
2. To identify and understand the nature of propagation paths and fire hazards
3. To determine the effects of combustion on the rates and magnitudes of temperature and pressure increases in the spacecraft during the tests
4. To identify toxic products resulting from combustion

MOCKUP TESTING TECHNIQUES

Because spacecraft wiring is a potential ignition source, it was necessary to demonstrate that no fire would propagate significantly beyond the region of ignition. It was assumed that accidental fires might start even in the best of designs and that a method of avoiding catastrophe is the prevention of flame propagation. Therefore, in the mockup tests, fires were started deliberately in various suspect locations. The following ground rules were established:

1. The mockups were configured carefully to yield true, worst-case, composite simulations of flight spacecraft.
2. The test-ignition technique selected was

representative of ignition possibilities within the spacecraft.

3. The test-environment-control and data-acquisition networks were composed of proven components.

4. Test-termination criteria were developed to make the most efficient use of the test article and to assist in defining problem areas.

5. Detailed quality-assurance monitoring was used to verify all buildup, checkout, test, and data-acquisition procedures.

MOCKUP CONFIGURATIONS

Each mockup employed spacecraft hardware in all areas to be tested. Examples of flight hardware used for the command module mockup are shown in figures 21 to 23. A view through the entrance hatch towards the guidance and navigation equipment is shown in figure 21. Part of the left-hand equipment bay and the commander's couch, hand controllers, and main display console are shown in figure 22. The right-hand equipment bay, including circuit breaker panels, is shown in figure 23. Production wire harnesses, second-

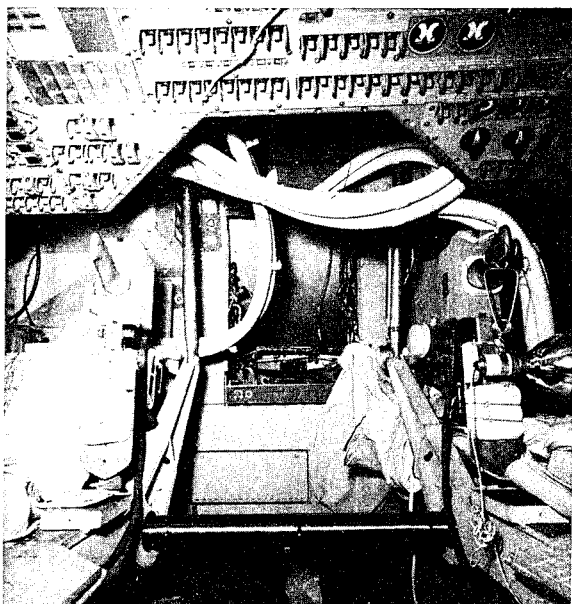


FIGURE 21.—Command module lower equipment bay and couches.

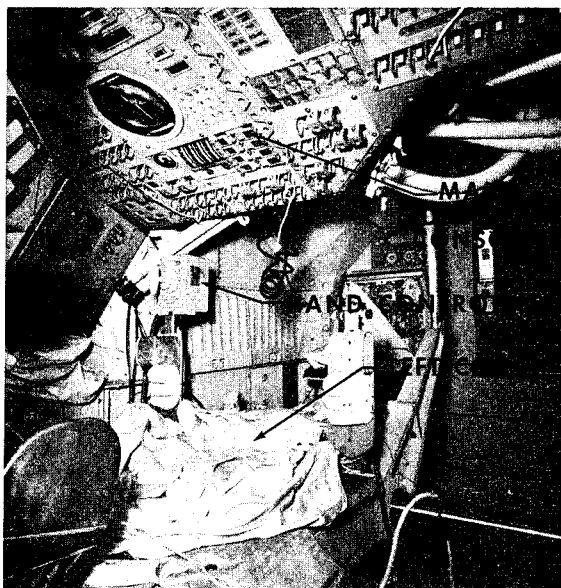


FIGURE 22.—Command module left-hand equipment bay and main display console.

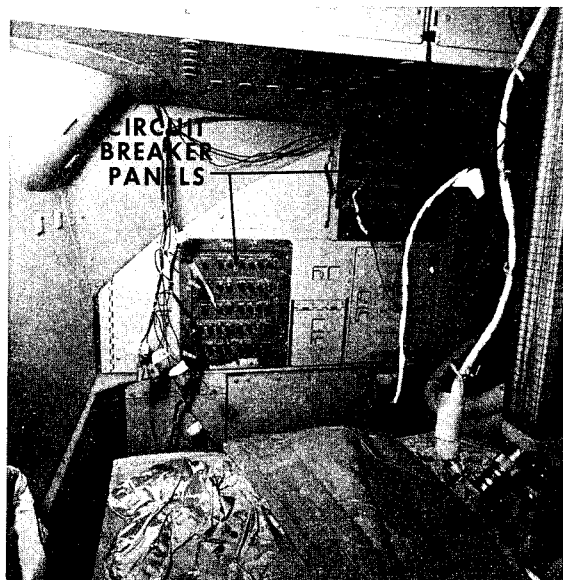


FIGURE 23.—Command module right-hand equipment bay.

ary structures, and stowage areas were used. All Government-supplied equipment was installed and either stowed or placed in the appropriate housekeeping situation.

The lunar module mockup was configured with the same degree of fidelity. A view of the left-hand side of the vehicle, including a

flight suit, circuit breaker panels, and the commander's main display console and hand controllers, is shown in figure 24. A view of the left-hand side towards the rear of the vehicle, showing stowage areas, oxygen

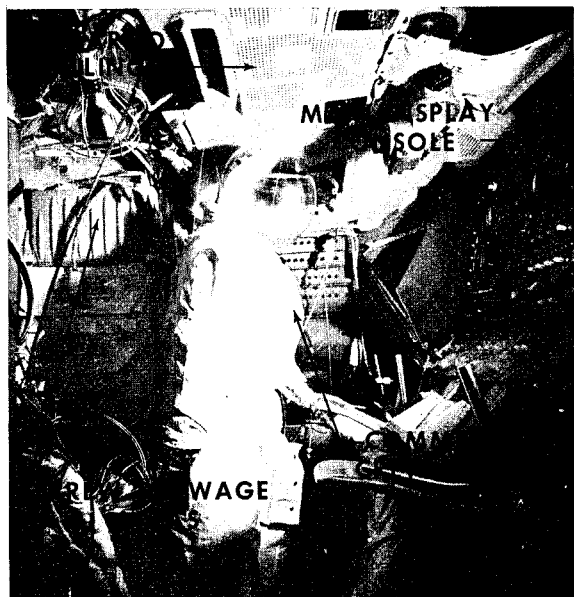


FIGURE 24.—Lunar module commander crew-station and displays.



FIGURE 25.—Lunar module right-hand side looking aft.

hoses, and the portable lift support system (PLSS), is shown in figure 25. Where major components are duplicated several times in the spacecraft, duplication was not complete in the mockup in order to minimize cost. For the same reason, components previously used in shock and vibration-qualification test programs were utilized where possible.

IGNITION TECHNIQUE

Either an external or an internal ignitor was used in each test. The external ignitor simulated flame impingement on the nonmetallic material and the internal ignitor simulated an internal short in electrical components. The source for internal ignition of electrical panels consisted of a 12- to 14-turn coil of 26-gage Nichrome wire formed by winding on a 0.12-in.-diam mandrel (fig. 26). The coil was buried in silicone-rubber conformal coating material, which was in turn covered with Ladcote, a fire-protective coating. For external ignition conditions, the coil consisted of eight turns of 20-gage Nichrome wire mounted in contact with the nonmetallic material to be tested (fig. 27). In this ignitor, a cylinder of silicone rubber, 1.25 in. long by 7/32-in. diameter, was inserted in the center of the coil to provide repeatable heat-energy input to the test item. Internal ignition was detected by adjacent thermocouples. The external ignition sources were capable of providing a visible flame for 20 to 30 sec.

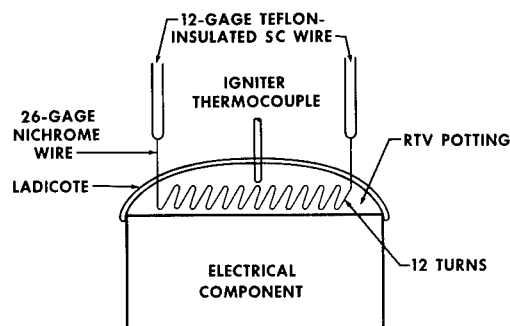


FIGURE 26.—Internal (hidden) ignitor configuration.

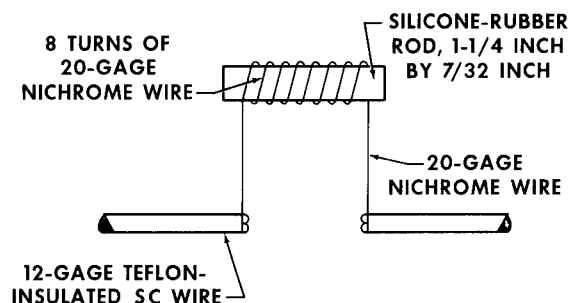


FIGURE 27.—External ignitor configuration.

In addition to these techniques, an electrically overloaded wire was used in several tests in which ignition of wire bundles was attempted. This technique consisted of incrementally overloading one of the larger conductors in the wire bundle over the entire length to determine whether ignition might occur at several locations simultaneously.

The specific type of ignition source and the ignition location are given in the individual test results presented in this paper. The general criteria used for the selection of ignition locations included these factors:

1. Proximity of ignition source to flammable materials (i.e., silicone clamps, spacers, etc.)
2. Apparent propagation paths, such as vertical configurations of wire bundles, connectors, or terminal boards
3. Large masses of nonmetallic materials
4. Evaluation of changes made to reduce flammability hazard
5. Proximity to stowage areas containing flammable materials

INSTRUMENTATION

Appropriate instrumentation was used to obtain data pertaining to all significant parameters.

Thirty Chromel-Alumel thermocouples with a range of 0° to 2500° F were used to monitor cabin ambient temperatures and to support the test-termination criteria in the ignition area. Two pressure transducers of 0- to 50-psia range were used to monitor cabin ambient pressure. Still photographs were

taken before and after each test. Each test was documented by as many as four cameras. One closed-circuit camera was used to monitor the testing.

Semicontinuous monitoring of oxygen content of the cabin environment was conducted by the use of a gas chromatograph. Gas samples were obtained before and during each test for detailed analysis. The gas samples were collected in a sampling bomb and analyzed in the following manner:

1. A Consolidated Electrodynamics Corp. Model 21-103C mass spectrometer was used to analyze all constituents present in concentrations greater than 0.2 percent.
2. An Instruments, Inc., Model C-40 gas chromatograph was used to analyze carbon monoxide in parts per million (ppm).
3. A Perkin-Elmer Model 521 infrared spectrophotometer equipped with a variable-path-length gas cell was used to analyze all other trace infrared techniques.

SPECIFIC TEST-TERMINATION CRITERIA

Tests were terminated on the basis of visual observation and data from thermocouples located in the area of ignition. Specific test-termination criteria for each individual test were included in the detailed test plan (ref. 1). The general criteria for test-termination for each of the various test conditions are given below.

Flame Self-Extinguishing

The test condition was maintained for a minimum of 5 min after the flame extinguished to verify that all temperatures were at ambient or below the nonmetallic-material-ignition temperatures.

Flame Propagation

In some cases, the test was terminated when the flame propagated a predetermined distance or when temperature limits were reached on specific thermocouples located in the test area.

Egress Time

This criterion was applicable to the command module for ground-test and launch atmospheres only, and the objective was to determine if the crew had adequate time to egress from the command module if a fire occurred. Actual egress time for three astronauts is a maximum of 85 sec, to which a safety margin of approximately 50 percent was added to provide a total egress-time factor of 125 sec. As applied to this test program, the egress time of 125 sec was started when smoke was observed in the cabin. If an excessively severe fire occurred during the 125 sec, or if flaming particles dripped onto the couches, or if flame was observed in any portion of the egress route, the test was terminated and an inadequate egress time was indicated. If the fire did not become excessively large during the 125 sec but did progress beyond the predetermined limits, the test conditions were maintained for the full 125 sec, at which time the test was terminated. If the fire did not progress beyond the predetermined limits during the 125 sec, the test conditions were maintained either until the fire self-extinguished or until it progressed beyond the predetermined limits, at which time the test was terminated.

COMMAND MODULE MOCKUP TESTS

An interior mockup of a command module was used to conduct 102 flammability tests. Thirty-seven tests were conducted in a 6.2-psia, 100-percent-oxygen atmosphere to duplicate a worst-case flight atmosphere. (The nominal cabin operating pressure is 5.0 psia.) In addition, 35 tests were conducted in a 16.2-psia, 60-percent-oxygen/40-percent-nitrogen atmosphere, and 30 tests were conducted in a 16.2-psia, 100-percent-oxygen atmosphere. The latter two series of tests represented optional launch atmospheres. Fires were started deliberately in the command module mockup at locations selected as representative of potential ignition hazards (ref. 1). Command module tests 126, 226, 326, 106, 206, and 306 are discussed in this

paper to illustrate the types of tests performed.

Tests 126, 226, and 326

The purpose of these tests was to determine the flammability of a large, vertical, Teflon-overwrapped wire bundle. Teflon overwrap (10 mils thick) was used extensively throughout the vehicle to protect wire bundles. The specific objective of these tests was to determine the extent of propagation of fire from an external ignition source at the lower end of the Teflon overwrap (fig. 28) at the three test conditions.

Test 126 was conducted at a cabin pressure of 6.2 psia in a 100-percent-oxygen atmosphere. A small amount of smoke was the only visible result of this test. No temperature rise occurred away from the immediate region of the ignitor, and the local fire near the ignitor self-extinguished.

Test 226 was conducted at a cabin pressure of 16.2 psia in an atmosphere of 60 percent oxygen and 40 percent nitrogen. In this test, smoke was observed 6 sec after application of ignitor power (T+6 sec), and flame in the ignition area was observed from T+26 sec to T+3 min. Instrumentation in-

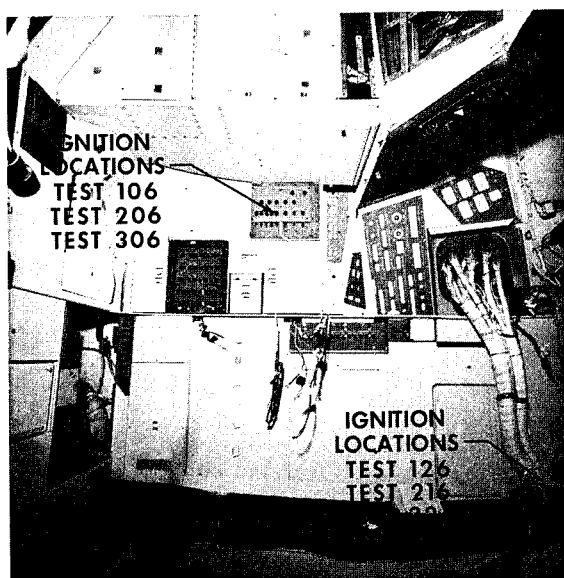


FIGURE 28.—Command module ignition locations.

licated continued burning for several minutes before self-extinguishment.

Test 326 was conducted at a cabin pressure of 16.2 psia in a 100-percent-oxygen atmosphere. Flame was observed at T+15 sec. The fire increased in intensity, and molten drippings were noticed at T+1 min 20 sec. At T+1 min 45 sec, fire propagated to the back of the large wire bundle and ignited the adjacent wire bundle. Fire continued to propagate upward, ignited two wire-bundle clamps at T+2 min 35 sec, and continued upward to the ground-support equipment window. Fire on the adjacent bundle propagated to the wiring on the cabin floodlight and above and behind panel 3. Dark smoke was observed in the cabin at T+3 min 30 sec, and soot was observed throughout the cabin at T+3 min 50 sec. Fires still were visible when the test was terminated at T+4 min 45 sec in accordance with test-termination criteria.

The following summaries are for tests 126, 226, and 326.

Test 126: The results indicated that the Teflon wrap did not provide a propagation path.

Test 226: The results indicated that there was considerable burning of the Teflon wrap. The fire eventually self-extinguished.

Test 326: The results indicated that the Teflon overwrap provided a propagation path whereby a localized fire could become widespread.

Results of these three tests indicate that the Teflon overwrap on wire bundles is safe at a cabin pressure of 6.2 psia in a 100-percent-oxygen atmosphere. At 16.2 psia in a 60-percent-oxygen/40-percent-nitrogen atmosphere, adequate egress time is available if the spacecraft is on the launch complex. At a pressure of 16.2 psia in an atmosphere of 100 percent oxygen, an unacceptable fire results. (See figs. 29, 30, and 31.)

Tests 106, 206, and 306

An internal ignitor placed under the conformal coating of a circuit breaker in panel 225 (which is on the upper right-hand side of

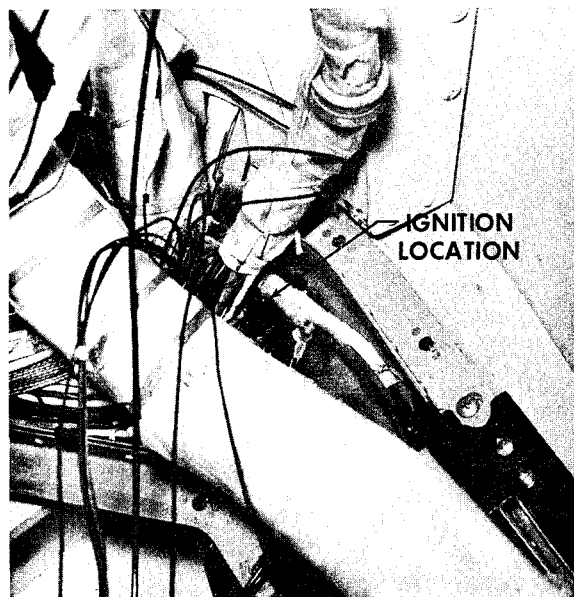


FIGURE 29.—Post-test damage (test 126).

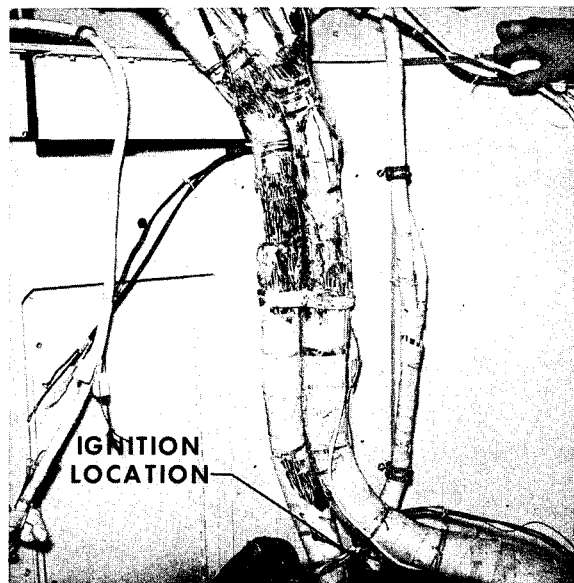


FIGURE 30.—Post-test damage (test 226).

the mockup) was used in these tests. The cabin ambient pressures and atmospheres were in the same sequence as in the three preceding tests.

Test 106: At T+30 sec, smoke was observed at the lower left-hand corner of the panel. At T+2 min 45 sec, smoke was ob-

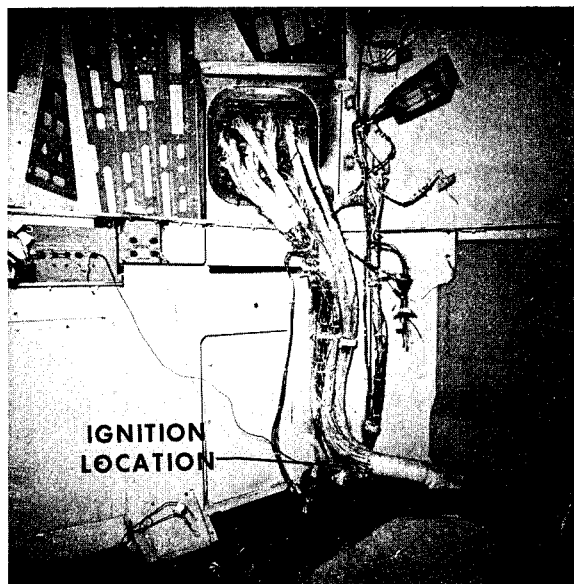


FIGURE 31.—Post-test damage (test 326).

served at the upper left-hand corner of the panel. No flame was observed, and all temperature data indicated that little or no propagation occurred. The test was concluded at T+7 min.

Test 206: Smoke was observed at T+45 sec and increased steadily before forced termination of the test at T+6 min 15 sec. At termination, the thermocouples between and on top of the circuit breakers indicated temperatures of 1780° and 1231° F, respectively.

Test 306: Light smoke was observed coming from the lower left-hand corner of the panel at T+38 sec. At T+1 min 5 sec a flash was observed in the panel area. At T+1 min 20 sec, light smoke rose from the top of the panel. Heavy smoke from the panel was observed at T+2 min 20 sec and caused a light haze throughout the cabin. At T+2 min 50 sec, flame emanated from the upper left-hand corner of the panel. At T+3 min 15 sec, the fire ignited the upper left-hand corner of the electroluminescent (EL) panel and began propagating downward and to the right. At T+3 min 20 sec, the fire was very intense, and dense smoke was visible throughout the cabin. Dripping was observed at T+4 min 20 sec. The test was terminated

at T+4 min 27 sec in accordance with test-termination criteria. Just before termination, the fire had propagated across approximately 75 percent of the EL panel; all related temperatures were above nonmetallic-materials ignition temperatures and rising.

The following summaries are for tests 106, 206, and 306.

Test 106: This test indicated that application of Ladcote on circuit breakers provides sufficient protection to prevent flame propagation.

Test 206: This test indicated that Ladcote is not sufficient protection for the circuit breakers.

Test 306: This test indicated that Ladcote does not provide adequate fire protection for the circuit breakers.

These tests indicated that 90 mils of Ladcote applied to circuit breakers is adequate protection for the flight atmosphere of 6.2 psia, 100-percent oxygen. The protection in a 16.2-psia, 60-percent-oxygen/40-percent nitrogen atmosphere is sufficient to provide adequate egress time. In a 16.2-psia, 100-percent-oxygen atmosphere, an unacceptable fire results. (See figs. 32, 33, 34, and 35.)

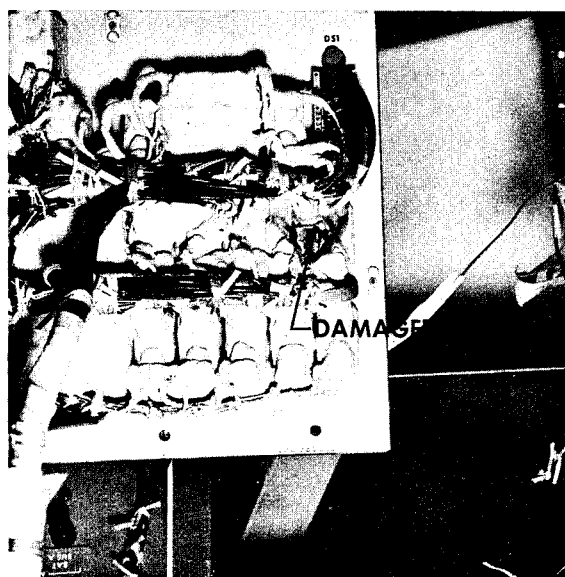


FIGURE 32.—Post-test damage (test 106).

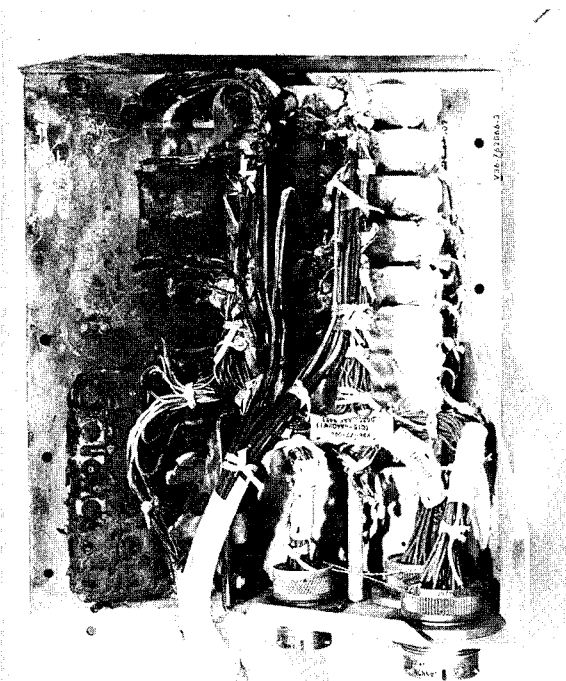


FIGURE 33.—Post-test damage (test 206).

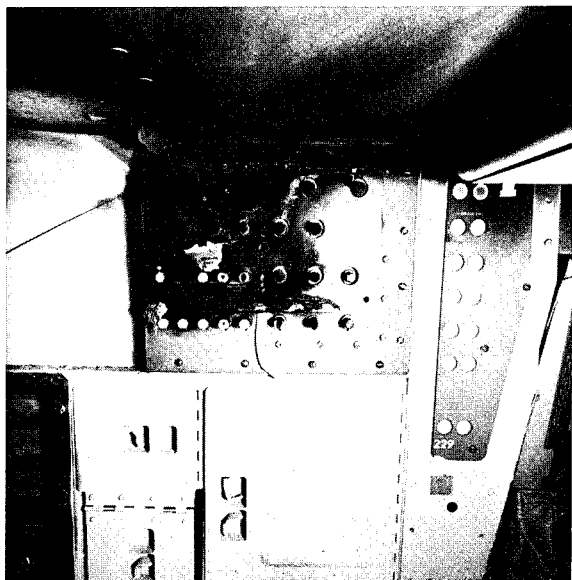


FIGURE 34.—Post-test damage, front view (test 306).

LUNAR MODULE MOCKUP TESTS

In addition to the command module tests, 72 flammability tests were conducted in an interior mockup of the LM in a 100-percent-oxygen atmosphere at 5.8 psia, which is a



FIGURE 35.—Post-test damage, rear view (test 306).

worst-case pressure for the LM. (The nominal cabin operating pressure is 5.0 psia.) Fires were started at locations selected as representative of potential LM ignition hazards. Three tests (12, 16, and 41) are discussed in this section.

Test 12

The purpose of this test was to determine the flammability characteristics of the PLSS and the possibility of fire propagation to other materials. An external ignitor was located on the bottom left-hand rear edge of the PLSS hard case that was not protected by the Beta thermal cover (fig. 36).

Ignition occurred at T+18 sec. The flame remained localized in the lower left-hand corner until T+1 min 40 sec. At T+1 min 45 sec, soot and smoke were observed, and the flame slowly propagated upward. More soot and smoke were observed at T+3 min 30 sec, and haze formed in the cabin at T+4 min. The flame propagated almost to the top of the PLSS at T+6 min 55 sec. The cabin was hazy, but visibility was not reduced appreciably. Sparks flew out into the cabin. The test was terminated at T+7 min 30 sec. At



FIGURE 36.—Lunar module ignition location (test 12).

termination, the flame impinged on the bottom and front of the on board-data stowage container.

The results of this test indicated that, although the fire was somewhat slow in starting, the material in the portable life support system (PLSS) hard cover provided the fuel and propagation path that caused the localized fire to become widespread. The purpose was to determine the extent of dripping or sparking and the possibility of secondary ignition of materials such as the Viton protective floor cover, the suit with Lexan helmet, or Velcro on the ascent-engine cover. (See figs. 37 and 38.)

Test 16

Ignition was caused by an electrically overloaded Teflon cable located above the Trevaro (fiber glass with silicon and resin) ceiling panel and the commander's station; the silver-plated cable was net-jacketed and shielded with copper. The overload was caused in a 22-gage, single-shielded conductor housed in the cable (fig. 39).

Ignition occurred at T+2 min 45 sec on

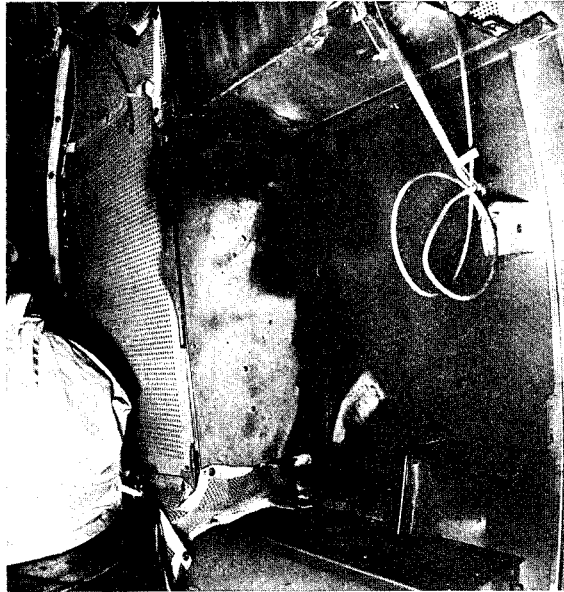


FIGURE 37.—Post-test damage (test 12).



FIGURE 38.—Post-test damage of PLSS (test 12).

the forward end of the wire above the center ceiling. Flame and sparking were observed, and the fire propagated for some distance along the cable. The 65-A overload current was intermittent, indicating a possible electric short to the metal jacket. No smoke

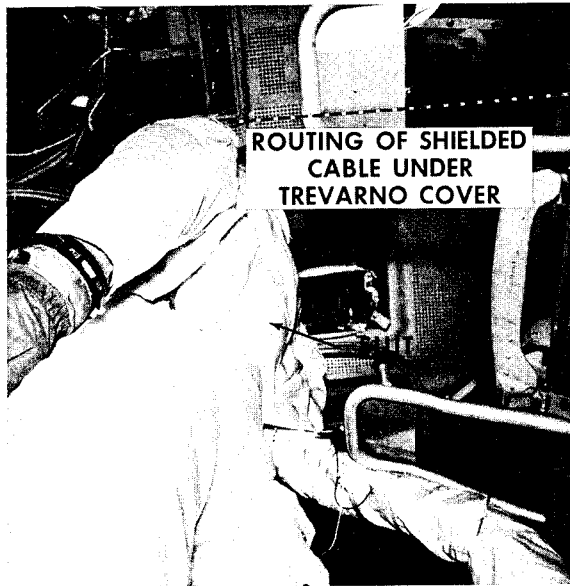


FIGURE 39.—Lunar module ignition location (test 16).

buildup in the cabin area was observed, and the fire self-extinguished. The test was concluded at $T+8$ min.

An excessive amount of flashing and sparking occurred; however, no fire propagated to other materials, and only localized damage resulted from this test. (See fig. 40.)

Test 41

A test more severe than the preceding ones was required to evaluate the thermal protection provided by the space suit when exposed to a fire of considerable magnitude. It was also necessary to determine whether propagation to adjacent panels would occur. An external ignitor was located between the pages on the left-hand side of the procedures manual mounted above the display and keyboard (DSKY) on panel 4. In addition, two food packets were located on the procedures manual (fig. 41).

The procedures manual was ignited and, along with the food packets, burned for 30 min before self-extinguishment, at which time the test was terminated. The most severe fire occurred during the first 5 min;

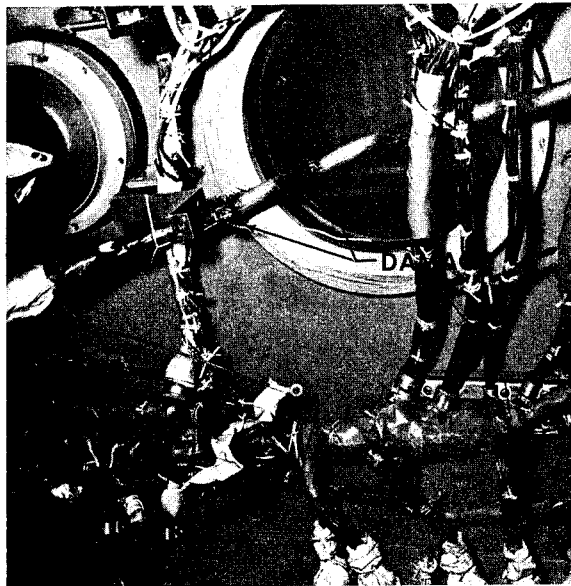


FIGURE 40.—Post-test damage (test 16).

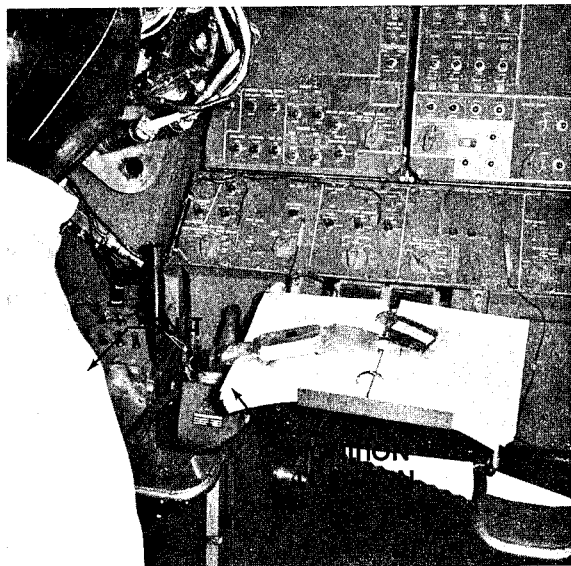


FIGURE 41.—Lunar module ignition location (test 41).

then the fire gradually subsided to a low level.

Despite the magnitude of the fire, no significant propagation or heat damage occurred to materials other than those in the immediate vicinity of the fire. (See fig. 42.)

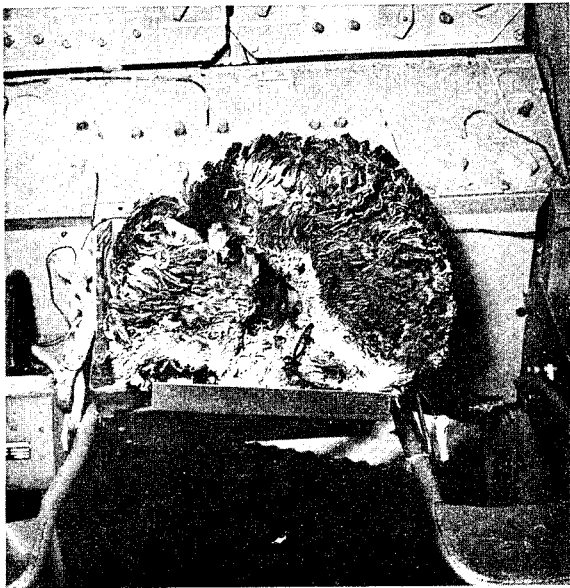


FIGURE 42.—Post-test damage (test 41).

MOCKUP TEST SUMMARY

Because most of the nonmetallic materials in the command module had been tested previously at a component level and found acceptable, the high degree of flammability of some materials and the substantial areas affected by some of the fires were unexpected. For example, in a 16.2-psia, 100-percent-oxygen atmosphere, the degree of flame propagation along the Ladcote flame-retardant coating on the back of the electrical panels was much greater than expected. Before full-scale testing was initiated, a number of component tests had indicated that Ladcote was a satisfactory flame retardant; however, during full-scale testing, the Ladcote failed to prevent excessive propagation. Other tests that showed certain components to be unacceptable in the spacecraft configuration (although component tests had shown these items to be acceptable) were the tests associated with the silicone-laminate scuff covers, Teflon chafe guards, and silicone wire-bundle spacers. The variations in the results of component tests when compared to the results of full-scale tests indicate that, although individual-component testing re-

mains a necessary first step, the results cannot be taken as conclusive when applied to a complete spacecraft. Such variables as location, heat-sink characteristics, airflow patterns, proximity to other materials, which can be represented only in full-scale tests, are significant factors in determining the flammability characteristics of individual and integrated components.

A summary of the command module and lunar module tests is presented in table VIII. As indicated in this table, the number of unacceptable fires in the command module tests was notably proportional to the oxygen partial pressure. Corrective action was taken for those cases requiring termination or when inadequate or marginal egress time occurred.

CORRECTIVE ACTIONS

Command Module

Teflon wire wrap, 16.2 psia, 100 percent oxygen—No satisfactory replacement materials or alternate systems have been found to replace the Teflon chafe wraps; therefore, the test results were instrumental in the decision to use a 60-percent-oxygen/40-percent-nitrogen launch atmosphere in the command module. No hazard exists in a 6.2-psia, 100-percent-oxygen environment.

Circuit breaker panels, 16.2 psia, 60 percent oxygen/40 percent nitrogen—The protection used is adequate for all spacecraft. The only propagation that could occur is during prelaunch operations. In this situation, the crew would have adequate time to egress. No hazard exists in 6.2-psia, 100-percent-oxygen atmosphere; therefore, no corrective action was required.

Protection against toxic products of combustion—All of the data on composition or spacecraft cabin atmospheres during and after the fire tests were furnished to the Medical Research and Operations Directorate for assessment of hazard to the crew. One result of this assessment was the provision of emergency oxygen breathing masks to be worn by the crew in the event of fire in the spacecraft when crewmen are not suited.

TABLE VIII.—*Summary of Lunar Module (M-6) and Command Module (BP-1224) Flammability Tests*

Environment	Total number of tests	Number of tests self-extinguished	Number of tests requiring termination	Tests terminated, percent	Number of tests with insufficient egress time	Number of tests with marginal egress time
Lunar module tests						
5.8 psia, >95 percent oxygen-----	72	65	^a 7	10	(^b)	(^b)
Command module tests						
6.2 psia, >95 percent oxygen-----	37	34	^a 3	8	(^b)	(^b)
16.2 psia, 60 percent oxygen/ 40 percent nitrogen-----	34	28	5	15	^a 1	1
16.2 psia, >95 percent oxygen-----	30	15	15	50	^a 3	4

^a Corrective action was taken in each of these cases, and subsequent tests indicated elimination of the problem.

^b Not applicable.

Lunar Module

Portable life support system—All exposed edges of the PLSS hard cover, which is aluminum honeycomb covered with fiber glass, were protected with an aluminum tape for Lunar Module 3. Portable life support systems for subsequent vehicles have a complete cover built of multilayers of nonflammable thermal protective materials. Subsequent tests verified the adequacy of this action.

Teflon, net-jacketed, shielded cable—This wire bundle was overwrapped with Hi-Rap Teflon tape. Subsequent tests verified the adequacy of this corrective action.

CONCLUDING REMARKS

As a result of information obtained from these full-scale flammability tests, it was concluded that, with the presently available materials, a spacecraft atmosphere of 16.2 psia, 100 percent oxygen should not be used. However, the material changes and other changes that have been made in the command module and lunar module have resulted in a fire-safe configuration in the 16.2-psia, 60-percent-oxygen/40-percent-nitrogen launch atmosphere and in the 6.2-psia, 100-percent-oxygen in-flight atmosphere. Consequently, these two

atmospheres were selected for launch and flight, respectively.

The full-scale mockup tests demonstrated that an extensive testing program for individual materials and components alone will not necessarily provide a safe composite in a hazardous environment. Materials with low-burning rates may provide propagation paths when used in long vertical runs. Firebreaks between flammable materials are highly desirable. Nonflammable covers and coatings are of considerable value in reducing the fire hazard.

The approach of using slow-burning materials, firebreaks, and protective covers and of avoiding propagation paths is probably suitable for other potential applications, such as aircraft, land vehicles, and surface and underwater vessels.

With the above design lessons intensively applied, future requirements for repetitive mockup testing will be minimized and the fire safety of vehicles can be greatly improved.

REFERENCE

1. BRICKER, R. W.; PRIMEAUX, G.; CRABB, J. P.; AND SCHOMBURG, C.: Apollo Command Module Mockup Flammability Tests. NASA TN D-5654, 1970.

Session II

MATERIALS DEVELOPMENT

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Nonmetallic-Materials Development for Spacecraft Applications

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Nonmetallic materials chosen for use in space flight were exposed to extreme variations in environment. The space and lunar environment (table IX) emphasizes the need for performance under the extremes of vacuum, temperature, and radiation. When used in manned spacecraft, all materials, both those inside the cabin and those exposed to the direct space environment, must remain functional. One important additional requirement for cabin materials is that the materials must exhibit no tendency to burn in the cabin environment (table X). Another important requirement is that the material must not offgas toxic products while in normal use.

A fireproof-materials program, which was initiated in 1964, used Beta fiber glass, an inorganic fiber, to meet the need for a totally

TABLE IX.—*Space and Lunar-Surface Environment*

Environment	Condition
Pressure	$\approx 10^{-14}$ mm Hg
Temperature (lunar surface)	
Upper	250° F
Lower	-250° F
Electromagnetic radiation	X-ray
	Ultraviolet
	Infrared
Solar winds	Materials must
	withstand exposure
Micrometeoroids	without functional
	degradation

TABLE X.—*Apollo Spacecraft Cabin Environment*

Environment	Pre-launch	Post-launch
Pressure, psia (maximum)	16.5	6.2
Temperature, ° F	70±10	70±10
Relative humidity, percent	30±10	60±10
Oxygen, percent	60	>95
Nitrogen, percent	40	0

nonflammable textile. Also in 1964, NASA began investigating the flame-resistant polybenzimidazole (PBI) fiber, which was being developed for the U.S. Air Force. To provide flame-resistant elastomers, NASA studied Viton and Fluorel. Samples of high-temperature polyimide film (Kapton) were obtained in 1965 and evaluated for thermal insulation.

After the Apollo 204 fire in January 1967, the development of nonmetallic materials within NASA was expanded, and the materials were used in prototype designs as they became functional. Material design parameters were especially complex because of the requirements imposed for additional fire safety and resistance to the free-space and lunar-surface environment. The success of the program contributed significantly to the successful lunar landing on July 20, 1969.

MATERIALS DEVELOPMENT FOR THE APOLLO PROGRAM

Some of the nonmetallic materials re-

quired in support of the Apollo Program are fibers, elastomers, thermoforming plastics, and thermosetting plastics. The functional classification includes knitted and woven fabrics, webbings, cords, tapes, foams, potting compounds, wire insulations, adhesives, coatings, lubricants, sealants, molded items, laminates, films, and Velcro fasteners.

TEXTILES

Of the textiles developed for the Apollo Program, the one most widely used in the spacecraft is Beta fiber glass (ref. 1). Because Beta fiber glass cannot withstand severe abrasion, PBI is used for spacecraft applications where abrasion resistance is a main functional requirement. Although PBI fiber will burn in oxygen, it burns so slowly that the hazard is minimal. It is completely non-flammable in air and retains approximately 75 percent of its strength at 725° F. A typical application of PBI fiber in a restraint harness is shown in figure 43.

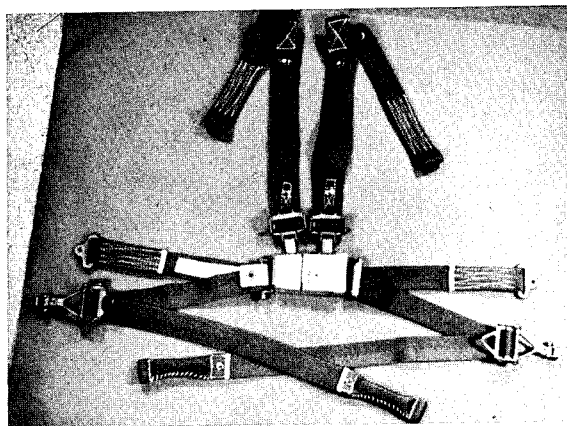


FIGURE 43.—Polybenzimidazole crewman restraint harness.

Teflon fiber, made from a fluorocarbon polymer that burns slowly in pure oxygen, has gained acceptance in the space program because of its excellent chemical resistance, good wearability, and low friction coefficient. The present Apollo intravehicular flight coveralls (fig. 44) are made of bleached-white Teflon fabric.

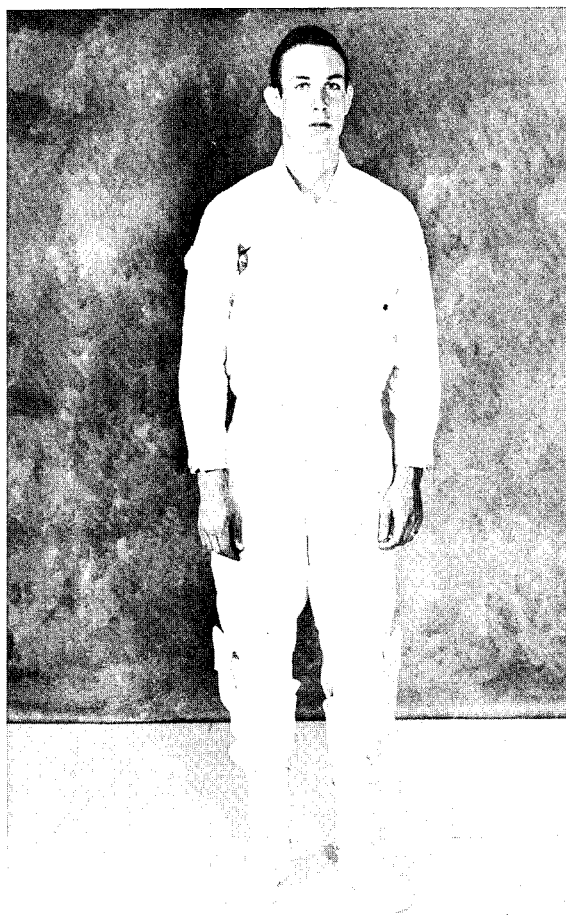


FIGURE 44.—Typical application of Teflon fabric for Apollo intravehicular coverall.

Asbeston is another fibrous material that has had some limited use in the space program. The structure and composition of the Asbeston fiber were modified for maximum flame resistance, tensile strength, and durability. This material must be covered to prevent particulate discharge. Asbeston covered with Beta fiber glass is used as a container for protection of flammable materials.

Table XI contains a list of the physical properties of the more recent developments of fibrous materials that can be used, in part, when the materials are considered for individual applications. For comparison purposes, the properties of Nomex, a more conventional and better known material, have been included in table XI. For restraint webbings, a fiber with low elongation and high

TABLE XI.—*Properties of Fibrous Materials*

Properties	Beta	PBI	Teflon	Asbeston	Nomex
Tensile strength, g/denier	15	4.5	1.4	2.5 to 3.1	5.5
Elongation, percent	4	12 to 13	15	2 to 3	17
Specific gravity	2.45	1.34	2.1	2.10 to 2.80	1.38
Service temperature, °F	-300 to +900	-65 to +800	-400 to +500	-200 to +2400	-65 to +500
Thermal conductivity, Btu/ft ² /°F/hr/in.	4.97	.9	1.7	.59	.9

strength is required. For a coverall or comfort liner, a fiber with high elongation is used. Some typical Apollo applications of the fibrous materials when woven into fabrics, webbings, and tapes are listed in table XII.

ELASTOMERS

The term "elastomer" is used to describe natural and man-made rubber-like materials that exhibit a high degree of resiliency or elasticity. Most of the available elastomers burn in oxygen. The silicones are good for high-and low-temperature use and are used extensively in the Apollo Program; however, the material is protected from possible fire by an overwrap of nonflammable material in these installations. Chloroprene and polyurethane also are used, but these also are shielded from fire in their applications.

Several new flame-resistant elastomers have been developed. These elastomers included carboxy nitroso rubber (CNR), fluorocarbon compounds (Fluorel (ref. 2) and Viton (ref. 3)), and fluorosilicones. Although these elastomers either meet the Apollo flammability requirements or exhibit im-

proved fire resistance, they do not yet exhibit all the requisite properties. In particular, low-temperature flexibility requires improvement.

Physical properties of these materials are listed in table XIII. All three have properties that are characteristic of high-quality elastomeric materials. Service temperatures are generally acceptable; however, improvement in both high-and low-service temperatures is highly desirable.

PLASTICS

The term "plastic" denotes a polymeric substance that possesses a high molecular weight that can be formed. Materials in this category include thermoforming plastics, which revert to a flowable state when heated, and thermosetting plastics, which crosslink on curing and cannot be remolded. Examples of thermoforming plastics include acrylics, nylon, ethylene, polycarbonate, styrene, vinyl, and tetrafluoroethylene. Typical thermosetting plastics are phenol formaldehyde, urea formaldehyde, melamine, polyester, and epoxy.

The relative flammability of many plastic materials has necessitated their replacement in unprotected applications with materials that have improved fire resistance. In some cases, replacement has been accomplished with metallic substitutions. Replacement of transparent plastics, such as space-suit visors, is particularly difficult. Limited success has been achieved in the application of transparent, flame-resistant coatings to the optical plastics by sputter-coating and plasma-spraying with silica and alumina.

TABLE XII.—*Typical Applications for Fibrous Materials*

Materials	Typical applications
PBI	Harnesses, tethers, straps, belts, and containers
Teflon	Flight coveralls and abrasion-resistant patches for space suits
Asbeston	Flame barrier or thermal insulation
Nomex	Comfort liner for Apollo space suit

TABLE XIII.—*Properties of Elastomeric Materials*

Properties	Fluorel	Viton	CNR rubber
Specific gravity.....	1.85	1.97	1.93
Service temperature, °F.....	−40 to 400	−65 to 400	−47 to 375
Tensile strength, psi.....	1500 to 2500	1500 to 2500	1000 to 2020
Elongation, percent.....	125 to 300	150 to 300	250 to 500
Durometer hardness, Shore A.....	60 to 90	60 to 90	60 to 80
Thermal conductivity, Btu/ft ² /°F/ hr/in. ..	.957	.702	.867

VELCRO FASTENERS

Velcro fasteners were used throughout Project Mercury and the Gemini Program and are used extensively in the Apollo missions where quick attachment and release are required. Standard Velcro fasteners, made from nylon, are highly flammable.

A new fastener called Astro Velcro (fig. 45) has been developed. The Astro Velcro pile is made from Teflon, and the ground tape is made from Beta fiber glass. The hook part of the fastener, which is made from flammable polyester, meets Apollo requirements when engaged with the pile. Velcro flammability test results are listed in table XIV. The Astro Velcro peel strength is equivalent to that of nylon Velcro, and approximately the same strength is maintained even after 100 cycles. A summary of the physical properties is shown in figure 46.

Improvements in the flame resistance and physical properties of Velcro fasteners are

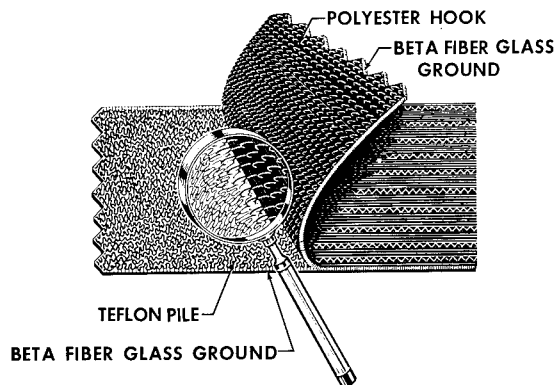


FIGURE 45.—Astro Velcro.

TABLE XIV.—*Flame Propagation Rate of Velcro*

[Bottom ignition; silicone ignitor]

Velcro type (engaged)	Propagation rate, in./sec	
	6.2 psia 100 percent oxygen	16.5 psia 60 percent oxygen/40 percent nitrogen
Nylon.....	1.66	1.66
Astro.....	.35	.37

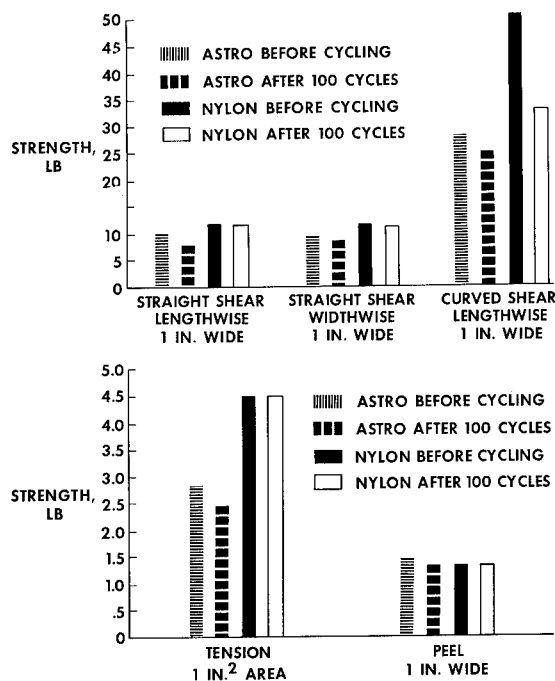


FIGURE 46.—Comparative physical properties of Astro and nylon Velcro fasteners.

being pursued. Other organic monofilaments are being considered to replace the flammable polyester hook. In addition, a newly molded Velcro hook has provided substantial increases in the shear and peel strength.

FLAMMABILITY AND OFFGASSING TEST DATA

To be considered for use in the Apollo Program, the selection criteria established in reference 4 and described in reference 5 are used. With respect to flammability and offgassing, the criteria listed in table XV apply. Categories A and B in this table refer to the usage category [that is, A (major exposed materials) and B (minor exposed materials)]. The offgassing characteristics of some of the previously described materials are included in table XVI. A comparison of the characteristics to the criteria in table XV indicates that the materials are well within the maximum allowable limits for odor, carbon monoxide, and total organic offgassing. The flammability data on these materials are presented in table XVII. The data in tables XVI and XVII are used with the criteria of table XV to determine the materials suitable for category A and category B usage.

NEW MATERIALS DEVELOPED

Investigating commercially available materials from industry and establishing requirements that necessitate new developments are two methods by which NASA obtains new materials. Some of the newer ones are described in the following paragraph.

Durette is developed by exposure of aromatic polyamide textile structures to a proprietary treatment that alters the molecular structure. Durette is commercially available. Fypro is another modified aromatic polyamide that also is being marketed. Polysulfone is a high-temperature-resistant plastic material that has good optical properties. Asbestos foam is a relatively new development; it is lightweight and can be used for static application of thermal insulation. A fluorinated polyurethane has been developed for adhesive application. Polyquinoxaline is a flame-

TABLE XV.—*Nonmetallic-Materials Test Criteria*

Test	Maximum limit
^a Total organics, $\mu\text{g/g}$ -----	100
^a Carbon monoxide, $\mu\text{g/g}$ -----	25
^a Odor, rating-----	2.5
Flammability	
^b Category A-----	Self-extinguishing
^c Category B, in./sec-----	.3

^a 155° F at 5 psia, 100 percent for 72 hours.

^b Category A, 100 percent oxygen, bottom ignition, silicone ignitor.

^c Category B, 100 percent oxygen, top ignition, silicone ignitor.

TABLE XVI.—*Offgassing Characteristics of Typical Apollo Nonmetallic Materials*

Materials	Total organics, $\mu\text{g/g}$	Carbon monoxide, $\mu\text{g/g}$	Odor
Beta-----	0	2.1	1.3
Teflon-----	34.0	.7	.9
PBI-----	.4	1.7	1.5
Asbeston-----	1.3	1.0	1.7
Nomex-----	1.0	.4	.7
Viton-----	.3	.4	.8
Fluorel-----	1.0	1.2	1.3
CNR-----	6.0	.8	1.8
Astro Velcro-----	2.0	.2	1.7

resistant polymer that shows promise as a structural laminate. Test results on these materials are shown in tables XVIII and XIX. The data in these tables can be compared to the Apollo criteria shown in table XV. All of these materials meet the stringent Apollo requirements for odor, carbon monoxide, and total organics offgassing. Although some of the materials do not meet the Apollo flammability requirements, the materials are self-extinguishing in air and can be used in many less hazardous applications.

CONCLUDING REMARKS

New materials are needed for future aerospace applications. Examples of new materials that are needed are a flame-resistant, optically clear, impact- and abrasion-resist-

TABLE XVII.—*Flammability Test Results on Typical Apollo Nonmetallic Materials*

[Silicone ignitor, 100 percent oxygen]

Materials	Burn rate, in./sec				
	Top ignition		Bottom ignition		
	16.5 psia	6.2 psia	16.5 psia	^a 16.5 psia	6.2 psia
Beta.....	^b NI	NI	NI	NI	NI
Teflon.....	SE	SE	.55	.30	.30
PBI.....	.20	.16	.41	.35	.30
Asbeston.....	^c SE	SE	SE	SE	SE
Nomex.....	.33	.16	1.00	.60	.60
Viton.....	SE	SE	SE	SE	SE
Fluorel.....	SE	SE	SE	SE	SE
CNR.....	SE	SE	SE	SE	SE
Velcro ^d	.02	.01	.50	.37	.35

^a 60 percent oxygen, 40 percent nitrogen.^b NI—No ignition.^c SE—Self-extinguishing.^d Astro Velcro.TABLE XVIII.—*Offgassing Characteristics of New Materials*

Materials	Total organic, μg/g	Carbon monoxide, μg/g	Odor
Durette.....	0.6	3.0	0.2
Polysulfone.....	.9	.2	1.0
Fluorinated polyurethane.....	89.0	8.0	.6
Polyquinoxaline.....	.5	4.3	1.3
Asbestos foam.....	4.1	3.7	1.7
Fypro.....	1.0	4.0	.7

ant plastic for helmet-visors and instrument panels. Flame-resistant plastic films for thermal insulations and packaging materials also are needed. In addition, the development of flame-resistant organic fibers, elastic fibers, finer diameter glass fibers, elastomers, coatings, adhesives, films, and fasteners is continuing with emphasis on improved physical properties.

Many of the materials developed for the Apollo Program are in commercial and military use. Interchanges of information are taking place with the aircraft industry,

which is interested in building improved flame-resistant airplane interiors, with the U.S. Army for possible use as flameproof, inflatable-portable hospitals, and with the U.S. Navy for potential sea laboratory applications. Other potential applications are noted in table XX.

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2. SUPKIS, DANIEL E.: Development and Applications of Fluorel. Paper presented at the NASA Conference on Materials for Improved Fire Safety (Houston, Tex.), May 1970.
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4. ANON: Apollo Spacecraft Nonmetallic Materials Requirements. MSC-PA-D-67-13, Feb. 1968.
5. KATSIKAS, C. J.; AND LEVINE, J. H.: Manned Spacecraft Nonmetallic-Materials Flammability Selection Criteria and Requirements. Paper presented at the NASA Conference on Materials for Improved Fire Safety (Houston, Tex.), May 1970.

TABLE XIX.—*Flammability Test Results on New Materials*

[Silicone ignitor, 100 percent oxygen]

Materials	Burn rate, in/sec				
	Top ignition		Bottom ignition		
	16.5 psi	6.2 psia	16.5 psi	* 16.5 psia	6.2 psia
Durette.....	0.41	0.31	1.00	0.55	0.41
Polysulfone.....	.02	.01	.10	.04	.03
Fluorinated polyurethane.....	^b SE	SE	-----	SE	SE
Polyquinoxaline.....	SE	SE	.02	SE	SE
Asbestos foam.....	^c NI	NI	NI	NI	NI
Fypro.....	.45	.33	1.25	.83	.71

* 60 percent oxygen, 40 percent nitrogen.

^b SE—Self-extinguishing.^c NI—No ignition.TABLE XX.—*Potential Applications of Flame-Resistant Aerospace Materials*

Materials	Applications		
	Military	Commercial	Household
Fibrous materials			
Beta PBI Asbeston Nomex Durette Fypro	Fire-protective clothing, parachutes and lines, belts and straps, tents and tarpaulins.	Thermal insulations, hospital and industrial uniforms, vehicle upholstery, packaging, seat belts, tents, cargo compartment liners, cargo and boat covers, carpets and curtains, racing-car-drivers' coveralls.	Clothing, curtains, draperies, bedspreads, blankets, decorative panels, sewing threads, mattresses, sofa tickings, table cloths, upholstery, carpets and rugs.
Elastomeric materials			
Fluorel Viton CNR Asbestos foams Fluorinated silicone Fluorinated polyurethane	Aircraft interior coatings, gas masks, survival equipment, coatings for cargo covers, shields for hazardous operations, tents.	Heat insulations, ceiling tiles, wall panels, floor coverings, wire and cable insulations, automotive parts and accessories, warehouse fireproof coatings, fuel pipeline insulations, furniture and fixture covers, hospital equipment, mine-safety appliance parts, building insulations, packaging, toys, mail bag coatings, and coatings for hotels, hospitals, schools, and public buildings.	Foam pillows and mattresses, decorative coatings for walls and panels, ceiling tiles, wall panels, floor coverings.

Development and Applications of Fluorel*

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To minimize the potential fire hazard associated with the 100-percent-oxygen crew-cabin environment of the Apollo spacecraft (command and lunar modules), new materials were required for the replacement of flammable components. Alternatively, in those areas where material substitutions were unavailable or impracticable, flame-propagation barriers that would localize any potential problem area were established. For these purposes, a material had to exhibit properties comparable to the component replaced or had to be compatible with the component shielded. In addition to requirements for nonflammability in 100 percent oxygen at 16.5 and 6.2 psia, new materials had to satisfy certain minimum requirements for toxicity, odor, and total organics outgassing.

Analysis of specific requirements for such new materials disclosed the need for a substitute for flammable elastomer products, such as boot soles, belts, wire insulation, tubing, and hoses. Adhesive was needed for the flammable cements used to laminate spacecraft components and substrates. New conformal coatings, and coatings for nonreplaceable items also were required. The primary purpose of this paper is to describe the development and use of Fluorel in the Apollo Program.

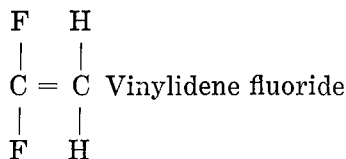
DEVELOPMENT OF A NONFLAMMABLE ELASTOMER

To satisfy the diverse requirements for Apollo, a nonflammable elastomer that could be foamed, extruded, compression molded, and cast was required. When dissolved in the

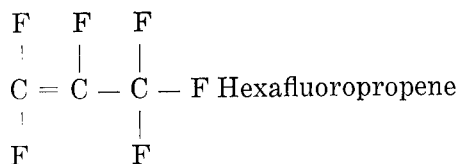
appropriate solvents, the material had to maintain the viscosity necessary for conformal coating and caulking operations and also had to yield a solution suitable for spray-coating. For use in the Apollo spacecraft, a material was required to be self-extinguishing when ignited at the bottom of the test specimen in a 100-percent-oxygen atmosphere at both 16.5 and 6.2 psia.

Preliminary Investigation

Preliminary screening of several materials and processes revealed that fluorine-based hydrocarbons showed low flammability and represented a logical choice. Numerous rubber and elastomer suppliers were contacted for sample materials containing fire retardants, extinguishers, and quenching agents. Several suppliers were willing to undertake the task of modifying their products to obtain an elastomer tailored to meet Apollo specifications and requirements. The Chemical Division of Minnesota Mining and Manufacturing Co. (3M Company), working with saturated and partially saturated fluorine compounds, submitted samples of a fluorocarbon elastomer (Fluorel) for evaluation. Fluorel is a copolymer of hexafluoropropene and vinylidene fluoride.



*Fluorocarbon trade name (Minnesota Mining and Manufacturing Co.).



Early samples exhibited very good physical adaptability but burned under spacecraft conditions. However, one formulation (submitted for routine analysis) was a "reluctant combustible" that evidenced self-extinguishing traits, although it did burn under spacecraft test conditions. Further extrapolation of this formulation yielded samples that were mostly nonflammable. Physical properties and adaptability showed excellent promise. The 3M Company information was made available to the Mosites Rubber Co. and to Raybestos-Manhattan Inc., who were also working on the problem. Further development produced formulas that exhibited a wide range of physical properties. The materials that have been qualified for use in the Apollo spacecraft are shown in table XXI.

Processing

In processing this fluorocarbon elastomer solution, the factors of selecting additives and catalysts, providing adhesion, and storing and handling have been given considerable attention. The solution can be used with a room-temperature cure and passes the strictest flammability tests.

The pure solution has been supplemented with various additives. Inorganic pigments have been used for coloring purposes but generally must be limited to less than 5 percent by weight to prevent adverse effects on the elongation properties of the film. Those pigments successfully used with the solution are listed in table XXII.

Asbestos also has been added to the solution to improve the thermal and electrical-insulation characteristics. The asbestos can be added in any quantity up to 50 percent by weight, at which point the cured mixture becomes brittle. Under atmospheric conditions, only a 3-mil coating of 100 percent fluorocarbon is needed to flameproof ordinary paper

MATERIALS FOR IMPROVED FIRE SAFETY

TABLE XXI.—*Fluorel Compounds Qualified for Category A Flight Use*

Description	Number	Use
Mosites Rubber Co.		
Gum stock.....	1059 (3M L-2231)	Hoses, headrests, cable coatings
Low-density closed-cell sponge	1062.....	Shock absorbers, spacers, eye-pieces
High-density closed-cell sponge	1062C.....	Shock absorbers, spacers, eye-pieces
High-density open-cell sponge	1064J.....	Shock absorbers, spacers, eye-pieces
Film.....	1066.....	Adhesives, surface coatings
Gum stock.....	1071, 1076, 1077, 1079K, 1087JJ	Developed for lower operating temperatures and greater flexibility
Raybestos-Manhattan, Inc.		
Gum stock.....	L-3217 (3M L-2231)	Hoses, headrests, cable coatings
Gum stock.....	L-3251-3..	Space-suit boot soles
Film.....	L-3203-6..	Adhesives, surface coatings
Film (basic L-3206-6 stock with asbestos added)	RL-3492, RL-3550	Fireproof coatings

TABLE XXII.—*Flight-Qualified Fluorel Pigments*

Color	Prescription number
Meteor pink.....	7132
Meteor green.....	7465
Meteor cobalt blue.....	7540
Meteor red brown.....	7751
Meteor tan.....	7729
Meteor yellow buff.....	7370
Meteor black.....	7890
Cadmium light red.....	1530
Cadmium medium red.....	1560
Gray.....	1462
Inorganic gray.....	1236

exposed to a propane-torch flame. At 16.5 psia in a 100-percent-oxygen atmosphere with bottom ignition and using a silicone ignitor (the most stringent flammability test), a 30-mil coating of a 50-percent-asbestos solution is required to protect against flammability. The asbestos solution can be tailored to satisfy any requirement between these extremes. A mixture containing 75 percent fluorocarbon and 25 percent asbestos provides the optimum flexibility/flammability characteristics. A 10-mil coating of the 75/25 mixture weighs approximately 0.17 g/in². It should be noted that the asbestos additives render the coatings gas permeable. This permeability can be overcome by using pure fluorocarbon as a nonpermeable subcoat or overcoat.

Catalysts, such as hexamethylenediamine carbamate, have been added to improve the finished-coating physical properties. If this compound is not temperature cured, the service use is limited to below +150° F, because the catalyst boils off above that temperature, producing a very unpleasant odor. The recommended cure is +150° F for at least 3 hours, but this is not required for nonflammability.

The adhesion of these fluorocarbon-elastomer coatings has been improved on metal substrates using General Electric 4004 primer, on silicone substrates using Dow Corning 3145 primer, on neoprene using Products Research PRC-1513 primer or toluene, and on leather using 3M Company 2216 adhesive. It should be noted that, if the Fluorel solution is applied too rapidly or too heavily, the toxic methyl ethyl ketone (MEK) solvent may be trapped in the compound and randomly boil off. Proper application procedures have been developed (ref. 1 and appendix A). Also, premature heating or excessively high drying temperatures, or both, may cause blistering or cracking of the coating. However, an overnight drying before oven drying precludes this problem.

Because these solutions have limited shelf life and restrictions on shipping, it is suggested that the solution be mixed as needed. The procedure for mixing is contained in appendix B.

APOLLO APPLICATIONS

Flight Items

Fluorocarbon elastomers have been used liberally in the Apollo spacecraft. Some of the Apollo flight items that were either fabricated from or modified by the elastomeric materials are the oxygen umbilical hoses, eyeglasses, relief-tube assembly, vacuum-screen caps, oxygen and smoke mask hoses, headrest pads, floodlight glare shield, coating on cuff cards (Apollo 11), command module window gaskets, guidance and navigation gasket, and suit-harness bend-relief boot. An oxygen umbilical hose is shown in figure 47, eyeglasses in figure 48, and relief-tube assembly in figure 49. It is interesting to note that the transparent 0.5-mil coating on the space-suit cuff cards used on the lunar surface by the Apollo 11 astronauts was not ap-

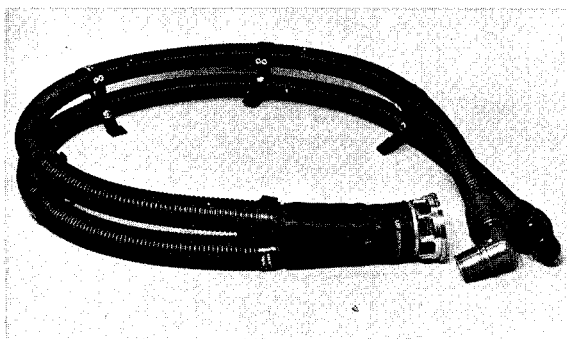


FIGURE 47.—Fluorocarbon-elastomer oxygen umbilical hose.

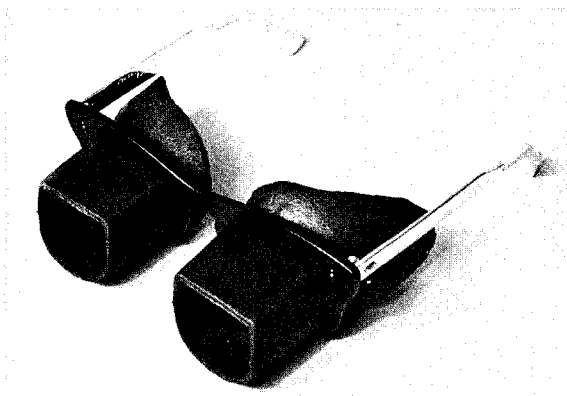


FIGURE 48.—Fluorocarbon-elastomer-foam eyepieces.

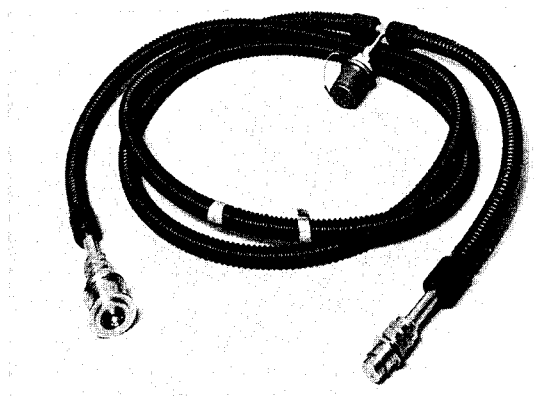


FIGURE 49.—Fluorocarbon-elastomer relief tube.

plied to reduce flammability. The coating improved readability and prevented fading and blurring of the ink in the lunar environment.

Comparative flammability tests are shown in figure 50 for a silicone smoke-mask hose and an identical fluorocarbon hose. Whereas the silicone hose burned freely, the other hose did not ignite. Fluorocarbon coating has been applied to Beta cloth for insulation and fireproof wrapping, and a solution has been used as an adhesive to attach Astro Velcro pile and to bond Beta cloth.

Conformal Coating

The fluorocarbon material has been used as a conformal coating on spacecraft electrical components. Circuit breakers were covered with a 10- to 15-mil coating and over-coated with approximately 20 mils of a 75-percent-fluorocarbon/25-percent-asbestos solution. Flammability tests in a 100-percent-oxygen atmosphere at 16.5 psia resulted in successful ignition, but the fire did not propagate. A coated printed circuit board is shown in figure 51.

The largest single application of this new coating solution has been the fireproofing of the interior of the mobile quarantine facility (MQF), in which the Apollo 11 and 12 astronauts stayed following their return from the moon (ref. 1). Flammability tests were performed on samples of the MQF interior surfaces in accordance with the Airwor-

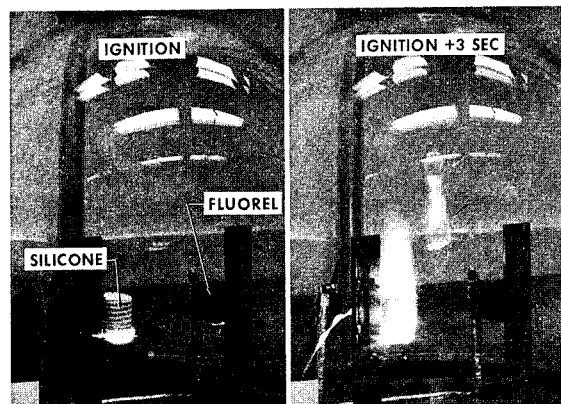


FIGURE 50.—Flammability test: silicone compared with fluorocarbon hose (6.2 psia, 100 percent oxygen) at (left) ignition and (right) ignition + 3 sec.

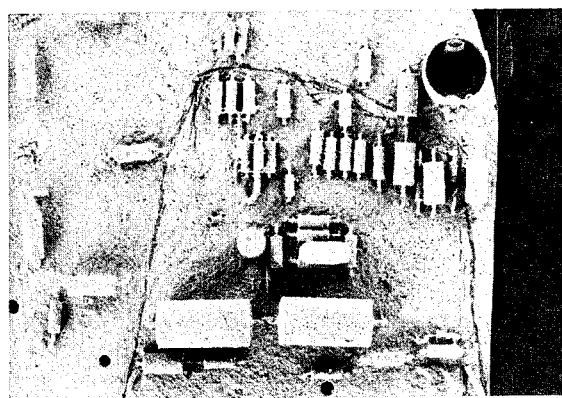


FIGURE 51.—Electrical-panel fluorocarbon-elastomer conformal coating.

thiness Standards, Transport Category Airplanes, part 35, section 25.853, Test Procedure. All the original samples (except vinyl on aluminum) failed the test. However, samples that were coated passed the test. As a result, all of the wood and vinyl interior surfaces were coated with the solution. The coating, which is originally tan in color and has a leatherette texture, was pigmented to provide a compatible color scheme. Although the coating was applied with almost no surface preparation, satisfactory adhesion was obtained. The use in this instance made it unnecessary to replace the original materials.

As a result of this successful use of the

material, fluorocarbon-elastomeric coatings have been used to enhance the safety of the McDonnell-Douglas space-station environmental simulator. As an example, the chairs have been coated with a solution that protects against ignition but allows retention of fabric texture (fig. 52).



FIGURE 52.—Upholstery fireproofed with fluorocarbon elastomer.

POTENTIAL FUTURE AEROSPACE APPLICATIONS

A new approach to the use of this elastomeric compound in future aerospace applications currently is being evaluated. Rather than coating or spraying existing components, experimental components have been fabricated from the compound by molding or extruding. For example, a nonflammable circuit-breaker case (fig. 53), temperature cured to a hardness approaching that of ceramic, weighs less than a conventional case and is practically unbreakable. Printed circuit boards, toggle switches, and other electrical components can be fabricated successfully. Newly developed, very-low-temperature, highly flexible fluorocarbon materials can be used effectively for fabricating hoses and bladders that have low-temperature brittle points below -80°F .

Deerskin that has been fireproofed with a fluorocarbon exhibits excellent shrinkage properties: 2 percent to 250°F and 9 percent to 300°F , compared to uncoated values of 6.3 percent to 250°F and 12.6 percent to 300°F . Deerskin leather boots (fig. 54), coated with blue fluorocarbon and incorpo-

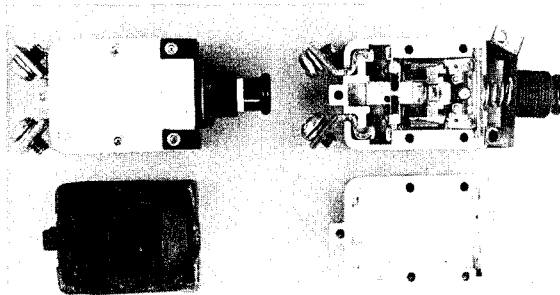


FIGURE 53.—Comparison of fluorocarbon (left) and Apollo circuit-breaker cases.



FIGURE 54.—Fluorocarbon-elastomer-coated leather boots.

rating fluorocarbon-elastomeric magnet inlays in soles and heels, are being considered for possible use in future space programs.

OTHER POTENTIAL APPLICATIONS

The successful use of the fluorocarbon compounds in the Apollo Program indicates their potential for nonaerospace use. The military has expressed an interest in using these compounds. A requirement for fireproofing wooden ammunition boxes for the U.S. Army has resulted in a recent evaluation of the coatings. The U.S. Navy is considering use of a fluorocarbon compound for fabricating nonflammable wet suits to reduce the flammability hazards in the oxygen-enriched atmosphere of decompression chambers.

Application of fluorocarbon elastomers in the medical field, in which oxygen-enriched environments are encountered, should be advantageous. Anesthesia hoses and masks made of the material would reduce flammability risks substantially. Fluorocarbon hospital-bed mattress protectors would form barriers to flame propagation.

CONCLUDING REMARKS

Each successive step of the fluorocarbon-elastomer developmental program for Apollo has, in effect, increased the potential uses of the material. The basic formulation has been shown to be a workable material for economical solvation, foaming, extrusion, compression molding, and casting. The usefulness of naturally adhesive Fluorel solutions, ranging

in viscosity from paste to spray-coating consistency, has been demonstrated.

Because this compound, in many forms and with many properties, can be used to flameproof virtually any substrate, the possibilities for application in many fields (particularly in transportation and construction) are very considerable. In time, this material, which shields the fuel from the combustion process, may prove to be one of the more valuable and useful byproducts of the manned exploration of space.

REFERENCE

1. BASS, RODERICK S.; AND HIRASAKI, JOHN K.: Fire-Safety Design of a Mobile Quarantine Facility. Paper presented at the NASA Conference on Materials for Fire Safety (Houston, Tex.), May 1970.

APPENDIX A

Procedure for Fluorel Coating the Floodlight-Glare Shield

1. Clean the bronze screen wire in accordance with MSC Spec-C-8, class A.

2. Using 3M number 361 tape, cover the screen wire over an area sufficient to hold the wire in place after cutting.

3. After cutting the screen wire to the required size, use a hand roller and roll the tape to remove the trapped air. Apply a strip of the 1-in. number 361 tape around all the edges, overlapping 0.5 in. on each side; roll again to remove air.

4. Care must be taken during steps 2 and 3 to guard against contaminants from the work area.

5. Bend tape-covered screen wire as in accordance with drawing requirements.

6. Mix black pigment (Harshaw Chemical Company meteor black 541-214-37, number 7890) in MEK using a ratio of 115g of black pigment to 101g of MEK per quart of Fluorel L-3203-6, 20 percent homogenized solution (Raybestos-Manhattan). (See appendix B.) This final pigment mixture can be increased by multiplying the above formula by the

number of quarts needed to accomplish the task. The pigment mixture is added to the Fluorel solution and mixed with the means of a Red Devil paint mixer for 5 min. Caution; Do not permit an excessive quantity of MEK to evaporate from the final pigment and Fluorel mixtures before application.

7. The black-pigmented Fluorel L-3203-6 solution is sprayed using a Binks Model 7 spray gun having a 36 SD nozzle at an operating pressure of 35 psi.

8. The black-pigmented Fluorel L-3203-6 solution is sprayed on the tape slowly, vaporizing the maximum quantity of MEK during spraying so as not to allow the MEK to dissolve the tape adhesive, to obtain a 6 ± 2 -mil coating on each side of the floodlight-glare shield.

9. The floodlight-glare shield is air dried for a minimum of 12 hours. No heat is to be applied in any manner during this period as it may cause the coating to crack or blister.

10. Oven dry the floodlight-glare shield for 4 hours at 250° F.

APPENDIX B

Procedure for Preparing 20-Percent Homogenized Fluorel L-3203-6 Solution

To produce 1 gallon of solution, use the following procedure.

1. Soak 550g of L-3203-6 mil sheet (chopped) in 2600g of MEK overnight to soften the rubber.

2. Homogenize the solution using an Ep-

penbach explosion-proof Homo-Mixer, model 1-LA, until the Fluorel is dissolved (approximately 5 min.).

3. Filter the solution through a gauze screen to remove any undissolved solids.

Development and Application of Flame-Resistant Polymers and Composites

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Two basic safeguards against fire that have been adopted for spacecraft design are (1) minimization of possible ignition sources and (2) minimization of the amount of flammable materials. Because the Apollo spacecraft cabin is filled with pure oxygen, the second goal is particularly difficult to achieve. NASA and industry efforts and accomplishments toward meeting this goal, in the areas of elastomers and plastic composites, are discussed in this paper.

ELASTOMERS

By definition, elastomers are materials that can be stretched repeatedly to 150 percent or more of the initial length and, thereafter, return rapidly and with force to approximately the original length. Commercial elastomers have been available for many years and, by judicious selection and compounding, meet almost all possible commercial needs. However, because of more specialized and stringent requirements, many of the materials have proved to be inadequate for the space program. Elastomers used in manned spacecraft generally can be divided into two categories: (1) those used for spacecraft interiors and (2) those used for spacecraft exteriors and extravehicular equipment. Each application imposes a different set of criteria. In addition to the normal functional requirements necessitated by end-item needs, the major exposed elastomers used in the spacecraft interior must be nonflammable

in pure oxygen and, if inadvertently overheated, must not emit toxic or nauseous gaseous products. If the elastomers for extravehicular applications are stowed in the crew-bay areas, the materials must meet the specified requirements, in addition to being compatible with and remaining functional in the space environments. For such uses, elastomers can be exposed to ultrahigh vacuum, solar-particulate-flux bombardment, the total electromagnetic radiation spectrum, and temperatures ranging nominally from 250° to -250° F.

Of the elastomers available at the beginning of the Apollo Program, the silicones were the most favorable. These polymers can be compounded to meet many needs. In particular, silicones can be cured at low temperatures, have a good service temperature, good elongation, low compression set, reasonable tensile strength, and—most important for deep-space applications—remain more flexible than any other good elastomer at low temperatures. Unfortunately, the silicones make an excellent fuel in pure oxygen, and attempts to render them nonflammable have not been particularly successful to date. The only apparent successful method to render organic polymers nonoxidizing is to end link molecular chains heavily with halogens; however, when these same halogens are released during thermal decomposition, toxic products, such as carbonyl fluoride, are produced. The key to the problem appears to be heavily fluorinated elastomers that are stable

at temperatures beyond those normally encountered in the in-use configuration and in assuring that thermal decomposition by fire is virtually an impossibility.

CARBOXY NITROSO RUBBER

Initial efforts toward obtaining a nonflammable substitute for silicone were made using carboxy nitroso rubber (CNR), which is a terpolymer synthesized from trifluoronitrosomethane, tetrafluoroethylene, and nitroso perfluorobutyric acid. Typical properties of CNR raw gum and CNR elastomer are shown in tables XXIII and XXIV. As shown in these tables, CNR exhibits excellent elastomeric properties. However, the greatest asset of CNR is nonflammability in any oxygen atmosphere and usage thickness. The development of this compound was in the preliminary stage during the early periods of the Apollo Program, and the total Government and industry demand for an elastomer nonflammable in oxygen was not sufficient to permit reducing the cost of CNR by increasing production. A second disadvantage to CNR is that it "unzips" (rapidly de-

composes) when heated to approximately 500° F, liberating appreciable quantities of toxic products.

Because of the inherent nonflammability, chemical resistance, and good elastomeric properties, CNR could have wider use in industry. Although it degrades badly at 500° F, it does pass all the Apollo toxicity-test criteria below that temperature. Because of this characteristic, use of this material should be limited to areas that have temperatures well below 500° F. Another problem to be overcome is the high cost, which could be reduced by further research and development and industry acceptance of CNR.

FLAME RESISTANT FLUOROCARBON POLYMERS

Because of the problems encountered with CNR, programs were initiated to develop nonflammable elastomers from copolymers of vinylidene fluoride and hexafluoropropene. These fluorocarbon elastomers have been available for many years under the trade names of Viton and Fluorel; however, as normally produced, they are flammable in oxygen. Recent efforts by their suppliers have resulted in compounds that are resistant to flame and are even nonflammable in many applications. Initially, nonflammability could be attained only at the expense of elasticity. Recently, fluorocarbon elastomers have been produced that exhibit acceptable elastomeric properties while remaining flame resistant. Recent efforts toward development of flame-resistant Viton elastomers resulted in a variety of flame-resistant elastomers, conformal coatings, sprayable coatings, sponge material, and other elastomeric forms that exhibit excellent structural and flame-resistant properties.

The flammability properties of the gum stock in slab form and on hose sections are shown in table XXV. The technique used in the development of this material was selecting carefully a basic flame-resistant polymer and compounding to optimize the nonflammability. This approach differs from the usual method of obtaining nonflammability by addition of large quantities of inorganic fillers.

TABLE XXIII.—*Typical Properties of CNR*
[Cured gum stock]

Property	Cure agent	
	Chromium trifluoroacetate	Dicyclopentadiene dioxide
Tensile strength, psi..	1000 to 2000	600 to 1800
Elongation, percent..	250 to 800	150 to 1200
Durometer hardness, Shore A.	35 to 80	35 to 80
Compression set, percent.	15 to 30	10 to 15
Flammability ^a	Nonflammable	Nonflammable
Offgassing ^a		
Odor	Acceptable	NA ^b
Carbon monoxide..	Acceptable	NA
Total organics.....	Acceptable	NA

^a Per the Apollo spacecraft nonmetallic-material requirements.

^b Not available.

TABLE XXIV.—*Effects of Fillers and Plasticizers on CNR*

(a) Filler reinforcement				
Filler compound ^a	Mechanical property			
	Tensile strength, psi	Elongation, percent	Durometer hardness, Shore A	
No filler.....	430	350	50	
Silstone 110, 20 parts.....	1790	175	80	
Hi-Sil 233, 20 parts.....	1560	75	85	
Statex R, 20 parts.....	1520	75	85	
Thermax, 20 parts.....	1600	150	70	

(b) Plasticization				
Plasticizer compound ^b	Mechanical property			
	Tensile strength, psi	Elongation, percent	Modulus, 200 percent	Durometer hardness, Shore A
CTA, 5 parts.....	1850	500	640	65
CTA, 5 parts; Fombyln Y, 40 parts.....	1250	550	510	35
DPD, ^c 2 parts; benzoic acid, 0.5 part.....	1530	600	490	54
DPD, 2 parts; benzoic acid, 0.5 part; Fombyln Y, 10 parts.....	1565	850	305	45
DPD, 2 parts; benzoic acid, 0.5 part; Halo-carbon 14-25, 10 parts.....	1650	950	200	35

^a Base of 100 parts CNR and 5 parts chromium trifluoroacetate (CTA).^b Base of 100 parts CNR and 20 parts Silstone 110.^c Dicyclopentadiene dioxide.TABLE XXV.—*Flammability Properties of Flame-Resistant Viton Elastomers*

Viton compound	Pressure, psia	Gas	Ignitor	Propagation rate, ^a in/sec
ASTM slabs ^b				
238-46-2	6.2	100 percent oxygen.....	Silicone.....	0.0
	16.5	60 percent oxygen/40 percent nitrogen.....	Silicone.....	0.0
238-26-1	16.5	100 percent oxygen.....	Silicone.....	0.0
Spacecraft hose sections				
238-26-1	16.5	60 percent oxygen/40 percent nitrogen.....	Silicone.....	0.0
	6.2	100 percent oxygen.....	Silicone.....	0.0
	16.5	100 percent oxygen.....	Silicone.....	Burned ^c

^a All tests bottom ignition.^b Sample 5 by 7 by 0.125 in.^c Nonextinguishing glow; burn rate too slow to measure.

These fillers produce smoke if ignition does occur and degrade low-temperature flexibility, processability and other desirable elastomeric properties. Although totally nonflammable in air, thin sections of these compounds can be ignited in pure oxygen but will burn slowly.

A new gum stock, which exhibits good elastomeric and fire-resistant properties, is designated 238-26-1. This compound can be processed easily and was used to fabricate the oxygen hoses, oxygen masks, and eye patches. Another compound, designated 238-46-1, has properties similar to those of the compound 238-26-1, except that 238-46-1 has better flexibility at low temperatures.

In addition to material that is used for molding, protective coating materials have been developed. One such material is designated as 238-99-1. This compound is a thick paste or caulk that can be air dried at room temperatures. The compound is stiff but can be flexed. It is resistant to shock and impact and should be satisfactory for protecting relatively rigid substrates. A 1/10-in. thick sample of the material was found to be totally nonflammable in 16.5-psia pure oxygen when tested with a standard silicone-rod ignitor. An Apollo flight circuit breaker was coated with this material and tested in 6.2-psia pure oxygen. The ignitor used in this test was a standard silicone rod plus an unprotected circuit breaker. This combination is even more severe than the silicone alone and is the requirement used to qualify the circuit-breaker coatings for flight. The circuit breaker, when protected with approximately 1/16 inch of the 238-99-1, was nonflammable in this test and was operational at the conclusion of the test. The minimum thickness capable of protecting the breaker was not ascertained.

To test the limits of protection afforded by the 238-99-1 coating, a piece of balsa wood was protected with a 1/32-inch-thick coating and ignited with a standard silicone-rod ignitor in 6.2-psia pure oxygen. In this test, the lower portion of the balsa wood was left unprotected to permit ignition. The flame extinguished when it reached the coating.

Heavy conformal coatings, such as the one described previously, have limitations. In many applications, a need exists for thin fire-proof coatings that will exhibit good elastomeric and flexibility properties. These coatings are required for dynamic applications on flexible substrates, such as cushions, fabrics, cables, rubber mounts, and similar end items. Accordingly, compounds have been formulated that can be sprayed and that provide protection in very thin coatings. Two such coatings are designated 238-97-1 and 238-98-1. These coatings should be of considerable interest for commercial applications because they have been formulated without the loss of flame-resistant properties.

To test the performance of these coatings, five flammable materials were selected and coated in thicknesses from 2 to 5 mils. The materials selected were kraft paper, Mylar film, balsa wood, neoprene-coated nylon, and a flame-resistant neoprene sponge. All of these materials, when unprotected, burned in 6.2-psia pure oxygen when ignited with a tissue paper/Nichrome-wire ignitor. The same materials failed to ignite under identical conditions when coated with 2 to 5 mils of 238-97-1 or 238-98-1. To evaluate the performance of these coatings in air, the coated materials listed previously were exposed to a constant 1800° F, flame source in air. None of the materials ignited except the kraft paper, which took 16 seconds to ignite.

FLUORO SILICONES

Because of the superiority of silicones at very low temperatures, efforts currently are being expended to develop a silicone elastomer that is flame resistant in pure oxygen. To date, a currently funded effort has had only limited success. The effect of a bromine additive on the ignition point of a silicone rubber compound is shown in figure 55. As shown in this figure, higher oxygen enrichment is required to support ignition of the material as the bromine additive is increased. The effect of the bromine additive on the elastomeric and tensile properties of

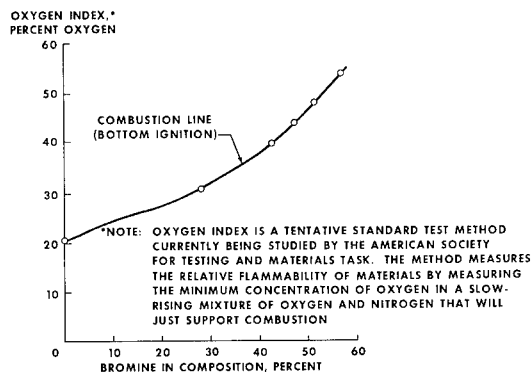


FIGURE 55.—Effect of bromine additive to silicone rubber compound SE-517.

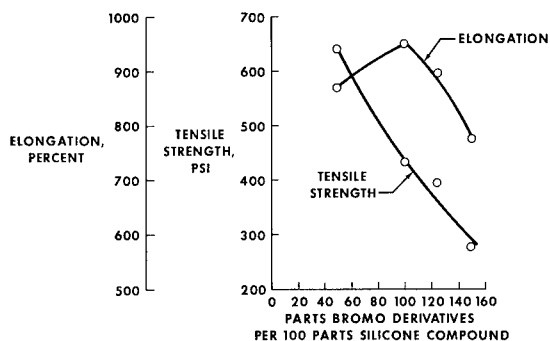


FIGURE 56.—Effect of bromine additive on physical properties.

the materials is shown in figure 56. As can be seen, a trade-off is made between tensile strength, elongation, and flame resistance. All of the silicone compounds developed to date are flammable in the Apollo cabin environment, although they are nonflammable in less severe environments.

COMPOSITES

Another major category of nonmetallic materials that was required to be nonflammable in the Apollo cabin environment is the composite structural laminates that are used for hard containers, cupboards for various equipment stowage, and mounting panels. Composites are a class of materials in which a reinforcing material is the load-carrying medium, and the binder distributes the ap-

plied load uniformly to the reinforcing material. A common example is the protective helmets used by motorcyclists. In this case, a resin is reinforced by fibrous materials. Today, reinforcing fibers are typically glass, boron, graphite, nylon, or metal, and the matrix material can be organic polymers, ceramics, metals, or new materials that exhibit different properties. Typical reinforcing fibers and the associated properties are shown in table XXVI.

Composites are used extensively in the Apollo spacecraft because of the high strength-to-weight ratio, resistance to impact, and thermal and electrical properties. For most applications within the Apollo spacecraft interior, extremely high strength is not critical, but flame resistance, ease of fabrication, and offgassing assume larger magnitudes of importance. For those applications where the end item will be used outside the spacecraft, strength and impact resistance are more important, as is the ability to withstand the deep-space environment without degradation.

POLYIMIDE/GLASS COMPOSITES

The development in polyimide/glass-fabric composites has been successful and has found wide use in the Apollo command module. This effort was conducted by the prime contractor for the command module, using a polymer designated PI 2501. As shown in table XXVII, these laminates are self-extinguishing or nonburning in a 16.5-psia, 100-percent oxygen atmosphere, in thicknesses of approximately 0.045 in. (five ply) or greater, with resin contents of as much as 19 percent. The flammability of polyimide laminates is sensitive to resin content, necessitating good quality-control techniques. The mechanical properties of this lay-up at a resin content of approximately 17 percent are shown in table XXVIII. The command module contractor has been successful in fabricating parts by vacuum-bag techniques and has been able to use plaster and high-temperature epoxy molds because of the relatively low precure temperature requirements. To date, from this polyi-

TABLE XXVI.—*Representative Properties for Fiber Reinforcements*

Fiber	Typical fiber diameter, 10 ⁻³ in.	Density	Modulus of elasticity tension, lb/in ² × 10 ⁻⁶	Tensile strength, lb/in ²	Expansion coefficient, α, 10 ⁻⁶ in./in.-° F	Thermal conductivity, K, Btu/hr-ft ² -°-F-in.
E-glass.....	0.4	0.092	10.5	450 000	2.8	7.5
S-glass.....	.4	.090	12.3	650 000	-----	-----
970 S-glass.....	.4	.091	14.5	800 000	-----	-----
Boron on tungsten.....	4	.095	60	400 000	-----	-----
Graphite.....	.2 to .4	.053 to .065	35 to 100	250 000 to 500 000	~1.5	60
Beryllium.....	5	.066	45	180 000	6.4	87
Silicon carbide on tungsten.....	4	.126	60	360 000	2.2	29
Stainless steel.....	.5	.283	29	385 000 to 600 000	30	100 to 170
Asbestos.....	.001 to .01	.090	25	100 000 to 300 000	-----	-----
Aluminum.....	.2	.097	20 to 60	200 000 to 300 000	3.7	-----
Polyamide.....	.2 to .5	.041	0.4	120 000	45 to 50	1.7
Polyester.....	.8	.052	0.6	100 000	45 to 50	1.7

TABLE XXVII.—*Flammability as a Function of Ply Construction—Polyimide/Glass-Fabric Laminate*

Laminate description			Flammability test results (100 percent oxygen at 16.5 psia—silicone ignitor, bottom ignition)		
Number of plies	Thickness, in.	Cured resin content, percent	Number of specimens	Combustion rate, in./sec	Remarks
1	0.010 to 0.011	19.4 to 19.5	3	0.177	Fire consumed all specimens.
2	0.018 to 0.020	18.4 to 19.1	3	0.098	Fire consumed one specimen; two specimens self-extinguishing after 2-3/4 and 4-3/8 in. flame travel.
3	0.029 to 0.030	19.7 to 20.2	3	0.069	All specimens self-extinguishing after 2-1/2 to 2-15/16 in. flame travel.
4	0.036 to 0.038	18.3 to 18.8	3	0.053	All specimens self-extinguishing after 1-11/16 to 1-15/16 in. flame travel.
5	0.041 to 0.045	16.6 to 18.9	125	No rate	All specimens self-extinguishing after 1 to 1-5/16 in. flame travel.
7	0.059 to 0.064	16.9 to 18.3	250	No rate	All specimens self-extinguishing after 5/8 to 13/16 in. flame travel.
12	0.117 to 120	22.0 to 23.0	1	No rate	No ignition.

TABLE XXVIII.—*Mechanical Properties of Thin Polyimide/Glass-Fabric Laminates*

Sample orientation	Mechanical property						
	Tensile strength, psi	Tensile modulus, psi×10 ⁶	Compressive strength, psi	Flexural strength, psi	Flexural modulus, psi×10 ⁶	Interlaminar shear strength, psi	Resin content, percent
4-ply laminate, 0.034 to 0.036 in.							
Fill.....	65 400	3.6	30 000	78 900	4.2	-----	16.75
	51 700	3.3	30 100	77 600	4.2		
	56 700	3.3	-----	-----	-----		
	56 000	3.4	^a 30 000	^a 78 200	^a 4.2		
	-----	-----					
	^a 57 400	^a 3.4					
Warp.....	46 500	3.2	33 800	66 900	3.0	-----	16.75
	44 500	3.3	34 000	67 200	3.5		
	40 500	3.2	34 400	-----	-----		
	44 800	3.1	-----	^a 67 000	^a 3.2		
	-----	-----	^a 34 100				
	^a 44 100	^a 3.2					
7-ply laminate, 0.059 to 0.061 in.							
Fill.....	57 400	3.7	34 300	69 000	2.9	2204	16.35
	61 500	3.6	35 200	67 900	3.1	2122	
	-----	-----	-----	-----	-----	-----	
	^a 59 400	^a 3.6	^a 34 800	^a 68 400	^a 3.0	^a 2163	
Warp.....	45 100	3.1	43 200	101 200	3.8	2898	16.35
	45 400	3.1	44 500	89 200	3.6	3061	
	-----	-----	43 500	-----	-----	-----	
	^a 45 200	^a 3.1	-----	^a 95 200	^a 3.7	^a 2980	
			^a 43 700				

^a Average.

imide system, more than 2000 parts (representing more than 50 different designs have been manufactured for use in the Apollo Program.

POLYQUINOXALINE/GLASS COMPOSITES

Attempts were made under a NASA contract to develop a useful composite using a polyquinoxaline matrix. As shown in table XXIX, composites were successfully fabricated that are nonburning in a 16.5-psia, 60-percent-oxygen, 40-percent-nitrogen atmos-

phere, in thicknesses as small as 0.030 in. (three ply) with resin contents of as much as 30 percent. This material also has been formed into simple structures by vacuum bag techniques. The mechanical properties shown in table XXX are for lay-ups that were cured under 15-lb pressure. Although the polyquinoxaline composites are flame resistant, the costs have been high to date, with the result that polyimides have been used for all applications requiring good mechanical and flame-resistant properties.

TABLE XXIX.—*Characteristics of Prepreg and Laminates Prepared With Polyquinoxaline Resin*

Laminate characteristic	Sample					
	1	2	3	4	5	6
Number of plies.....	6	6	3	6	6	3
Laminate pressure, psi.....	100	50	100	15	15	15
Laminating temperature, ° F.....	750	750	750	500	600	600
Resin content, percent.....	28.0	28.0	25.6	28.6	25.0	25.0
Specific gravity, g/cm ³	1.80	1.75	1.75	1.62	1.67	1.69
Thickness, mil/ply.....	9.4	9.7	9.5	10.4	9.9	10.3
Void content, percent.....	9.1	11.6	13.7	18.2	17.4	16.3
Flame propagation rate, in/sec:						
6.2 psia, 100 percent oxygen.....	0.0	0.0	0.073 a(0.0)	0.0	0.0	0.075 a(0.0)
16.5 psia, 60 percent oxygen/40 percent nitrogen.....	0.0	0.0	0.072 a(0.0)	0.0	0.0	0.0 a(0.0)

^a Postcured in nitrogen at 750° F.

TABLE XXX.—*Typical Mechanical Properties of Polyquinoxaline/Glass-Fabric Laminates*

Property	Sample			
	1		2	
Laminate characteristics:				
Resin content, percent by weight.....	28.9		28.9	
Specific gravity, g/cm ³	1.60		1.65	
Void content, percent by volume.....	18.5		16.0	
	As cured ^a	Post- cured ^b	As cured	Post- cured
Mechanical properties:				
Flexural strength, psi×10 ³	45.4	70.4	55.0	70.8
Flexural strength, psi×10 ⁶	2.84	2.78	2.78	3.11
Tensile strength, psi×10 ³	75.1	55.0	74.4	69.1
Tensile strength, psi×10 ⁶	2.86	3.05	2.77	3.83

^a Cured for 2 hr at 15 psi and 500° F.

^b Postcured in nitrogen at 750° F.

OTHER FIBERS AND MATRICES

The mechanical properties of various available graphite fibers for applications where higher strength-to-weight ratios are required are given in table XXXI. The specific tensile strength of a graphite-reinforced ceramic composite (Chemceram) as com-

pared to some other high-temperature materials as a function of temperature is shown in figure 57. This figure reveals that the composite material has much higher strength-to-weight properties at elevated temperatures than high-temperature metallic materials. As indicated in table XXXII, the material is not

TABLE XXXI.—*Some Commercially Available Graphite Fibers*

Supplier	Strength, <i>S</i> , psi × 10 ⁶	Modulus, <i>E</i> , psi × 10 ⁶
Courtaulds, Ltd. ^a		
Type HM.....	250 to 350	50 to 60
Type HT.....	300 to 400	32 to 40
Type A.....	250 to 300	25 to 32
Morganite R&D, Ltd. ^b		
Type I.....	200 to 300	55 to 65
Type II.....	350 to 450	35 to 45
Hitco		
HMG 25.....	150	25
HMG 40.....	250	40
HMG 50.....	300	50
Union Carbide Corp.		
Thornel 25.....	180	25
Thornel 40.....	250	40
Thornel 50.....	285	50
Thornel 50-S.....	220	50
Thornel 75.....	375	75

^a Courtaulds, Ltd., markets in the United States through Hercules, Inc.

^b Morganite R&D, Ltd., markets in the United States through Whittaker Corp.

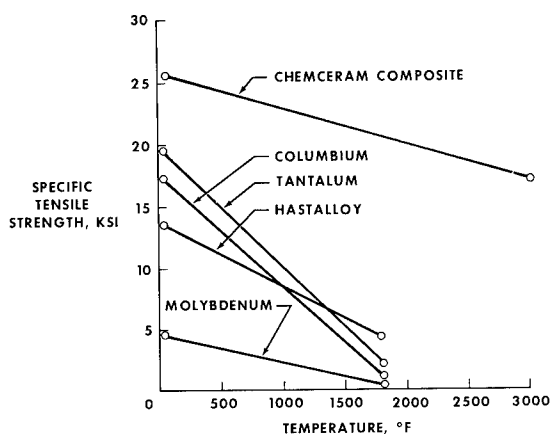


FIGURE 57.—Specific tensile strength as a function of temperature for various materials.

flammable. The material generally would be used where strengths lower than those available from other nonmetallic structural materials, such as epoxy-based laminates, can be accepted with the benefit of flame resistance and minimal reduction in strength at elevated temperatures. Chemceram can be vacuum-

TABLE XXXII.—*Typical Mechanical Properties of Chemceram/Glass-Fabric Laminates (Glass Type S994, Fabric Style 143)*

[Autoclave pressure, 100 psi; cure schedule, 325° F for 2 hr followed by postcure at 100° F/hr to 600° F]

Mechanical property	At 70° F	At 1000° F
Tensile strength, psi × 10 ³	35	11.3
Flexural strength, psi × 10 ³ ..	21.7	22.6
Compressive strength, psi × 10 ³	11.6	15.4
Interlaminar shear strength, psi × 10 ³	3 to 4	3 to 4
Flammability ^a	(^b)	(^b)
Specific gravity, g/cm ³	1.8 to 1.9	1.8 to 1.9

^a Flammability: 0.030-in.-thick sample ignited in 16.5 psia, 100 percent oxygen with a silicone ignitor per the Apollo spacecraft nonmetallic materials requirements.

^b Nonflammable.

TABLE XXXIII.—*Potential Applications of Structural Composites*

Industry	End item
Aircraft.....	Air-distribution systems Firewalls Antenna systems Nacelles Decorative paneling, overhead racks, and printed circuits
Marine.....	Vent ducting Crew quarters and engineer rooms Pleasure craft
Computer science....	Computer structures
Automotive.....	Firewalls
Construction.....	Fire doors

bag formed, which precludes the need for expensive matched-metal molds and presses. The material is cured at temperatures significantly lower than those required for the polyimide or polyquinoxaline structural laminates.

CONCLUDING REMARKS

Information has been presented on both

polymers and composite materials that exhibit little or no burning in oxygen-enriched environments and that have physical and mechanical properties warranting consideration in a variety of uses. Elastomers, elastomeric coatings, and structural composites that reduce fire hazards can be used in commercial, industrial, household, and military applications. Several protective commercial/industrial uses for the structural composites with improved fire and temperature performance are given in table XXXIII.

The NASA requirements for durability, weathering, cleaning, and so forth differ considerably from those in commerce and industry. Accordingly, developmental work probably is required to improve the performance of the materials in these areas to meet commercial applications. The initial work described in this paper is an excellent base for such work.

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Development of Nonflammable Potting Compounds for Spacecraft

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As the space program progresses, the requirements for dielectric materials for electronic components become more stringent. To date, all manned space programs have used an oxygen atmosphere in the crew areas. This atmosphere creates a flammability hazard if conventional dielectric materials are used. In some applications, such hazards have been reduced by covering the conventional dielectric materials with a relatively thick overlay of inorganic coatings sealed with a spray coat of carboxy nitroso rubber. Although quite effective in reducing the fire hazard, some significant problems result from this approach, including the difficulty of performing wiring rework, weight penalties, and availability of acceptable carboxy nitroso rubber. These problems have led to considerable effort by NASA to produce a dielectric material that is relatively inexpensive, easy to manufacture, and readily available.

The purpose of this report is to relate the progress of this effort and to describe some of the materials developed. Some materials were produced that, although not applicable for spacecraft, seem usable for industrial purposes as potting compounds and also as conformal coatings. These materials will be described and the potential area of application will be discussed.

DISCUSSION

For our purposes, a potting compound is defined as a material that is used to seal

cable connectors and that is cast (at least partially) into a preformed metal case by the use of a catalytic system that hardens a polymeric or ceramic material to form a dielectric. Critical circuit components in spacecraft are protected by potting compounds to isolate these components from the environmental effects of oxygen, moisture, and temperature. Also, operational hazards caused by current leakage, mechanical shock, and vibration are minimized by encasing components in a potting material.

Polymeric or ceramic materials also are used as conformal coatings. In this application, a dielectric is applied in a more or less constant thickness, following the contour of the electrical component that it is protecting or covering.

To discuss spacecraft potting compounds, it is necessary to understand the criteria for these compounds because these criteria differ from those for ordinary commercial potting material. The most difficult criterion to meet is that of flammability. A spacecraft potting material must have a significant degree of nonflammability in an oxygen atmosphere. Flammability testing and acceptance criteria for Apollo spacecraft material and the procedure used are given in reference 1.

A material that passes the flammability test is not qualified for spacecraft usage by virtue of that fact alone but must pass additional functional tests to ensure that it meets all of the requirements for a potting material. These additional tests are (1) general, (2) electrical, (3) physical, and (4) manu-

TABLE XXXIV.—*Flammability, Odor, and Outgassing Requirements*

Property	Requirement	Environment	Test specification
Flammability, A.....	Self-extinguishing---	60 percent oxygen/ 40 percent nitrogen	D-NA-002, test 5
Flammability, B.....	No propagation to adjacent com- ponent	60 percent oxygen/ 40 percent nitrogen	Special double-plug test
Organic offgassing, ppm	Less than 100 $\mu\text{g/g}$ Total organics, less than 25 ppm carbon monoxide	100 percent oxygen, 5 psia	D-NA-0002, test 6
Odor.....	No objectionable odor	100 percent oxygen, 5 psia	D-NA-0002, test 7
Vacuum outgassing at 10^{-4} torr and 250° F, percent weight	No loss greater than 0.02 percent/hr after 24 hours	Vacuum.....	Special

facturing. The requirements and the test criteria are outlined in tables XXXIV to XXXVII. (Also see references 2 to 5.)

The polymers that have been used traditionally for potting and encapsulating are epoxies, urethanes, and silicones, all of which can be prepared as thermosetting continuous solids. However, the requirement for non-flammability (in oxygen-enriched atmospheres) negates the use of many of these polymers.

Upon initiation of the development program, a review was conducted to select polymer systems potentially capable of meeting the previously stated requirements. The following materials were selected for further evaluation:

1. Room-temperature-vulcanizing (RTV) compounds
 - a. Silicones
 - b. Fluorosilicones
2. Nonflexible materials
 - a. Ceramic compositions
 - b. Fluorocarbons
3. Brominated polyesters

ROOM-TEMPERATURE-VULCANIZING SILICONES

One effort in this program was to flame-retard the silicones. Silicone material is used on the Apollo spacecraft and has proven to be an excellent material in oxygen when pro-

TABLE XXXV.—*Electrical Requirements*

Property	Requirement	Test specification
Dielectric constant	5.0.....	ASTM ^a 150
Power factor.....	0.09.....	ASTM 150
Dielectric strength (50 mil), V/mil	500.....	ASTM D 749/ FTMS ^b 406
Volume resistivity, ohm-cm	1×10^{12}	ASTM D 257
Surface resistivity, ohm-cm	1×10^{12}	ASTM D 257
Arc resistance, sec	45.....	ASTM D 495/ MIL-C-5015
Insulation resistance, megohm	100 000 at room temperature, 750 at 100° C	MSFC-SPEC- 202A
High-potential resistance (60 Hz)	No breakdown	MSFC-SPEC- 202A
Temperature re- sistance, Ohm-cm	1×10^9 from 0 to 250° F	

^a American Society for Testing and Materials.

^b Federal Test Method Standard.

^c Marshall Space Flight Center.

ected by nonflammable inorganic coatings and an overcoat of carboxy nitroso rubber. After considerable testing, a dimethyl siloxane silicone resin was selected because of its high-strength, room-temperature-curing properties, excellent dielectric properties,

TABLE XXXVI.—*Physical Requirements*

Property	Requirement	Test specification
Elongation, percent	125	FTMS 601 method 4
Tear strength, lb/in	25	FTMS 601 method 4
Tensile strength, lb/sq in.	500	FTMS 601 method 4
Shrinkage, percent	3, linear	
Compression set, percent	35	ASTM D 395
Viscosity, P	450	Brookfield
Adhesion, lb	15	
Repairability	Required	
Specific gravity	2.00 maximum	FTMS 601 method 4
Hardness (Shore A)	50 to 60	ASTM D 2240

TABLE XXXVII.—*Manufacturing Requirements*

Property	Requirement
Applicator	Injection or extrusion gun
Cure temperature	No higher than 150° F
Shelf life	Stable 6 months in air
Repairability	Required rework possibility
Pot life	1 hr

and self-extinguishing characteristics in air. The shrinkage of this resin is less than that of most silicones, and, in addition, the resins are pourable polymers. However, in 6.2 psia pure oxygen, the unretarded resin burns vigorously. Various flame retardants were evaluated as additives to the dimethyl siloxane resin. Powdered glass, ammonium phosphate, ammonium chloride, and tetrabromophthalic anhydride were mixed into the resin material in various percentages and were cured in the configuration of a potted connector. These connectors were tested according to the specified test requirements.

Five formulations of these flame-retarded silicones, all of which attain a good flame resistance in an oxygen atmosphere, are

shown in table XXXVIII. Formulation SG12F1, which is typical of this class of compounds, is a flexible rubberlike material with satisfactory physical properties. The flammability characteristics are improved by the addition of a coating called FTA-3, which can be brushed onto the silicone. It is interesting to note that Fluorel and Viton C-10 can be used interchangeably in the preparation of this sealer coat. This sealer coat, developed by Emerson and Cuming, Inc., consists of 200 parts by weight of a 20-percent solution of Fluorel or Viton in methyl ethyl ketone (MEK), seven parts by weight of magnesium oxide, and 40 parts by weight of tabular alumina, 325 mesh. These materials are ball-milled together for 1 to 2 hours. Before use, 2.5 parts of a 25-percent solution of diethylene triamine is added per 100 parts of the coating material. After applying a coat of sealer, the part is left at room temperature for approximately 1 hour, then cured at 120° F (49° C) for at least 4 hours before the next coat is applied. At least three coats of sealer are recommended. It is necessary to prime with Chemlock 607 primer before each coat of sealer. After the final coat, the material is cured for 12 hours at 120° F (49° C) and then in a vacuum oven at 150° F for 24 hours to ensure that all solvent has been removed (ref. 6).

All of the formulations of the SG12 series meet, without a sealer coat, the requirements of test 5 for flammability in 6.2 psia pure oxygen (ref. 1). The topcoat is applied to reduce moisture transmission and to provide further improvement in flammability characteristics.

Test data showing the flammability resistance of most of these formulations are summarized in table XXXIX. A precise comparison of the flame resistance for these formulations is given by the downward propagation rates shown in table XL.

ROOM-TEMPERATURE-VULCANIZING FLUOROSILICONES

Considerable work has been performed by one contractor in the area of RTV fluorosili-

TABLE XXXVIII.—*Flame-Retarded Silicones*

[Figures shown are 100 parts by weight of elastomer to
corresponding parts by weight of other ingredients]

Ingredients	Compound				
	SG12	SG12D	SG12F1	SG12K1	SG12K1C
Dimethyl siloxane resin.....	100	100	100	100	100
Curing agent.....	10	10	10	10	10
Tetrabromophthalic anhydride.....	100				
Glass frit 1710.....	65	65			
Glass frit 7570.....		65	25	50	50
Ammonium phosphate.....				75	
Ammonium chloride.....					75

TABLE XXXIX.—*Silicone Compounds
Oxygen Flammability Data*

[60 percent oxygen, 40 percent nitrogen]

Compound	Pressure, psia	Test results
SG12.....	16.2	Passed
SG12D.....	16.2	Passed (simulated connector)
SG12F1 with FTA-3	16.5	Wire-overload test: sustained combustion approximately 30 seconds minimum, 200 seconds maximum 2-connector test: passed silicone ignitor
SG12K1C....	16.5	Wire-overload test: passed wire overload to ignition; failed wire overload to fusion 2-connector test: passed silicone ignitor

cone materials (ref. 7). A material designated as 175X is a typical example of this type of fluorosilicone. The compound is, for practical purposes, flameproof without a sealer coat in 60 percent oxygen, 40 percent nitrogen under the conditions of test 5 of reference 1. When so tested, some flame damage was noted on the surface of the sample connector at the wire terminals, but the flame then self-extinguished in less than 1 in. from the entry of the wires.

The 175X compound is flexible. Prelimi-

TABLE XL.—*Flame Propagation Rate for
Fire-Resistant Silicones*

[Test atmosphere: 6.2 psia O₂]

Compound	Propagation rate downward, in/sec
SG12.....	0.017
SG12D.....	.015
SG12F1 with FTA-3.....	Self-extinguishing
SG12K1.....	.013
SG12K1C.....	.008
SG12K1C with FTA-3.....	Self-extinguishing
Conventional silicone.....	.063

nary electrical tests show an insulation resistance of 600,000 megohms at 77° F. This compound passes the organic offgassing requirements for total organics and carbon monoxide. The exact formulations are listed in table XLI. More detailed information about this effort can be found in reference 7.

Numerous nonaerospace applications exist for potting, encapsulating compounds, and conformal coatings. These applications include connectors, printed circuit boards, and wire-harness terminations. Criteria for many such applications do not require nonflammability in pure oxygen atmospheres or high moisture resistance; hence, it might not be necessary to employ a sealer coat. Flame resistance superior to that of conventional potting materials can be achieved by the use

TABLE XLI.—*Furane Formulations for 175X Compound*

Component	Formulations, parts per hundred parts of rubber					
	175X	231	230	266	280	299
77-024 (fluorosilicone RTV).....	100		100			
77-033 (fluorosilicone RTV).....				100		
RTV 615A (silicone RTV).....						100
L-2344 (dihydroxy terminated fluorocarbon polymer).....					100	100
Boric acid (100 percent through 170 mesh).....	125		150		150	150
Ammonium fluoroborate.....				150		
Molecular sieves:						
13X.....		100				
Krytox 143 AC (perfluorinated fluid).....		298				
F-231.....			100			
77-024 catalyst.....	10		10			
77-033 catalyst.....				10		
A-110 (gamma-aminopropyltriethoxysilane).....					80	
Toluene diisocyanate.....						6
RTV 615 B.....						10

of SG12F1 glass-filled resin alone. The material has a broad temperature range (-65° to $+400^{\circ}$ F) and can be employed as a thermal barrier material against flame and excessive heat.

CERAMIC COMPOSITIONS

Some applications for dielectric insulation do not require flexibility; hence, a totally inorganic composition called formulation QC-15 has been made for potting. The composition is as follows:

Material	Parts by weight
Asbestos fiber	10
Glass microballoons	20
Silica, 325 mesh	30
Anhydrous sodium silicate	4

After being mixed together, the resulting powder is passed through a 20-mesh screen and then thoroughly blended. The powder is mixed with Ludox (a silica hydrosol) and cast into a mold. Within 24 hours, the entire mass solidifies. The mold is removed and the water is allowed to evaporate (ref. 6).

Because the QC-15 formulation results in porous castings after curing, a sealer coat is required to exclude moisture. This coating is

the same as that used to seal the coated silicone previously described (i.e., FTA-3). The addition of organic solids to the basic polymer reduces flammability. A series of coatings was made up in which the inorganic solids were 88, 84, 78, and 74 percent of the total. The first three of these coatings did not ignite in an oxygen atmosphere, but the one with 74-percent inorganic solids ignited and burned.

Formulation QC-15 can be applied by a hypodermic syringe or caulking gun and has a life of at least 1 hour. The material can be removed mechanically; and, even after several sealer coats have been applied, it can be cut off or removed from a casting. Formulation QC-15 has a specific gravity of 0.81. The electrical properties are not as good as those for the SG12F1 silicone material; however, the formulation passes such tests as the dielectric-constant test, the power-factor test, the arc-resistance test, and the high-potential test. Under conditions of high humidity and without a sealer coat, the material electrical properties are degraded (ref. 6). Formulation QC-15 without the sealer maintains physical strength and possesses acceptable electrical properties up to 2000° F (in the absence of high humidity).

With or without a sealer coat, tests (ref. 6) show that the material has outstanding fire resistance. Coupled with its low specific gravity, it would seem ideal for fire walls on aircraft and rockets. In industrial uses where oxygen atmospheres are encountered and where high humidities are not expected, this material could well be used as a conformal-coating material. It is rated as nonburning in any oxygen environment at a pressure lower than 10 psia. When strengthened with fiber glass, it is usable as conduit for insulated wires to give high reliability against fire.

FLUOROCARBONS

Considering the commercially available polymers that have essentially no hydrogen, the fluoroelastomers offer certain advantages. One formulation is as follows.

<i>Formulation number 1015</i>	<i>Parts by weight</i>
20-percent Viton C-10 in MEK	48
20-percent Viton C-10 in methylisobutyl ketone (MIBK)	12
25-percent DETA in MEK	2.5
Asbestos (Powminco grade 25PM)	10
Eccospheres R	15
Oncor 23A	5
Magnesium oxide	2

This material, as with QC-15, must use an FTA-3 sealer coat. Formulation number 1015 passes the flammability test in 16.5-psia oxygen as specified in test 5 of reference 1. The specific gravity of cured 1015 material is 0.36. The material can be repaired and reworked. The electrical properties rate good to excellent, but shrinkage is somewhat high. However, the exceptionally light weight and the oxygen-atmosphere flame resistance make it attractive for many aerospace and industrial applications. (See tables XLII and XLIII and reference 6 for additional details.)

BROMINATED POLYESTER—MRTA-5

The developer of QC-15 and 1015 materials also has developed a low-viscosity, 100-percent-reactive system, which has good fire-

TABLE XLII.—*Fluorocarbon-Based Potting Compound (1015A) With Sealer Coat*

[Summation of properties from tests]

Property	Test result
Application.....	Can use hypodermic syringe or caulking gun
Repair and rework.....	Can be mechanically removed—can be patched
Temperature rating, ohms	
0° F.....	0.82×10^{10} insulation resistance
250° F.....	2.58×10^{10} insulation resistance
Moisture resistance (after humidity cycles), ohms	3.5×10^8 insulation resistance
Dielectric constant.....	1.42
Power factor.....	0.019
Dielectric strength, V/mil..	200
Volume resistivity, ohm-cm	1.79×10^{12}
Surface resistivity, ohm-cm	3.81×10^{12}
Arc resistance, sec.....	123
High potential.....	No breakdown
Specific gravity.....	0.36
Flammability.....	Self-extinguishing in 16.5 psia O ₂

retardant properties, based on a brominated polyester termed MR-670 from W. R. Grace Company. This material, MRTA-5, can be used as a conformal coating. The formulation is given as follows:

<i>Material</i>	<i>Parts by weight</i>
MR-670	100
Tabular alumina, 325 mesh	340
Cobalt naphthenate, 6 percent	0.1

The electrical properties, as shown in table XLIV, are outstanding. The specific gravity, 2.53, is somewhat higher than for the two materials previously discussed. However, the tensile strength is good and shrinkage is acceptable. The material MRTA-5 should be a serviceable spacecraft conformal coating. It also should be usable in the aircraft industry in a similar capacity and as a caulking-type compound. More details for this com-

TABLE XLIII.—*Emerson and Cuming Formulations*

Component	Formulations, part by weight							
	Potting compounds					Sealer coat		Con-formal coating MRTA-5
	X1015	Y1015	Z1015	1015	QC-15	XSC	SC	
Viton C-10.....	20	20						
Fluorel 2141.....						20		
Ludox ^a					^b 14			
MR-670 (styrene containing brominated polyester).....								100
Asbestos (grade: Powminco 25 PM).....				11	10			
Oncor 23A (antimony oxide).....				5.5				
Maglite Y (magnesium oxide).....				2.2			^b 7 to 15	
Eccospheres SI (glass microballoons, acid treated).....				16.5				
Eccospheres R (glass microballoons).....					20			
Silica, 325 mesh ^a					30			
SS-65 PWD (anhydrous sodium silicate (ground glass)).....					4			
Alumina (tabular, -325 mesh).....							140	340
MEK.....	80		75			80		
MEBK.....		80						
X1015.....				52				
Y1015.....				13				
XSC.....							200	
Diethylene triamine (DTA).....			25					
Z1015.....				2.7				
Cobalt naphthaneate, 6 percent (64 to 85 parts by weight).....								0.1
MEK peroxide (grade not specified; assume same as for 1015 potting compound).....								1

^a Grade not specified.^b Variable.

pound are given in tables XLIII and XLIV and in reference 6.

CONCLUDING REMARKS

In summary, the flame-retarded silicone material with the FTA-3 overcoat is proposed as a spacecraft potting material for the following reasons. It is nonflammable and flexible. The electrical properties appear to be adequate based on testing to date. It is relatively inexpensive and easy to manufac-

ture, and materials of manufacture are readily available. Toxicity that would present problems in normal usage of the material has not been indicated by testing.

Usages other than for spacecraft seem indicated for any of the materials discussed. For example, aircraft fire walls, oceanographic-diving chambers, and submarine electronic components would appear to constitute potential applications. Areas using oxygen-rich atmospheres, such as operating rooms and hyperbaric chambers, contain considerable

TABLE XLIV.—*Polyester Conformal Coating (MRTA-5) Electrical Test Results (Summary)*

Property	Results
Dielectric constant.....	4.78
Power factor.....	.008
Dielectric strength, V/mil....	400
Surface resistance, ohm-cm....	4.05×10^{14}
Volume resistance, ambient, ohm-cm	4.72×10^{14}
Arc resistance, sec.....	213
High potential resistance, 60 Hz/sec	No breakdown
Moisture resistance, ohms at 76° F	9.9×10^6 minimum, 19×10^{10} maximum
at 212° F.....	1.3×10^7 minimum, 2.6×10^{10} maximum
Temperature resistance, volume resistivity at 250° F, ohm-cm	3.77×10^{13}

amounts of electronic equipment that should be protected. In addition, oxygen is being used with increasing frequency in industry. Potting materials and conformal coatings developed in the space effort can be adapted

readily for use in industrial areas in which oxygen is used.

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New Materials for Manned Spacecraft, Aircraft, and Other Applications

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The NASA nonmetallic-materials development program has achieved a high degree of fire safety within the Apollo spacecraft. When properly adapted for other uses, many of the nonflammable and fire-resistant materials developed by NASA should make a significant contribution toward fireproofing aircraft and other interiors.

Although the overall objectives of fireproofing a spacecraft cabin are similar to those of fireproofing an aircraft interior, some significant differences merit consideration in the final selection of materials. The spacecraft crew bay contains a closed environment, while an aircraft cabin contains a ventilated, open environment. Therefore, considerations of odor and toxic offgassing are much more critical for spacecraft than for aircraft. In addition, manned spacecraft to date have operated in space with a 100-percent-oxygen atmosphere, while most aircraft operate with an air or mixed-air-and-oxygen atmosphere. This factor has severely limited the use of materials in spacecraft interiors because very few nonmetallic materials exist that will not burn in oxygen.

When materials for aircraft are selected, other considerations are of greater importance. Foremost among these considerations is durability. Because of the relatively short usage time in currently operational spacecraft, compromises have been made in this area in favor of improved fire safety. Functional utility for the duration of a single mission (with adequate margins) has been an acceptable criterion. However, nonmetallic

materials that will withstand the rigors of repetitive usage are required for aircraft. With the advent of increasingly long space missions, the variation in durability criteria between aircraft and spacecraft lessens.

For the airlines, aesthetic considerations are almost as important as durability. To date, this factor has been of little concern in spacecraft-interior design. However, aesthetic considerations become important with increasingly long space missions.

While many of the fibrous materials used in the spacecraft cannot be dyed and are available only in white or varying shades of brown, methods of coloring fire-resistant fibers are being sought actively by industry. The applicability of many of the recently developed nonflammable and fire-retardant spacecraft materials for many commercial-aircraft items such as curtains, upholstery, carpets, decorative panels, cabinets, paper products, oxygen lines (and associated equipment such as masks), and straps is reviewed and discussed in this paper.

FIBROUS MATERIALS

Asbestos Fiber

Undoubtedly, the highest degree of nonflammability can be obtained with inorganic fibers such as asbestos and fiber glass. Asbestos, a natural mineral fiber, is not used in any exposed areas of the spacecraft, however, because of a tendency to shed particulate matter. This shedding is caused by the short staple length of the individual fibers,

which work loose from the fabric surface with minimal manipulation. Asbestos is used in composite layups in which the asbestos is contained within an assembly; therefore, any shedding that does occur is retained within the assembly. Assemblies containing asbestos exhibit a high degree of resistance to the conductive passage of heat and are used extensively in the spacecraft for containers that have flammable contents.

Glass Fiber

Fiber glass is the inorganic glass fiber used most extensively within the spacecraft, as indicated by reference 1. The type of fiber glass used almost exclusively is called Beta fabric. This fiber is characterized by an extremely fine diameter (3 microns). Because of this fine fiber diameter, textile structures can be fabricated that provide the maximum in flexibility and performance characteristics within the limits of the inherently low abrasion resistance characteristic of fiber glass.

Polyimide Fiber

Polybenzimidazole (PBI) (ref. 2) is a fiber that was developed by the U.S. Air Force. PBI has a breaking strength of 4.5 g/denier and retains 50 percent of its tensile strength at 700° F. In the spacecraft, PBI is used primarily in the form of webbing, tapes, and cords that are required to withstand dynamic flexing. The fiber is completely nonflammable in air, but it does burn slowly in oxygen environments. The burning rate is dependent upon the textile geometry, with the more dense constructions having the slower burn rates. The relative flammability of PBI compared to fiber glass is a penalty necessarily accepted to obtain performance characteristics not obtainable from fiber glass. The cost of the PBI fiber is currently high; however, the USAF is initiating a large-scale evaluation of it for flight clothing, and the other military services are conducting evaluations. If sufficient demand is generated to warrant large-scale production, it is anticipated that unit costs could be reduced greatly (ref. 3).

The natural color of PBI is a golden brown, and some success has been achieved in initial attempts to dye it. Polybenzimidazole fibers have been coated to change the color; however, the penetration of intramolecular spaces with coloring matter required for true dyeing has not been achieved.

Teflon Fiber

Teflon is another fiber that has essentially the same flammability characteristics as PBI. In the bleached form, Teflon is used for the Apollo astronaut's shirt-sleeve garment (that is, the inflight coverall garment). Fiber tenacity is relatively low (approximately 1 g/denier) but is adequate for most spacecraft usage. A number of specialized uses should be brought to mind by the high chemical resistance and low frictional surface characteristics of this fiber.

Metallic Fibers

Another group of high-temperature fibers used in the space program is the metallic fibers, which are available in fine-filament form (approximately 0.5-mil diam.). Fabrics with the flexibility and sewing characteristics of conventional textiles can be woven of metallic fibers. A Chromel-R fabric is used on the Apollo space suit to protect areas that are particularly susceptible to abrasion. Chromel-R is a single-drawn, nickel/chromium-alloy fiber.

A bundle-drawn Karma fabric is being considered for the outer shell of an advanced suit currently under development. This fiber is also a nickel/chromium alloy but is less costly than Chromel-R because multiple filaments are drawn at the same time. Stainless steel fiber is also available and is being used extensively in industry to reduce the static-electricity propensity of floor coverings made from synthetic fibers.

Durette Fiber

Durette (X-400) is a recently developed material made from a modified aromatic polyamide. Durette is nonflammable in air and

in moderately enriched oxygen atmospheres. The tenacity of the material is in the range of 4 to 5 g/denier, and other physical properties are good. The natural color is golden, and developmental effort to dye the fiber with colors of requisite fastness is underway. Monsanto Co., the fiber producer, is promoting commercial uses for this material.

Fabrics designated X-410 and X-420 are modifications of the X-400 fabric and are available only in black shades. These fabrics have better flame resistance than X-400, especially in oxygen-enriched atmospheres, and hence are of interest for future manned space programs.

Fypro

Fypro is another modified aromatic polyamide similar to Durette, but is made by a different proprietary process. The natural color of Fypro is brown, and the physical properties are good. The material is non-flammable in air, but minimal oxygen enrichment of the test environment will cause flaming. This material is available from Travis Fabrics, New York, N.Y.

Kynol

Kynol is a phenolic-type fiber recently developed by the Carborundum Corp.; it is orange-yellow in color. Kynol will not burn in air, but it will burn in oxygen-enriched environments. The fiber will retain its whole-fiber identity when exposed to flame temperatures as high as 2500° C. Current applications are mostly for felts and batting-type structures, but the manufacturer has indicated that significant progress has been made in improving the spinability of the fiber such that conventional knitted and woven fabrics should be available in the near future.

Other Fibers

Nomex is foremost among the more conventional fire-resistant organic fibers that have been evaluated by NASA. Physical properties are very good, but slight oxygen

enrichment of the atmosphere will produce flaming and, under some conditions, Nomex will burn in air.

Other fibers that will not burn in air are Saran and the modacrylics. An off-the-shelf fabric containing these two fibers was used to manufacture the curtains of the Mobile Quarantine Facility used to transport the astronauts to the Lunar Receiving Laboratory (ref. 4). Because of the air transport involved, the curtains and other interior components of the van had to meet the current Federal Aviation Agency airworthiness standards.

Fabric Data

Rather extensive testing and evaluation have been conducted on the various fabric materials discussed in the previous sections. A summary chart listing these fabric materials, significant performance characteristics, and other pertinent data are given in table XLV.

NONFLAMMABLE PAPER

The Papierfabrik Scheufelen of Oberlenningen, Germany, has developed a cellulosic material that has been processed primarily as a paper. This material carbonizes in the presence of a flame but does not propagate the flame. This nonflammable characteristic is evident in both air and oxygen-enriched atmospheres; and, with some minor exceptions, other physical properties are comparable to those of conventional paper in both atmospheres. Although Scheufelen paper tends to embrittle in a vacuum, it lends itself well to printing, and the use of this paper on the Apollo 12 mission proved to be very satisfactory. Scheufelen paper also can be made into a continuous sheet of 0.5-inch-thick foam, similar to papier-mache. When placed on a ceiling, for example, the foam has both the appearance and function of conventional acoustic tile and offers the additional advantage of nonflammability.

Because Scheufelen paper derives its nonflammability from a chemical variation from conventional manufacturing processes rather than from a subsequent chemical treatment,

TABLE XLV.—*Fabric-Characteristics Summary*

Fabric	Weight, oz/sq yd ^a	Combustion rate, in/sec								Physical			
		Air	10 psia 35 percent oxygen, 65 percent nitrogen	6.2 psia oxygen	16.5 psia oxygen	16.5 psia 60 percent oxygen, 40 percent nitrogen	Elongation, percent (b)	Breaking strength (warp), lb/in. (b)	Tear strength, g (c)	Wear resistance, number of cycles (d)	Folding endurance, number of cycles (e)	Stiffness, in/lb (f)	
Nylon.....	6.9	^a NA	NA	0.78	NA	NA	22	350	>6400	174	>5000	0.002	
Beta 4190B.....	6.5	0	0	0	0	0	8.1	106	2400	148	>5000	.003	
Beta 4484/Teflon..	6.1	0	0	0	0	0	8.9	142	>6400	151	>5000	.003	
Teflon—bleached T162-42	8.7	NA	0.29	.13	0.435	NA	67	59	5100	93	>5000	.0002	
Teflon—natural....	16.9	NA	NA	.21	.725	NA	56	172	5400	343	>5000	.002	
Nomex (HT 90- 40)	6.2	NA	.121	.63	1.00	NA	40	325	>6400	689	>5000	.001	
Nomex—treated— POCl ₃ Br ₂	7.3	NA	NA	.42	NA	NA	10	128	3000	353	>5000	.004	
Polybenzimidazole—untreated	5.0	NA	NA	.003	.009	NA	20	149	4600	206	>5000	.004	
Polybenzimidazole—treated— POCl ₃	8.0	0	NA	0	NA	NA	60	188	>6400	234	>5000	.002	
Polybenzimidazole—treated— POCl ₃ Br ₂	5.9	NA	NA	.14	NA	NA	20	184	5700	721	>5000	.002	
Durette (X-400)...	6.2	NA	^p SE	.31	.813	NA	30	138	5900	126	>5000	.0003	
X-410.....	5.0	NA	SE	.29	NA	NA	14	200	3000	96	>5000	.001	
X-420.....	5.6	NA	NA	.30	NA	NA	13.3	124	4100	93	>5000	.002	
Nickel chromium (Karma cloth or Chromel-R)	18.0	0	0	0	0	0	NA	176	5400	869	>5000	.003	
Fypro 5007/7.....	6.0	0	.29	.7	NA	0.8	24	154	3800	836	>5000	.003	
Kynol fiber.....	NA	NA	.27 (SE)	.71 (SE)	NA	5.0 (SE)	20	^q 1.7	NA	NA	>5000	NA	

^a Physical test method according to Federal Standard (FED STD) 191, method 5041.^b Physical test method according to FED STD 191, method 5104.^c Physical test method according to FED STD 191, method 5132.^d Physical test method according to FED STD 191, method 5302.^e Physical test method according to American Society for testing materials specification ASTM-D 2176.^f Physical test method according to FED STD 191, method 5202.^g Physical test method according to FED STD 191, method 5306 (C517 wheel).^h Physical test method according to FED STD 191, method 5304 (600-grit paper).ⁱ Physical test method according to FED STD 191, method 5450.

characteristics

Outgassing

Abrasion, number of cycles (g)	Abrasion, number of cycles (h)	Air permeability, ft ³ /ft ² /min (i)	Electrostatic charge, nanocoulombs (j)	Thermal conductivity, cal/sec-cm ² (°C/cm) (k)	Sample thickness, in. (l)	Odor (m)	Carbon monoxide, μg/g	Total organics, μg/g	Cost, dollars	Availability	Supplier
2468	870	7.98	8.0	1.49 × 10 ⁻⁴	0.0145	12	1.2	0.0003	3/yd	Commercial.....	Stern and Stern
198	85	.5	2.0	1.69 × 10 ⁻⁴	.008	NA	NA	NA	6/yd	Commercial.....	Owens-Corning
125	1200	22.7	18.0	1.2 × 10 ⁻⁴	.008 to .009	NA	NA	NA	10/yd	Available on special order	Owens-Corning
584	600	4.8	20.0	2.1 × 10 ⁻⁴	.009	0.9	.7	34.0	30/yd	Commercial.....	NA
1075	1952	11.2	32.0	1.8 × 10 ⁻⁴	.018	1.7	4.2	9.0	30/yd	Commercial.....	E. I. du Pont
943	260	4.9	8.0	1.58 × 10 ⁻⁴	.013	7	.4	1.0	8/yd	Commercial.....	Stern and Stern
450	227	10.9	.06	1.6 × 10 ⁻⁴	.014	NA	NA	NA	° 6/yd	Experimental...	Dynatech
629	143	98.5	40.0	3.0 × 10 ⁻³	.0135	5	2.4	3.0	200/lb	Government use only	Celanese
2481	1651	26.9	2.6	3.2 × 10 ⁻⁵	.017	NA	NA	NA	° 6/yd	Experimental...	Dynatech
1200	1500	38.7	2.4	4.8 × 10 ⁻⁵	.014	NA	NA	NA	NA	Experimental...	Monsanto
467	116	89.1	2.0	1.3 × 10 ⁻⁴	.012	NA	3.7	0	25 to 50/yd	Being evaluated.	Monsanto
145	65	28.9	18.0	1.8 × 10 ⁻⁴	.0118	11	2.8	1.0	NA	Experimental...	Monsanto
100	350	43.4	.01	2.0 × 10 ⁻⁴	.013	NA	NA	NA	NA	Experimental...	Monsanto
2034	977	68.8	0	NA	.010	NA	NA	NA	150 to 1500/lb	Available on special order	Fabric Research Laboratory
217	41	49	12	2.0 × 10 ⁻⁴	.015	.7	4.0	1.0	6.50/yd	Commercial.....	Travis Mills
NA	NA	NA	NA	NA	NA	NA	NA	NA	5/lb	Commercial.....	Carborundum

ⁱ Physical test method according to Sweeney test method.

^k Physical test method according to Cenco-Fitch test method.

^l Physical test method according to FED STD 191, method 5030.

^m Physical test method according to MSC specification MSC-PA-D-67-13; 2.5 or lower is acceptable.

ⁿ Not available.

^o Treated.

^p Self-extinguished.

^q Breaking tenacity, g/denier.

the characteristic is permanent. The chemical additive is physiologically inert, and the manufacturer states that it can be ingested without deleterious effects. Scheufelen paper is relatively inexpensive and is available off the shelf in some forms. Developmental work is continuing for the improvement of the paper for vacuum-compatibility and application of the proprietary process to other cellulosic materials, such as rayon, cotton, and wood-pulp.

FLUOROPOLYMERS

The fluorocarbon elastomers (refs. 5 and 6) are basically copolymers of hexafluoropropene and vinylidene fluoride. By themselves, the elastomers are flammable in the spacecraft atmosphere. However, through the judicious use of compounding ingredients and plasticizers, nonflammability concomitant with a wide range of physical properties has been achieved. The compounded elastomer can be foamed, cast, molded, or extruded. The material can be controlled as a paste, coating, or spray solution. The replacement of flammable spacecraft components has been achieved in many cases by using this material. Of special interest is the fact that fluorocarbon elastomeric coatings will effectively protect flammable substrates and will do so in minimal applied thicknesses. Oxygen and smoke-mask hoses have been extruded; boot soles, eyepieces, and headrests have been molded; foams have been used as shoulder pads and as spacers in survival-kits; sheet stock has been cut into gasketing material; and gloves, urine bags, and Beta fabric have been coated. Circuit breakers and other critical areas of electrical systems can be coated to provide barriers for incipient ignition points. Circuit breakers also can be molded from the material to a tolerance of 0.002 in. The extrapolation of these developmental efforts for aircraft to promote survivability in crash-fire situations is obvious.

Mineral pigments in a wide variety of colors can be formulated into fluorocarbon-based paints. Such paints applied to panelboards made from nonflammable composites

enable many aesthetic effects to be achieved that are necessary for habitable considerations in proposed long-term space missions. Fluorocarbon-based paints should have direct and immediate application in commercial aircraft.

In an effort to determine what could be done with fluorocarbon elastomers in commercial aircraft, a series of sample decorator fabrics, coatings, and so forth was fabricated in-house at the Manned Spacecraft Center (MSC). These samples include wallpapers and other wall coverings, ceiling tiles, rugs and other floor coverings, and paints.

Fabricated samples were tested for flammability and compared with conventional aircraft-interior materials such as Naugahyde and paper coatings. This flammability test is the flame-impingement test described in reference 7. The increased times attained before flame breakthrough occurred are shown in table XLVI. Generally, a significant increase in time to flame breakthrough is obtained by coating existing substrates, and a flame-breakthrough increase from seconds to minutes is obtained by using substitute materials from design inception. Comparative physical characteristics of various decorator panels are shown in table XLVII.

Although finishes can be used to fireproof existing materials, the commercial fabrication of composite paneling with fluorocarbon adhesives, finishes, and base material appears attractive. Samples of panels fashioned of fluorocarbon-backed Scheufelen paper, to which any type of decorative pattern may be applied, have been manufactured at MSC. The panel faces were protected from stain and abrasion by an overcoat film of transparent Kel-F. Varying the application technique of the various coatings gives a range of textures from that of antique wallpaper to a glossy sheen. The addition of Kel-F-fastened Beta lace to the finished surface lends an elegant and nonflammable flair. The inclusion of asbestos in the backing provides insulating properties. This combination of lightweight, fireproof, sandwich construction affords much flexibility in decorative paneling.

The staining and cleaning characteristics

TABLE XLVI.—*Comparative Fireproof Characteristics of Decorative Panels*

Material	Thickness, in.	Flame burnthrough, min			Remarks
		Uncoated (^a)	Coated with Fluorel (^b)	Laminated with Fluorel, Beta lace, and scrim	
Vinyl on fiber glass.....	0.012	0.25	0.5	^c NA	Presently used by United Airlines
Scheufelen paper.....	.012	NA	1.0	NA	NASA substitute
Vinyl on ABS ^d with Tedlar overlay.....	.032	.25	.5	NA	Presently used by United Airlines
Laminated Scheufelen paper.....	.021	NA	6.5	>8.0	NASA substitute
Vinyl with Tedlar overlay.....	.012	.25	.5	NA	Presently used by United Airlines
Scheufelen paper.....	.012	NA	1.0	NA	NASA substitute
Laminated vinyl with clear vinyl overlay.....	.061	.25	1.0	NA	Presently used by United Airlines
Scheufelen paper.....	.077	NA	NA	>8.0	NASA substitute
Plain cardboard.....	.065	NA	1.5	NA	NASA substitute
Scheufelen board, 2 ply.....	.036	NA	NA	^e 2.50/5.50	NASA substitute
	.066				
Scheufelen board, 4 ply.....	.106	NA	>8.0	NA	NASA substitute
Scheufelen board, 2 and 4 ply....	.081	NA	NA	^e >8.0	NASA substitute

^a Sample continued burning.^b No propagation of fire.^c Not available.^d Acrylonitrile butadiene styrene.^e Asbestos interlayer.

of nonflammable materials compared to those of conventional aircraft-interior materials offer additional incentive to aircraft decorative-panel designers. The stain resistance and relative ease of cleaning for various materials tested are given in table XLVIII, which describes the effectiveness of the stain resistance in percent residue remaining. Generally, the surface of these new materials is stain resistant and may be cleaned easily except for some cases when lipstick is applied.

Coating of this new material applied to polyurethane foams (both open and close cell) have produced very favorable flammability characteristics. When the material is applied as a thin coating on either form of polyurethane foam, even on thin sections, the resultant item is nonflammable in air. Thus, seat cushions obviously can be made non-

flammable. Similarly, when applied to other cellulose-base materials such as kraft paper and kitchen sponge, the material renders the substrate nonflammable. The physical strength and insulating properties of coated cellulose sponge suggest a multitude of possible insulation applications (e.g., plumbing, aircraft skin, and residential and commercial building construction). Even wood and paper are fireproofed effectively by this coating treatment.

Typical of these fluorocarbon elastomers are Fluorel and Viton. The physical and flammability characteristics of these materials are given in table XLIX.

COMPOSITE LAYUPS

For spacecraft applications in which a single material will not provide the flame pro-

TABLE XLVII.—*Comparative Physical Characteristics of Decorative Panels*

Material	Thickness, in. (^a)	Weight, oz/sq yd (^b)	Puncture, lb	Breaking strength, lb (^c)	Flexi- bility (^d)	Wax pick (^e)
Vinyl on fiber glass.....	0.012	13.1	34	149	4.8	26
Scheufelen paper with spattered Fluorel.....	.012	12.8	48	28	4.0	26
Vinyl on ABS ^f with Tedlar overlay.....	.031	30.0	70	111	67.4	26
Laminated Scheufelen paper with Fluorel.....	0.20	18.7	9.5	43	21.3	26
Laminated Scheufelen paper coated with Beta lace and scrim.....	.036	25.6	22.0	118	49.0	20A
Vinyl with Tedlar overlay.....	.012	11.5	25	38	1.7	26
Scheufelen paper with spattered Fluorel.....	.012	12.8	48	28	4.0	26
Laminated vinyl with clear vinyl overlay.....	.061	60.7	130	280	477.8	26
Scheufelen board, 2 and 4 ply, with Beta scrim and asbestos/Kel-F finish and Fluorel coated.....	.081	67.3	61	350	477.8	26
Scheufelen paper with Beta-scrim backing coated with Fluorel.....	.077	68.4	118	505	204.7	26
Plain cardboard coated with Fluorel.....	.065	39.8	50	344	297.5	26
Two-ply Scheufelen-board laminate coated with Fluorel with Beta scrim and asbestos having a Kel-F finish.....	.051	42.2	29.8	112	71.1	26A
Two-ply Scheufelen-board laminate coated with Beta lace.....	.066	46.3	33	^g NA	NA	5A
Four-ply Scheufelen-board laminate coated with Fluorel having a Kel-F finish.....	.106	83.0	98	680	477.8	26
Scheufelen 2- and 4-ply board laminate coated with Fluorel with Beta scrim and asbestos having a Kel-F finish.....	.081	67.3	61	350	477.8	26

^a FED STD 191, method 5030.^b FED STD 191, method 5041.^c FED STD 191, method 5104.^d FED STD 191, method 5202.^e Wax pick determination of surface smoothness (maximum smoothness is 26). (FED STD 191, method 5132.)^f Acrylonitrile butadiene styrene.^g Not available.

tection needed, composite layups have been used, especially in containers that hold flammable contents. The most commonly used layup is a six-layer, unbonded assembly consisting of an outer layer of Teflon-coated Beta fabric, a layer of 1-mil aluminum foil, a layer of woven asbestos, another layer of asbestos followed by a layer of aluminum foil, and finally a layer of Teflon-coated Beta fabric. A temperature differential of 1600° to 1700° F can be maintained with this layup for 10 min.

The Langley Research Center also has developed a composite layup to form the inside of a possible lunar shelter. This layup is designed to act as a flame barrier as well as a gas sealant. From the inside out, the components are 0.5-mil aluminum foil, Refrasil (quartz) fabric, 1-mil aluminum foil, 50-mil fluorocarbon elastomer sponge, 1-mil Aclar (fluorocarbon) film, Beta fiber-glass fabric, and 1-mil aluminum foil. The entire composite is bonded together with a fluorocarbon-elastomer-based adhesive.

TABLE XLVIII.—*Evaluation of 7-Day Material Stain Characteristics*

[Water and soap are cleaning agents]

Stain	Residue remaining, percent											
	Acrylonitrile butadiene styrene with Tedlar overlay			Vinyl on fiber glass with textured Tedlar overlay			FX 703 (Kel-F)			Kel-F-3700 (Scheufelen paper)		
	Water	Soap	Water	Water	Soap	Water	Water	Soap	Water	Water	Soap	Water
	Water	Soap	Water	Water	Soap	Water	Water	Soap	Water	Water	Soap	Water
Mayonnaise	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Oil	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Butter	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Catsup	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Writing ink	0	N/A	0	N/A	0	N/A	50	0	100	50	0	50
Milk	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Bourbon	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Nicotine	0	N/A	0	N/A	0	N/A	100	0	100	0	100	0
Orange juice	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Coffee	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Mustard	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Alcohol	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Hair tonic	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Lipstick	100	0	100	0	0	0	0	0	0	0	0	0
Cocoa-Cola	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
Nail polish	100	100	100	100	100	100	100	100	100	100	100	100
Ball-point ink	100	20	100	20	0	100	100	25	100	100	10	100
Crayons	100	0	100	0	0	100	100	20	100	100	0	100

^a Different design.^b Not applicable.

TABLE XLIX.—*Characteristics of Fluorocarbon Elastomers*

Material	Combustion rate, in/sec (^a)					Physical characteristics					
	10 psia 35 percent oxygen, 65 percent nitrogen	6.2 psia oxygen	16.5 psia oxygen	16.5 psia 60 percent oxygen, 40 percent nitrogen	Elongation, percent (^b)	Tensile strength, psi (^b)	Tear strength, lb/in. (^c)	Embrittlement temperature, °F (^d)	Specific gravity (^e)	Durometer, Shore A (^f)	Hydrogen permeability, 1/m ² /24 hr (^g)
Fluorel 1059 L-23171-1.....	NA	SE	NA	NA	210	2045	122	NA	1.99	71	NA
Fluorel 1071.....	NA	NA	SE	NA	200	1370	55	-50	2.03	55	NA
Fluorel 1076.....	NA	SE	SE	NA	350	1250	77	-85	1.97	45	NA
Fluorel 1079K.....	NA	SE	0.040	NA	300	1523	75	-90	2.02	49	NA
Fluorel L-3203-6.....	NA	NA	SE	NA	75	1558	128	NA	2.11	97	NA
Fluorel L-3251-3.....	NA	SE	SE	NA	75	1820	61.5	NA	2.08	96	NA
Fluorel L-3203-6 RL 3550, 25 percent asbestos.	NA	NA	SE	NA	25	100	128	NA	1.94	97	NA
Viton 238-12-1.....	NA	SE	0.030	NA	NA	613	NA	NA	NA	NA	NA
Viton 238-26-1.....	NA	0.016	0.025	SE	230	800 to 1240	95	m-65	2.11	57	NA
Viton 238-97-1 on Beta.....	NA	.037	NA	NA	NA	NA	NA	NA	NA	NA	NA
Viton 238-46-1.....	NA	NA	.016	NA	NA	NA	NA	NA	NA	NA	NA
Viton 238-46-2.....	SE	SE	SE	NA	500	1587	156.2	-222	2.0	70	0
Viton 238-98-1 n.....	NA	SE	NA	NA	70	765	NA	NA	NA	° 50	NA
Viton 238-99-1 p.....	NA	SE	SE	NA	NA	NA	NA	NA	NA	° 40	NA
Viton DR-8380.....	NA	SE	.016	NA	400	1720	140.0	-50	NA	82	0
Carboxy nitroso rubber.....	NI	NI	NI	NI	NA	NA	NA	NA	NA	NA	NA
Polyquinoxaline, laminated...	NA	SE	.007	SE	NA	1700	NA	-323	NA	NA	NA
Fluorinated urethane.....	NA	NA	NA	SE	NA	NA	NA	NA	1.87	100	NA
Polyimide laminate.....	NA	NA	NI	NA	NA	5200	NA	NA	1.75	NA	NA

^a Tissue ignitor. All listed materials are nonflammable in air.^b Physical test method according to American Society for Testing Materials (ASTM) standard D 412.^c Physical test method according to ASTM standard 624.^d Physical test method according to MSC test method.^e Physical test method according to FED STD 601, method 14011.^f Physical test method according to ASTM standard D 2240.^g Physical test method according to ASTM standard D 815.^h Physical test method according to FED STD 191, method 5030.ⁱ Not available.

Physical characteristics		Outgassing					Application	Availability	Supplier
Shrinkage, percent (d)	Sample thickness, in. (h)	Odor	Carbon monoxide, $\mu\text{g/g}$	Total organics, $\mu\text{g/g}$	Cost, dollars				
NA	0.070	1.3	2.7	1.0	2000/lb	Hoses and headrests	Commercial	Mosites Rubber, Raybestos-Manhattan.	
3.3	.075	1.4	.9	1.0	3750/lb	Tubes and hoses	Commercial	Mosites Rubber.	
(^k 4.4)									
3.7	.080	.4	.5	1.0	3750/lb	Tubes and hoses	Commercial	Mosites Rubber.	
(^k 4.6)									
6 (^k 6)	.069	1.2	.4	1.0	3750/lb	Tubes and hoses	Commercial	Mosites Rubber.	
NA	NA	1.0	.7	1.0	2220/lb	Nonflammable coatings	Commercial	Raybestos-Manhattan.	
NA	NA	1.2	1.3	3.0	2220/lb	Boot soles (softer than L-3203-6)	Commercial	Raybestos-Manhattan.	
NA	NA	NA	NA	NA	130.39/gal	Fireproof coating	Commercial	Raybestos-Manhattan.	
0	.125	.8	.4	0	NA	Tubing, hoses, and molded parts	Commercial	E. I. du Pont	
0	.125	.9	.4	0	19.35/lb	Tubing, hoses, and molded parts	Commercial	E. I. du Pont	
NA	NA	NA	NA	NA	NA	Fireproof coating	Commercial	E. I. du Pont	
NA	NA	NA	NA	NA	NA	Tubing, hoses, and molded parts	Commercial	E. I. du Pont	
NA	.125	.5	.4	0	37.10/lb	Tubing, hoses, and molded parts	Commercial	E. I. du Pont	
NA	.0055	NA	NA	NA	NA	Fireproof coating	Commercial	E. I. du Pont	
NA	NA	NA	NA	NA	NA	Conformal coating	Commercial	E. I. du Pont	
NA	.125	1.0	.6	.4	NA	Extruded elastomer	Commercial	Detroit Rubber	
NA	NA	2.7	1.0	24.0	500/lb ^s	Nonflammable, solvent-resistant elastomer	Not currently being produced	Thiokol Chemical	
NA	.125	NA	NA	NA	900/gal	Structural composite	Commercial	Narmco Research and Development Division, Whittaker Corp.	
NA	NA	.6	8.0	89.0	1800/lb ^s	Flame-resistant, flexible adhesive	NASA contracts only	Narmco Research and Development Division, Whittaker Corp.	
NA	.125	NA	NA	NA	5.97/sq yd	Structural composite.	Commercial	E. I. du Pont	

[†] Self-extinguished.

^k With grain.

[†] Silicone ignitor.

^m Centigrade.

ⁿ Stability (viscosity 50 cP)—no change in 14 days.

^o Shore D.

^p Stability—no change in 14 days.

^q Shore C.

^r No ignition.

^s Approximate.

CONCLUDING REMARKS

Many of the flame-resistant materials that have accrued from the Apollo Program appear to be particularly applicable to the design of aircraft and ground-vehicle interiors, to residential and commercial building construction, and to other fields. Furthermore, the potential for combining several of the materials to obtain additional desirable properties remains virtually untapped.

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The Performance of Lightweight Plastic Foams Developed for Fire Safety

RICHARD H. FISH

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The work at Ames Research Center on fire protection and fire suppression was started in September 1967 and was motivated by the realization that the principles utilized in the protection of entry vehicles from aerodynamic heating could be used to give some measure of protection from both spacecraft and aircraft fires. The use of a low-density, polyurethane-based foam to suppress a fire and to provide protection for the structure of an aircraft or spacecraft will be discussed and described.

In this program, certain ground rules were established that hopefully would avoid the normal long lead times between the generation of an idea and the production of a final useful product. First, a team of specialists from a number of organizational segments at Ames Research Center was gathered so that special skills could be concentrated on the problem in all disciplines needed. Second, it was stipulated that only commercially available materials were to be used in the first phase of the program to avoid the time delays in inventing and producing new material systems. These actions provided rapid progress and produced a useful product that could be improved further with additional work.

THEORY

The protection of any structure, entry vehicle, or aircraft against damage by heat can be accomplished by the same basic protective mechanisms. The source of heat is not important; heat generated by fire or by a hot gas

cap surrounding an entry vehicle is much the same. To damage a structure, heat must be carried to the structure by either free or forced convection or by radiation. Therefore, in principle, any or all of the heat-protective mechanisms can be utilized to afford protection (fig. 58).

The simplest form of heat protection is one that provides a high resistance to heat flow between the heat source and the structure. Low-density foam with a low thermal conductivity provides this feature. Another important mechanism, often overlooked in fire protection systems but widely utilized in spacecraft thermal-protection systems, is the release of gases from the thermal-protective material when subjected to heat load. These gases serve to protect the system in two important ways. First, gases near the surface

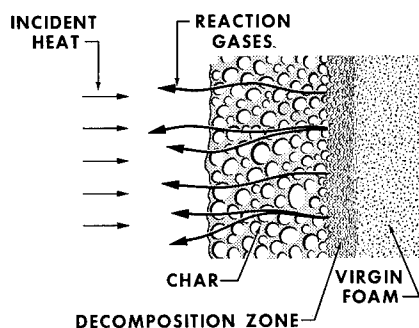


FIGURE 58.—Pyrolysis mechanism of char-forming ablators under unidirectional heating.

flow against the incoming heat, thus impeding the flow of heat to the surface. For example, in a spacecraft being protected against reentry heating, gases can block nearly all the convective heat flow. Second, in protecting against a fuel fire, gases can be made rich in halogens that can chemically scavenge the chain carriers by which fuel flames are propagated and thus serve as fire-extinguishing agents. This principle has been utilized in the polyurethane systems.

Another mechanism that affords protection against fires is a production of char resulting from the action of heat on the materials. If char with low-thermal conductivity and high-oxidation resistance can be formed, it will not only afford protection by virtue of low-thermal conductivity, but the surface will reach a high temperature and thus will be capable of reradiating a large fraction of the incident heat load. This mechanism is utilized in the systems that are being developed. In the polyurethane foam material, polyvinylchloride has been added, which, when heated, causes the polyurethane to form a stable, tough char of low thermal conductivity. This idea came directly from work on thermal protection systems for reentry vehicles.

An important point about the systems to be discussed is that these systems react to an applied heat load to provide a number of protective mechanisms not present in a system that does not respond to a fire. Thus, these are not passive systems; rather, they are dynamic systems that provide protection when exposed to a fire.

MATERIALS

The properties desired in a foam system for fuel-fire protection are:

1. Impact ignition avoidance
 - a. Low density-void-filling capacity to eliminate atomization of combustible liquids
 - b. Closed-cell foam structure with self-sealing skin to prevent outpouring of combustible liquids
 - c. Pyrolysis at low temperature and at

high rate to give hydrogen bromide, hydrogen chloride, or hydrogen fluoride and free radicals to inhibit ignition

2. Sustained fire protection

- a. Decomposes at moderate rate to give low molecular weight species to suppress flames

- b. Excellent low-heating-rate ablation efficiency to minimize heat transfer to aircraft structures

Several foam systems have been developed to provide a selection of materials with specific properties for various applications.

Urethane Foam (Ames Type 5I)

Urethane systems were examined and modified to yield the 5I composite foam, a base of α methyl glucoside and propylene oxide. A halogenated polymer, polyvinylchloride, which increases char yield and pyrolyzes to release HCl gas that acts as a free-radical flame scavenger, was added to this basic polymer system. An inorganic salt, potassium fluoroborate also was added to the foam system. The function of the inorganic salt is twofold: the salt produces fire-quenching or suppressing species, and the decomposition products of the salt potentially can react with the degradation products of the urethane foam.

The specific action of these alkali metal salts of fluoroboric acid is shown in figure 59. Degradation forms boron trifluoride, which can serve as a fire-quenching species and also react with the carbonaceous char to form carborane or boron carbide-like structures. A cross section of 5I foam undergoing thermal degradation and frozen in time is shown in figure 60. The outgassing of suppressant and scavenging species that cool the integral char structure can be seen as they are injected into the boundary layer. The highly emissive surface reradiates much of the incident flux, resulting in better sustained thermal protection (ref. 1).

The third additive that can be incorporated in foams to provide fire-quenching or suppressing species is microencapsulated volatile halogen-bearing molecules. With ther-

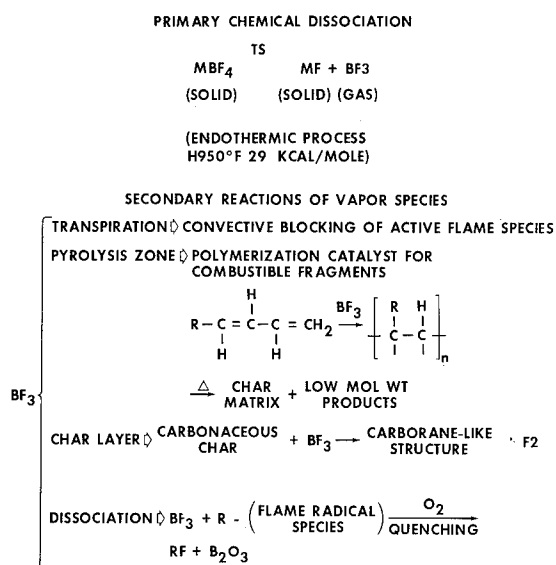


FIGURE 59.—Thermochemical action of alkali fluoroborates.

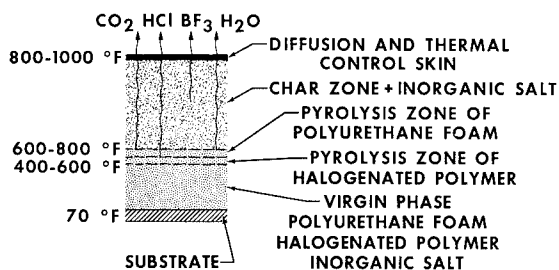


FIGURE 60.—Response of inorganic salt + halogenated polymer acetate-modified polyurethane foam to the heating input of a fuel fire.

mal degradation of the microcapsules, the halogen-bearing molecules are released, resulting in dilution of ejected gases and also providing species that can act as free-radical quenchers on the fuel-fire propagation species of the flame. A microcapsule, or balloon, and fire-retardant filler are shown in figure 61.

Urethane Systems (Fiber Loaded)

In areas where higher shear loads, both mechanical and thermal, are encountered, fiber-loaded 5I foam may be used. Of the many fibers tested, short glass or quartz

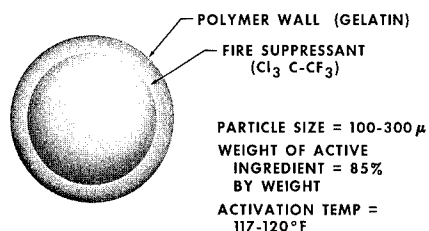


FIGURE 61.—Encapsulated fire-suppressant particle (microballoon).

fibers (about 0.25 in. long) in a 10-percent-by-weight concentration performed very efficiently. The addition of these fibers usually will increase the density of foam approximately threefold. However, the improvement in other thermal physical properties may outweigh the weight penalty. In its density range (i.e., 5 to 6 lb/ft³), this foam, designated 5I10AQ, performs very well under low heating rates.

Isocyanurate Rigid Foam

To obtain higher char yields than could be obtained with the urethane system, further research was needed. A new system, polyisocyanurate polymers, seemed to be one of the most promising (ref. 2).

An isocyanurate ring structure is formed by the cyclization of three isocyanate groups. The use of a polyfunctional isocyanate, such as diphenyl methane diisocyanate (MDI) or a polymeric isocyanate (PAPI), gives rise to a polymeric isocyanurate polymer. Polyisocyanurate polymers exhibit improved temperature stability when compared to a polyurethane polymer. The cyclization reaction is illustrated in figure 62.

The practical problem with the polyisocyanurate polymers for use in low-density foam materials is that of brittleness or friability of the foam structures. The brittleness is attributed to the cyclic structure that restricts motion in the polymer chain. The brittleness associated with the polyisocyanurate polymers has limited the use of this polymer system in low-density foam applications.

Investigations into methods to reduce the brittleness of the polyisocyanurate polymers

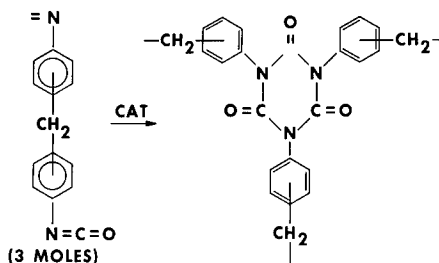


FIGURE 62.—Isocyanurate structure.

were undertaken. The technique demonstrated to have the most utility is that of introducing urethane linkages into the polyisocyanurate polymer. The disadvantage of this approach is the introduction of less stable urethane linkages in the system, which can lead to flammable gaseous species evolved during thermal degradation; so the choice of polyol to be used and the amount are extremely important. First, the polyol fragment must result in a char independent of the urethane linkage. Second, the reaction to form a high-temperature stable structure should occur before the initial urethane linkage degradation to minimize volatile fragment formation. Third, the polyol should have a low hydroxyl number so as to convert as few as possible of the isocyanate groups to urethane linkages in the polymer system. Fourth, the polyol should have a high molecular weight and low functionality so as to impart mechanical flexibility to the polyisocyanurate-polyurethane polymer structure.

Acrylonitrile was selected as the grafting monomer because nitrile linkages cyclize to form high-temperature stable heterocyclic ring structures when exposed to a thermal environment. Potassium fluoroborate, which improves char strength in polyurethane foams exposed to thermal environments (ref. 1), and zinc oxide, which aids in the curing of the acrylonitrile fraction, were added to the basic polymer system.

When a closed-cell foam is heated, the gas pressure in the cells increases. At approximately 250° F, the foam is softened to the extent that the increased gas pressure causes the foam to swell. Continued heating in air

causes the foam to begin degrading to a carbonaceous char structure while outgassing various compounds and shrinking in size. These changes in size are plotted as a function of temperature in figure 63. It may be seen that the isocyanurate foam (X-ISO) maintains better dimensional stability than the urethane foam (Ames 51). If the thermal gravimetric analyses (i.e., weight loss with increasing temperature) of these two foam systems are examined (fig. 64), it can be seen that the major reduction in weight occurs at a higher temperature with the X-ISO versus the 51 foam. At the higher temperatures, the increased weight of the X-ISO foam also can be seen, with the realization that this almost 50-percent increase at 1000° F represents the "char yield" that it was hoped to increase.

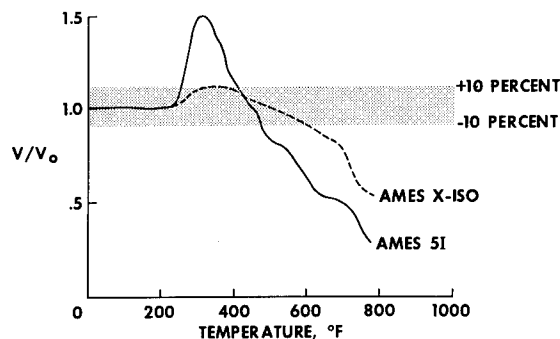


FIGURE 63.—Dimensional stability in air of Ames foams.

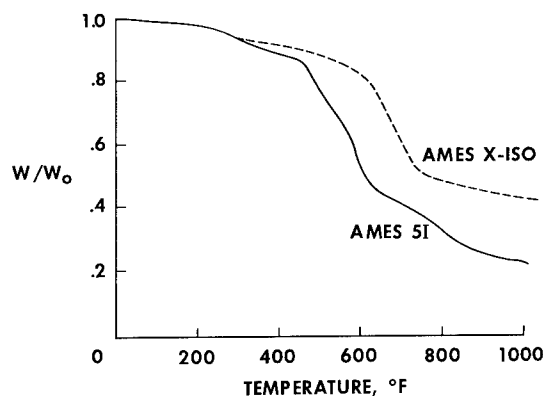


FIGURE 64.—Char yield in nitrogen of Ames foams.

Increasing the char yield is shown to be a linear function of the molecular structure of the polymer (fig. 65 and ref. 3). It now can be seen that the consequence of the cyclization of three isocyanate groups to form the isocyanurate ring structure led to a higher number of multiple bonded aromatic linkages per gram. Therefore, the higher percentage of char yield could be foreseen.

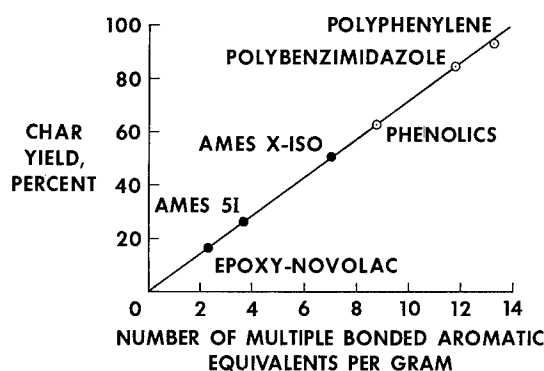


FIGURE 65.—Correlation of primary thermochemical char yield with molecular structure.

Higher Density Rigid Foams

Polybenzimidazole (PBI) (fig. 65) currently is being investigated for possible use as a refurbishable spacecraft heat shield; a foam matrix of PBI would be impregnated with a suitable, fire-extinguishing, ablating material. When it is exposed to a heat source, the impregnated material would ablate away, leaving the PBI foam. The PBI would then be reimpregnated and reused.

Another high-density material that is being investigated for high-temperature applications is polyphenylene. Although not directly used for fire safety, polyphenylene material with a 90- to 95-percent char yield currently is being made at Ames and tested for possible brake-lining application.

TESTING RIGID FOAMS

Sustained thermal protection presents a need for more sophisticated tests than have been or are in use as screening tests at many laboratories. The usual small-scale tests pro-

vide only limited data that are useful primarily for classification of a new material. On the other hand, full-scale simulation tests are too expensive, unwieldy, and time-consuming for daily screening of candidate materials. Thus, a new test was required by which the fire-protective effectiveness of the newer class of foam composites could be evaluated.

A free-burning JP-4 fuel fire gives a total heat flux of approximately 30 000 Btu/ft² hr, of which the radiative component is approximately 90 percent (ref. 2). To achieve a test that would approximate this environment, a specialized thermal test fixture was developed. This thermal test (T-3) allows for limited control of environment and rapid screening of materials. Data are acquired for backside temperature as a function of time, and observations are made of the physical behavior of the sample in the environment.

A schematic drawing of the Ames T-3 thermal test facility is shown in figure 66. An oil burner is used to burn JP-4 jet aviation fuel at the rate of approximately 1.5 gal/hr in the firebrick-lined chamber, and the combustion products are exhausted out the top rear of the unit. The test facility has these test areas: (1) directly over the combustion chamber, (2) in the flue to the rear of the combustion chamber, and (3) inside the combustion chamber under direct fire impingement. The flux levels available in each

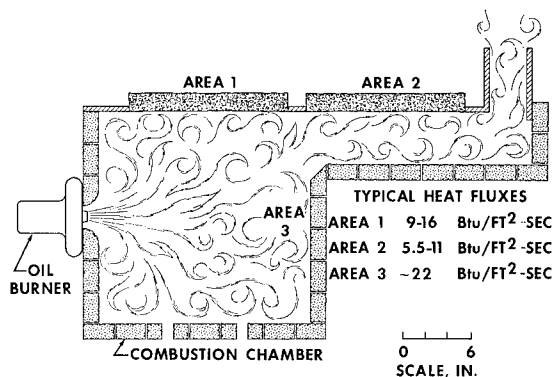


FIGURE 66.—Ames T3 thermal test facility (JP-4 fuel).

testing area are indicated in figure 66. For test area 1, the major portion of the heat flux (90 percent) is radiative. Area 2 is a reducing environment where the mode of heat transfer is distributed equally between radiation and convection. In area 3, the main mode of heat transfer is mainly convective, with direct impingement on the surface of the material.

The T-3 thermal facility is used for foam-screening tests. For most foam screening, area 1 is used, and the flow rate to the burner is adjusted to maintain 10 to 10.5 Btu/ft²-sec (36 000 to 37 800 Btu/ft²-hr) total heat flux. The area-1 temperature at the hot face of the sample is maintained at 1700° F minimum throughout the test.

The foam samples used for the test are 12-by-12-by-2-in. specimens. The sample assembly is shown in figure 67. The samples are backed with 1/16-in.-thick 2024-T4 aluminum alloy bonded to the surface of the foam with an epoxy resin. The backplate has a 2.5-in.-diam hole in the center, to which is bonded a 2-in.-diam aluminum calorimeter of the same class and thickness. The aluminum back or supporting plate has a dual function. First, it represents a more practical approach to the application in which the foam will be used; and second, it acts as a supporting plate for the foam in the T-3 test and prevents any warping of the foam sample during test.

After a period of conditioning at standard laboratory conditions (1 week at 74° F and 50 percent relative humidity), the samples are tested in the T-3 thermal facility. A mask of asbestos millboard, 12 by 12 in., with a 7-in.-diam hole in the center, is placed against the face of the foam and then placed over area 1. The aluminum back-face temperature is recorded continuously for the test duration.

Plotted in figure 68 are time-temperature histories for a bare control plate, the Ames-modified urethane system 5I (ref. 1), the Ames-modified polyisocyanurate system, and a conventional polyisocyanurate foam. The plot shows that the Ames-modified polyisocyanurate foam is far superior to the conven-

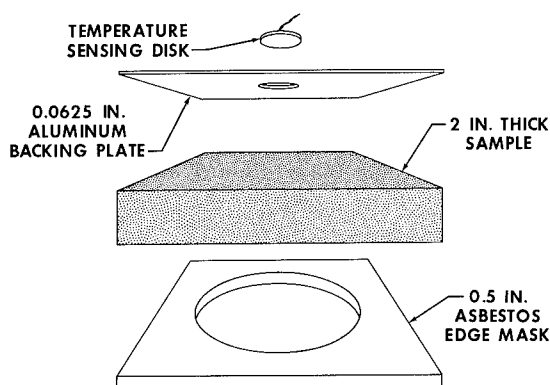


FIGURE 67.—Sample foam assembly.

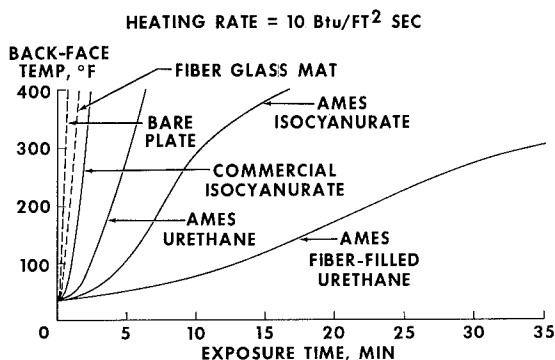


FIGURE 68.—Performance of various fire-retardant foams in JP-4 fuel fire.

tional polyisocyanurate foam presently available. Even the Ames-modified polyurethane foam gives backface temperature-time histories equivalent or better than the conventional polyisocyanurate foam. The major reason for the poor showing for the conventional polyisocyanurate foam is that deep fissures develop during thermal test. Application of the backplate or support plate to the conventional polyisocyanurate foam results in catastrophic thermal-stress failure, which is characterized by the loud sounds heard during tests. The rapid temperature rise for conventional isocyanurate foam results when fissures progress directly to the temperature-sensing disk area. Apparently, better performance results from samples in which fissuring progresses to the backplate adjacent to the center disk but not directly over the disk. Because the disk is shielded from

the backplate, the temperature is not a true representation of the substrate temperature and is not shown in the figure. Even though Ames urethane foam has a char yield less than the conventional polyisocyanurate foam, it may be seen by the plot for backface temperature as a function of time that the Ames material is better than the conventional polyisocyanurate foam because of the superior char integrity of the Ames polyurethane. Therefore, it is significant that a high char yield must be obtained and that char integrity is necessary for sustained thermal protection.

The physical properties of the modified polyisocyanurate foam are tabulated in table L. The data require little comment other than to note the favorable properties of the polyisocyanurate foams. The tensile and compressive properties of the polyisocyanurate are superior to the Ames polyurethane foam. The most significant feature of the polyisocyanurate foam is the increased times to reach a specific back-face temperature.

Many factors enter into the improved back-face temperature-time histories of the foam composites. These are reradiation from the frontface surface, transpiration cooling, thermal conductivity, endothermic decomposition, and surface recession and thermal conductivity. These factors were improved in the modified polyisocyanurate foam, as indicated by the higher char yield and integrity and lower thermal conductivity, resulting in longer time to reach specific backface temperatures.

NEOPRENE-ISOCYANATE FLEXIBLE FOAMS

To achieve a "nonburning" flexible foam system, Ames modified a neoprene-isocyanate foam by adding a halogenated copolymer, "Saran A," and postcuring the foam to 275° to 300° F to increase char yield; the resulting yield was 38 percent at 1000° F. These foams were tested ballistically in assemblies such as the one in use at Wright Patterson Air Force Base (fig. 69). The internal reticulated foam is present to reduce hydraulic "ram effect" and internal ullage explosions.

TABLE L.—*Physical Properties of Ames Urethane and Isocyanurate Foams*

[Test conditions—75°±2° F,
50±2 percent RH]

Physical properties of Ames urethane and isocyanurate foams	ASTM method	Ames urethane	Ames ICU
Nominal density, lb/ft ³	(D 1622)	2.5	2.5 to 2.7
Thermal conductivity:			
Btu-in/ft ² -hr-° F	(C 177)	0.175	0.150
W/cm-° C		0.00025	0.00022
Flame resistance	(D 1692)	Self-extinguishing	Self-extinguishing
Compressive strength:			
Parallel, psi	(D 1621)	25	27
Perpendicular, psi	(D 1621)	15	19
Compressive modulus:			
Parallel, psi	(D 1621)	600	1000
Perpendicular, psi	(D 1621)	360	500
Tensile strength, parallel, psi	(D 1623)	21	30
Shear strength, perpendicular, psi	(C 273)	15	14
Water absorption, volume, percent	(D 2127)	5	3.5
Back-face temperature			
Time to 200° F, sec	Ames T3	210	366
Time to 400° F, sec	Ames T3	390	786

The candidate foam is placed outside the cell between a function plate and the back cell wall. When corrected for off-bore hits, the number of fires per round in the flexible foam is reduced to zero.

FLEXIBLE FOAM FIRE BLANKET

A utility thermal blanket using the neoprene-isocyanate flexible foam was devel-

oped; that is, a 0.5-in.-thick sheet of the flexible foam was placed between two sheets of asbestos, thus forming a sandwich of

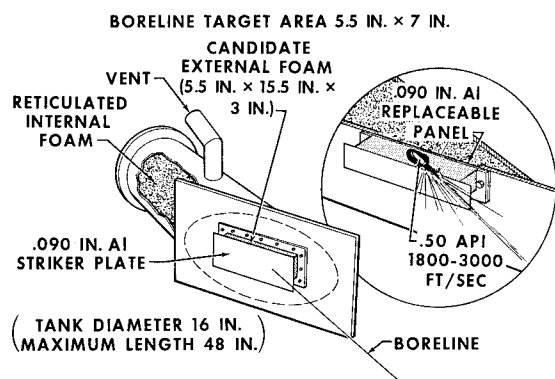


FIGURE 69.—Wright-Patterson Air Force Base test cell—17-gal capacity tank.

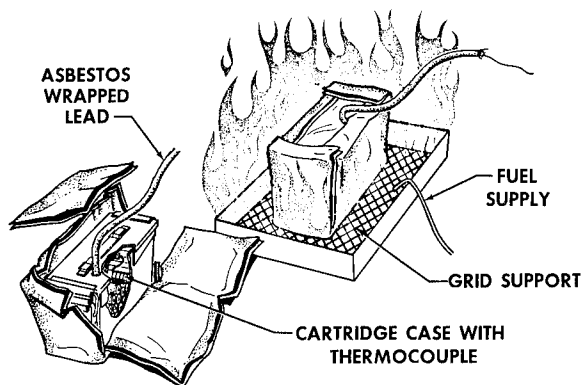


FIGURE 70.—Test of foam blanket to protect ammunition box.

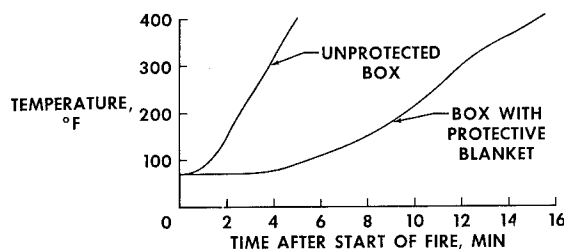


FIGURE 71.—Time-temperature history of caliber .50 cartridge in ammunition box, with added steel weights, JP-fuel fire.

foam in asbestos. This blanket could be placed over stockpiled materials and afford protection in the event of a fire. To demonstrate the usefulness of the foam, an ammunition can was wrapped with the blanket (fig. 70) and immersed in a JP-4 fuel fire. The temperature of the caliber .50 ammunition cases with added steel weights inside the box was monitored, and the results are plotted in figure 71. The temperature-time history for an unwrapped box also is shown on the same plot. Longer protection times could be expected from a blanket draped loosely over boxes of ammunition than for a single box wrapped tightly as it was for this test.

CONCLUDING REMARKS

It has been shown that the use of low-density plastic foams can be modified for use in effective thermal protection systems. Further work in the areas of reduction of flame spread, smoke generation and classification, and toxic byproducts is continuing.

However, it must be emphasized that the effectiveness of many fire suppressant or extinguishing materials lies in the generation of a large quantity of gaseous products. For the most part, these gaseous products range from mildly to severely toxic.

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Intumescence: An In Situ Approach to Thermal Protection

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As a result of the disastrous fires aboard the Apollo spacecraft and on the aircraft carrier U.S.S. Forrestal in 1967, the attention of the Thermal Protection Group at Ames Research Center (ARC), whose previous task was the development of heat-shield materials and thermal-protection coatings for spacecraft, was directed to the study of protecting heat- and fire-sensitive materials in general.

One immediate goal was the development of a means of thermal protection for stored bombs to prevent detonation when the bombs are subjected to the heat of burning fuels. The bombs must be protected for a time that is sufficient either to deploy firefighting equipment or to jettison the bombs. To accomplish this short-time thermal protection, it was desired to coat the bombs with a material that would swell, upon heating, to form a thermally resistant insulating layer. This process or phenomenon of swelling with heat is called "intumescence" (ref. 1).

Many people are familiar with a form of intumescence in the novelty item known as Pharaoh's Serpents. Another example of this phenomenon is the classroom demonstration that is used to introduce the subject of carbohydrate chemistry to college freshmen. In this demonstration, the dehydrating action of concentrated sulfuric acid on sugar produces a voluminous amount of black, low-density, carbonaceous solid.

The use of the intumescent process in the form of coatings to provide thermal protec-

tion for flammable substrates is not new. As an example, such coatings have been applied to cellulosic ceiling tiles for nearly 20 years. Early versions of these coatings made use of a reaction similar to the sugar and acid mixture mentioned previously in that the coatings consisted of a mixture of a carbohydrate, such as starch, as a char-forming material and a dehydrating catalyst, such as ammonium bisulfate or ammonium phosphate, compounded with a binder. Upon heating, these materials initially released ammonia gas, and the resulting sulfuric or phosphoric acid subsequently acted on the carbohydrate to yield the low-density, carbonaceous char, formed by the action of the liberated ammonia and steam (ref. 2). Continuing efforts by chemical and coating manufacturers to improve the intumescent coatings, both in the use as coatings and as thermal protectors, have led to the use of various other carbonaceous substances that usually are drawn from the class of polyols, such as pentaerythritol and dipentaerythritol. Other gas-producing materials and catalysts, such as ammonium polyphosphate, melamine phosphate, phosphoramidate, and dicyandiamide, also have been used in improved versions (refs. 1 to 3). The main drawback to the use of these previously developed coatings has been the lack of long-time stability to outdoor weathering. This deficiency has limited the use of those materials to interior or protected environments. What has been needed is a coating that is able to withstand contin-

uous outdoor exposure—conditions of high humidity, rain, wide fluctuation in ambient temperature, and, for bomb application, exposure to salt spray.

With the advent of new high-temperature and oxidation-resistant polymers, such as polybenzimidazoles, polythiazoles, polyphenoxazines, and polyquinoxalines (refs. 4 to 7), it was suggested that new kinds of char-forming materials might be developed. Such materials could bring about improved intumescent coating systems with high-temperature resistance that also would be nonburning, nonsmoking, and nontoxic, if a method could be found to make thermally these polymers in place. A general and idealized sequence of reactions required to obtain stable heterocyclic polymers (in sufficiently low density to be useful) formed by the process of intumescence is shown in figure 72. The approach for this research was the selection of monomers or prepolymers that are stable to at least 300° to 350° F and that thermally react at temperatures greater than 390° F to give the thermally and oxidatively stable, aromatic, heterocyclic polymers. During the process, the evolution of some and the partial retention of a fraction of the gases that are byproducts of the condensation polymerization should form a low-density foam in situ. As indicated in figure 72, the polymerization reaction must proceed through a molten phase to secure the desired degree of plasticity during the expansion. To obtain efficient

thermal protection, the polymerization and expansion reaction should occur preferably in the direction of the applied heating. Another important requirement of this polymerization process is that a sufficiently high degree of polymerization be obtained by the time the expansion is completed to obtain a mechanically coherent foam structure that will not collapse.

To secure a low thermal conductivity, the foam obtained by this process should be predominantly, closed cell and of low density. The possibility should exist to select monomers or prepolymers that polymerize to give off gaseous byproducts that, in addition to effecting the foaming of the polymer, can diffuse into the flame boundary to block convective heat transfer (ref. 1) and interact with and suppress free-radical chain carriers that are characteristic of the flame-propagation process.

APPLICATION OF THE REACTIONS OF SUBSTITUTED NITRO-AROMATIC AMINES AS INTUMESCENT MATERIALS

The formation of voluminous, black, spongy foam from the action of heat on a mixture of sulfuric acid and p-nitroacetanilide had been described by Alyea (ref. 8). In the study made at ARC, a number of variously substituted nitro-aromatic amines were examined for intumescent properties (fig. 73).

As indicated in figure 73, the expanded black polymer was formed from both o-nitroanilines and p-nitroanilines, as well as from substituted derivatives. These materials gave excellent expansion of 70 to 240 times the original volume. The process was found to occur within a temperature range of 390° to 500° F. Acetylation of the amino group did not seem to affect the intumescent process. It was observed qualitatively that the resultant dark polymeric foam was extremely resistive to the erosive action of an intense hydrocarbon gas flame. Originally, the belief was held that this intumescent reaction of nitroanilines could be caused only with concentrated sulfuric acid; however,

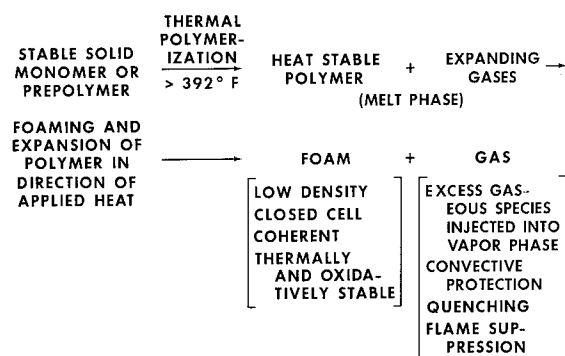


FIGURE 72.—General sequence of reactions producing intumescence.

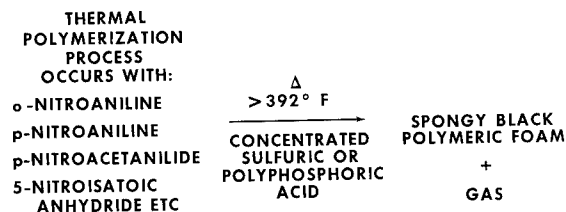


FIGURE 73.—Intumescent reactions of substituted nitro-aromatic amines.

subsequently, it was found that the use of concentrated phosphoric and polyphosphoric acids also promoted the reaction.

The observation of the effect of heat and sulfuric acid on p-nitroaniline led quickly to the development of the associated bisulfate salt as a dry compound, which is useful as an intumescent agent. This compound was prepared easily from inexpensive, readily available materials. The preparation and properties of this material are shown in figure 74 (refs. 9 and 10). Upon heating the p-nitroaniline bisulfate to temperatures greater than 430° F, a yield of black foam of approximately 50 to 54 percent by weight is obtained that is stable to temperatures greater than 1020° F.

To investigate in detail the reactions that occur during intumescence, three analytical techniques were used. Thermogravimetric analysis (TGA) of the weight loss of a sample of p-nitroaniline bisulfate was made, elemental analysis of the thermally reacted material was obtained, and, in a separate experiment, the kinds of gases produced were determined by gas chromatography.

An 8-mg sample of the p-nitroaniline bisulfate described previously was heated in dried, deoxidized nitrogen at a rate of 5.4° F/min. The weight loss was determined by means of a Cahn recording electrobalance and plotted as a function of sample temperature (fig. 75). The empirical formula for the initial salt can be written as shown at the right of figure 75. The theoretical weights that correspond to the thermolytic process also are shown. Three distinct and sequential reactions can be seen to occur in going from room temperature to 430° F, at which point,

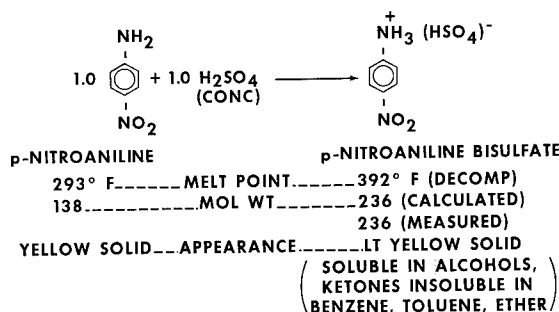


FIGURE 74.—Synthesis and characterization of intumescent intermediate p-nitroaniline bisulfate.

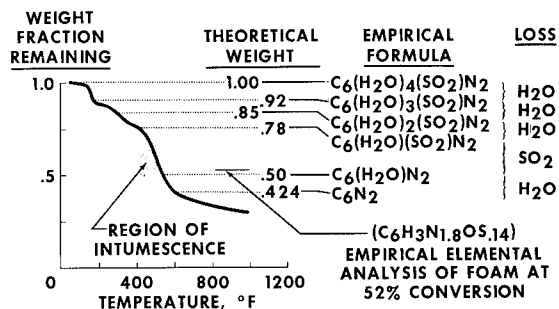


FIGURE 75.—Typical TGA of p-nitroaniline bisulfate (5.4° F/min in N_2).

a sudden intumescence is initiated. The weight loss associated with each of these three distinct processes is equivalent, on a mole basis, to the loss of one molecule of water. This loss produces a change in the composition of the residue material as indicated in the empirical formulas at the right of the thermogram. The water produced during this induction phase (that is, before intumescence) does not contribute to the foaming process but rather is injected directly into the adjacent gas boundary. As indicated in the thermogram, intumescence occurs at temperatures greater than 450° F with elimination of sulfur dioxide, and more water is eliminated at temperatures greater than 600° F.

Chromatographic analysis of the gases eliminated during the intumescence confirmed that sulfur dioxide and water, both good flame quenchers, were produced. Elemental analysis obtained on the black intu-

<u>C</u>	<u>H</u>	<u>N</u>	<u>S</u>	<u>O</u>
59.65	2.51	20.77	3.64	13.43%

WHICH CALCULATES TO GIVE AN EMPIRICAL FORMULA:

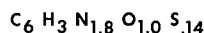


FIGURE 76.—Elemental analysis of black intumesced polymeric foam formed from p-nitroaniline bisulfate at 482° F.

mesced foam that was formed at 482° F was obtained as shown in figure 76. The analysis indicates that nearly all the sulfur is lost and all the nitrogen is retained.

Coatings were prepared using the p-nitroaniline bisulfate compound as the intumescent agent. The coatings performed quite well in the proper environment, as will be described subsequently. However, because of the nature of the material (salt of a weak base and a strong acid), it was easily affected by the presence of moisture, giving an extremely acidic milieu that both affected the vehicle in which it was combined and corroded metallic substrates upon humid exposure. To circumvent these deficiencies, other intumescent agents were desired that were neither easily hydrolyzed nor acidic.

One of the primary reactions between sulfuric acid and nitroaniline is sulfonation of the ring. By keeping mixtures of these ingredients at temperatures below that of intumescence, fair yields of p-nitroaniline-o-sulfonic acid were prepared, isolated as an almost white powder. This compound was found to intumesce quite easily at 450° F and to give char yield of 50 percent. The product of intumescence resembles and is similar in analysis to the materials obtained from p-nitroaniline bisulfate. The ring sulfonation in this second compound overcame the problem of hydrolytic stability encountered with p-nitroaniline bisulfate, but the problem of acidity remained. It was found that the ammonium salt of this sulfonic acid also would intumesce, but at a somewhat higher temperature (572° F). This material is prepared easily from the commercially

available sodium salt by reaction with ammonium chloride. The TGA of this material is shown in figure 77.

The intumescent reaction of the p-nitroaniline-o-sulfonic acid, or the associated ammonium salt, is not discussed in this report. However, the sulfonation of the aromatic ring is probably not a necessary step in the intumescent reaction, and the ring-substituted sulfonic acid actually acts as an in situ source of sulfuric acid when this compound is heated. Thus, the reaction is similar to that of p-nitroaniline and sulfuric acid.

Continuing research into the reactions of nitrogenous aromatic compounds has produced two other intumescent systems of interest. These systems are bis-(4-nitroanilino)-sulfone that intumesces when heated alone, and p-benzoquinone dioxine that intumesces when heated with concentrated sulfuric or phosphoric acid. In all these types of intumescent reactions, the role of the acid apparently is primarily that of dehydration.

Although it has been speculated that the polymer formed during the intumescence of p-nitroaniline bisulfate may be a ladderized polyquinoxaline or polyphenoxazine (ref. 11), no direct proof has yet been obtained. The materials obtained in the thermal reaction of all these classes of compounds are insoluble in all solvents tried, including concentrated sulfuric acid. Spectroscopic examinations have been inconclusive, and the scissioning reactions tried have, thus far, not yielded fragments that would aid in struc-

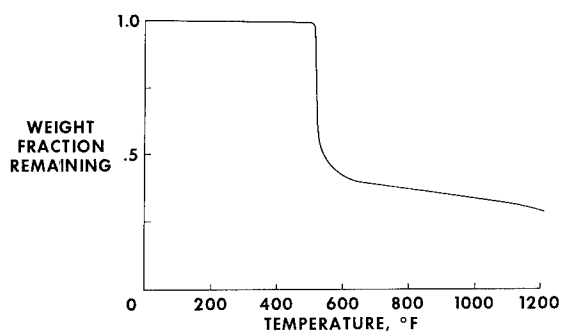


FIGURE 77.—The TGA of p-nitroaniline-o-sulfonic acid, ammonium salt (5.4° F/min in N₂).

ture elucidation. The primary investigative means used has been the elemental analysis of the black materials obtained and has led to the speculation that structures of the products of the thermal reactions are combinations of recurring units shown in figure 78. All structures are derived from the starting materials by addition, dehydration, hydrolysis, rearrangement, and ring closure to varying degrees depending on the temperature to which the material is exposed. These structures are similar to those proposed by Szita and Marvel (ref. 12) and Stille and Freeburger (ref. 13) for polymers derived from more complex starting materials in nonintumescent systems.

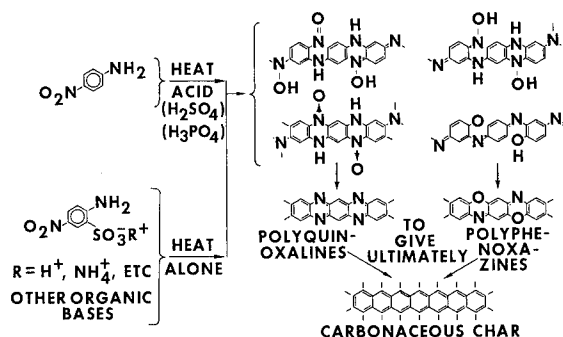


FIGURE 78.—Proposed generalized mechanism for polymerization.

COATINGS

Two intumescent agents described in the previous section, p-nitroaniline bisulfate and the ammonium salt of p-nitroaniline-o-sulfonic acid, were formulated into practical, useful coatings. The key to the successful formulation of these coatings has been the selection of a binder that does not interfere with the intumescent process, is compatible with the intumescent agent, and will not contribute significantly to the flammability of the system. The binder should be either thermoplastic or easily degraded thermally in the same temperature range in which intumescence takes place.

The use of the p-nitroaniline bisulfate salt also required that the binders be relatively

stable to strong acid. Water-based ones that are commonly used in paints were also eliminated from consideration with the bisulfate salt because of their hydrolytic instability. Two binders were selected for use with the p-nitroaniline bisulfate: nitrocellulose and a phenolic resin modified acrylonitrile-butadiene polymer. The formulations are given in tables LI and LII. The formulation using the ammonium salt of p-nitroaniline-o-sulfonic acid is shown as 45B3. This material did not

TABLE LI.—*Void-Filling Thermal Protection Coating*

[Formulation 341]

Material	Weight
Part A	
Nitrocellulose, ethanol-wet (12% N)	8.0
Methyl ethyl ketone	28.6
Part B	
p-nitroaniline bisulfate	43.7
Toluene	19.7
Butyl acetate	19.7

TABLE LII.—*Thermal Protection Coating*

(a) Formulation 410-1A

Material	Weight
Phenolic modified acrylonitrile-butadiene rubber solution	29.4
p-nitroaniline bisulfate	44.0
Cyclohexanone	14.5
Methyl ethyl ketone	12.15

(b) Formulation 453B3

Material	Weight
Part A	
Polysulfide polymer	14.1
Ammonium p-nitroaniline-o-sulfonate	57.0
Methyl ethyl ketone	28.9
Part B	
Epoxy resin, liquid	14.1
Toluene	14.7
Part C	
Tri(dimethylaminomethyl) phenol	2.8
Toluene	2.8

have the rather strict limitations of vehicle selection as with the first salt, because it is neither acidic nor hydrolytically unstable. These coatings were prepared by common paint-making techniques and were suitable for conventional brush or spray application. The air-dried coatings had good initial properties.

TESTS AND POSSIBLE APPLICATIONS OF COATINGS

Measurements in a typical JP-4 fire with free convection showed that heating rates applied to surfaces immersed in such fires are approximately 30 000 Btu/hr/ft², approximately 90 percent in the form of radiation. This fact made it possible to run screening tests on candidate intumescent coatings in the beam of a solar simulator (fig. 79) that is capable of the delivery of 30 000 Btu/hr/ft² to a 2-in.-diam specimen at a distance of approximately 4 in. from the focus.

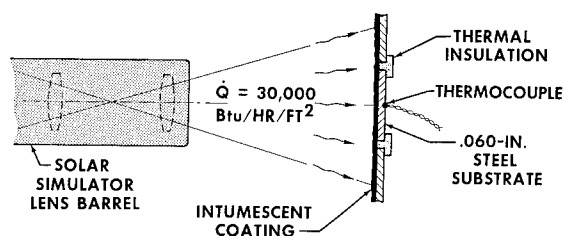


FIGURE 79.—Arrangement for tests of intumescent coatings in solar simulator beam.

This arrangement was used to screen various thicknesses of the intumescent coatings described previously. The spectral distribution of the solar simulator beam, which has its peak in the visible portion of the spectrum, did not match that of the JP-4 fire, which peaks at approximately 2.5 microns; however, the thermal-protection process appears to be independent of this difference in spectral distribution.

Intumescent coating formulation 341 was applied in thicknesses from approximately 0.007 in. to approximately 0.065 in. on a

0.060-in. thick cold-rolled steel substrate. The test specimens, which were 1 in. in diam, were surrounded by thermal insulation to eliminate edge effects, and a thermocouple was mounted on the backface to provide the time-temperature history.

The test of an intumescent coating specimen in the solar simulator beam is more severe than a JP-4 fire for two reasons. Although the average heating rate at the surface is 30 000 Btu/hr/ft², the intumescence causes the surface to grow outward toward the focus where the heating rate is higher. Furthermore, there is a radial energy gradient in the beam, and the irradiance is slightly higher on axis than the average value over the area of the test specimen.

A history of the substrate backface temperature during the test in the solar simulator is shown in figure 80. The bare metal without the coating reached 400° F in approximately 20 sec. On a similar metal substrate with the intumescent coating, the intumescence began within approximately 10 sec and was nearly complete within 20 sec.

The thermal insulation provided by the intumescence caused a much slower temperature rise of the metal substrate. The increasing slope that occurred later shows the effect of the intumescence growing closer to the focus of the solar simulator, where it experiences a much higher heating rate.

The results of numerous tests in the solar simulator beam and in JP-4 fires are given in figure 81. These results show how the time

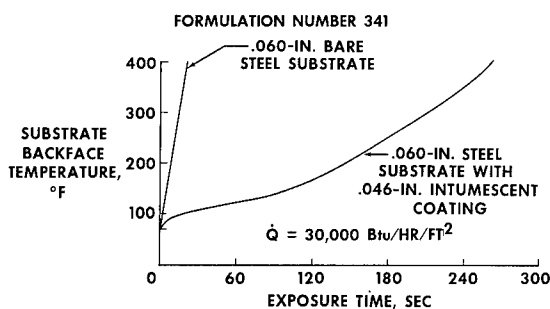


FIGURE 80.—Comparison of bare steel and intumescent coated steel in solar simulator radiation tests (formulation 341).

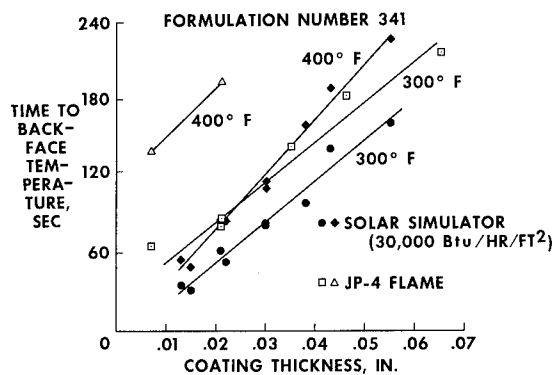


FIGURE 81.—Effect of intumescent coating thickness on back-face temperature rise (formulation 341).

required for the substrate to reach a given temperature varies with intumescent coating thickness. Temperatures of 300° and 400° F were chosen as limits for presenting these data. The relationship is linear, as might be predicted, because the thickness of the intumescence after heating is directly proportional to the thickness of the coating before heating. As can be seen in the figure, the times to reach 300° and 400° F are shorter for the solar simulator tests than for the fuel fires, demonstrating the greater severity of the solar simulator tests.

The fact that the coating formulation 341, using nitrocellulose as the binder, intumesces to give a thick, stable, closed-cell polymer that is highly resistant to heat leads immediately to the possibility of its application in such places as an airplane where fuel lines or hydraulic lines exist in fairly restricted volumes. A fire in such a location would be extinguished if the intumescence filled the available volume. To test this, a simulated section of fuselage was built, and two 2-in.-diam tubes (simulating fuel lines) were installed through holes in the section. This test setup (fig. 82) was 12 in. wide and 5.5 in. deep. The ends and one side of this box were sprayed on the inside with the intumescent coating to a thickness of 0.040 in. A fuel pan containing 200 cm³ of JP-4 was placed under the box, and the fuel was ignited. The fire caused the intumescent coating on the surface to fill the available volume, thus ex-

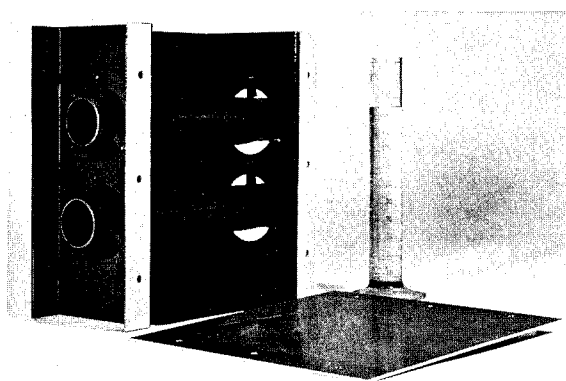


FIGURE 82.—Test setup of simulated fuselage section coated with void-filling thermal protection coating (formulation 341).

tinguishing the fire before 30 cm³ of the fuel had been consumed.

Because of the nature of the p-nitroaniline bisulfate salt and its high loading in formulations 341 and 410-1A, these coatings did not retain good properties upon long exposure to humid environments. The acidity of this salt caused corrosion of metallic substrates and deterioration of the vehicles. However, in certain controlled or protected environments, or if suitably protected by a top coating, the coatings have great utility as just described.

The intumescent coating, formulation 45B3, is composed of the ammonium salt of p-nitroaniline-o-sulfonic acid dispersed in a binder composed of equal parts of a polysulfide polymer and an epoxy resin. After application, the coating has a hard, glossy, abrasion-resistant surface. It has good adherence to the substrate.

The coating has been tested for its effectiveness in protecting a structure from fire. The heating of a 1/16-in.-thick steel plate with and without the protection of the coating is shown in figure 83. The tests were made in a specially constructed furnace that exposed the samples to a controlled JP-4 fire. With no protection, the temperature of the plate rose to 400° F in less than 1 min. When the plate was protected with an 80-mil-thick coating, the heating of the plate to 400° F was delayed for 5 min.

The effect of a high-humidity, high-tem-

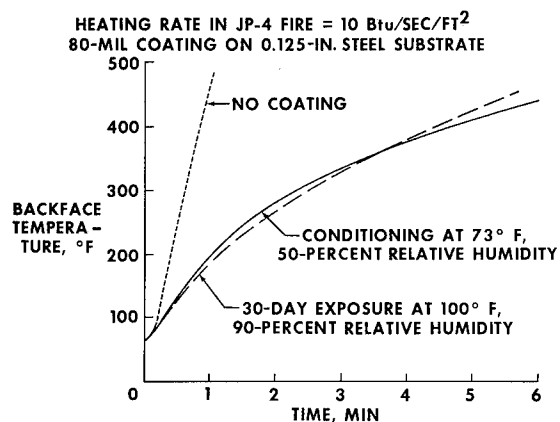


FIGURE 83.—Fire-protective effectiveness of 45B3 intumescent coating.

perature environment on the thermal performance of the coating has been measured. The results of this test also are shown in figure 83. The temperature history of a coated steel plate that had been exposed for 30 days in high humidity (90 percent) at a temperature of 100° F is compared with the temperature history of the coated plate that had been conditioned in the laboratory atmosphere (50 percent humidity, 73° F). The comparison shows that exposure to the humid environment had no significant influence on the thermal protection afforded by the coating. The small difference between the curves is within the limits of experimental reproducibility for this test.

Samples of the coating also have been exposed for a 90-day period to the natural weather conditions on the roof of the laboratory. Coating samples on 3- by 6-in. steel plates were placed at a 45° angle above the horizontal, facing south. During the period of exposure, approximately 9.7 in. of rain fell. The coating was darkened by the exposure, but its intumescence was not affected. Figure 84 is a photograph comparing an exposed test sample with a control sample, both of which were heated in an oven to complete intumescence following the exposure. No important difference in the intumescent characteristics of the two samples is evident. The coating thus shows good stability under humid environments for at least a 10-day pe-

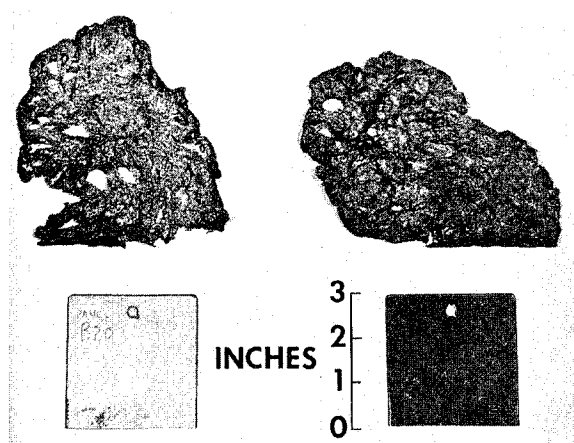


FIGURE 84.—Intumescence of 45B3 coating after 90-day exposure to outdoor environment (coating thickness 40 mils).

riod. Two environmental tests are continuing.

A slightly modified version of the 45B3 formulation was applied to a simulated bomb casing consisting of a section of 5-in. pipe with 0.25-in. wall thickness. The time for the interior wall of the pipe to attain a temperature of 400° C, the critical temperature for the explosive charge, was approximately 8 min. The time for an uncoated section of pipe to reach the same temperature was approximately 30 sec. The intumesced coating appeared to have acceptable char integrity and adhesion, which were better than other coatings tried. A full-scale test using 500-lb bombs is currently in progress.

Many applications of intumescent coatings are possible; for example, on electric motor casings; in fuel and chemical plants and tank farms; and on engine canopies, ventilator grids, and building exteriors. At the present state of development, it is not recommended that these coatings be used in populated or unventilated areas because of the quantities of sulfur dioxide released.

Preliminary specifications for the various coating systems have been established and are available from NASA headquarters.

A research contract has been let to study further intumescent coating systems, especially the relationship of the properties of

several classes of polymers as vehicles, in combination with certain selected NASA-developed intumescent agents. The influence of polymer type, cross-link index, glass transition temperatures, and other properties on the intumescent process is expected to result from such a study.

Other ongoing research within NASA will study the chemistry of intumescence and the synthesis of other intumescent agents, with the objectives of developing materials more suitable for use in viable environments and developing a range of activation temperatures. Another possible result is the use of the intumescent materials as an inexpensive, refurbishable, heat-shield material.

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Session III

CONFIGURATION CONTROL AND MATERIALS APPLICATIONS

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Nonmetallic-Material Configuration Control in the Apollo Spacecraft

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A primary problem confronting configuration management is the difficulty of properly identifying configuration articles. This problem is much more severe for materials configuration management, because the materials normally do not possess a unique usage or identification.

The realization that a formal system of nonmetallic-materials configuration management was required by NASA, because of the high oxygen concentration in the Apollo spacecraft crew bay, resulted in extensive changes to the Apollo Spacecraft Program. For the first time, contractors were required to implement controls to ensure accounting for and assessment of all the nonmetallic materials used in the oxygen-enriched-atmosphere portions of the spacecraft. Previously, industrial practice did not require this rigorous control. The methods employed by NASA to establish configuration control of nonmetallic materials on the Apollo spacecraft are described in this report.

IDENTIFICATION

Contractor-Furnished Equipment

As a first step in the Apollo nonmetallic-materials-control program, joint drawing reviews were conducted to identify materials. The NASA Manned Spacecraft Center (MSC) materials personnel initiated and conducted a drawing and piece-part review of all items that were exposed to the crew bay of the Apollo spacecraft. These drawing

reviews were designed to discover every nonmetallic material that was exposed to the oxygen-enriched environment. To support these drawing reviews, the contractor materials-engineering organization was required:

1. To analyze each nonmetallic material for flammability and toxicological hazards
2. To identify and define the quantity of each material used and to specify the weights and surface areas involved
3. To provide engineering review sheets for MSC approval
4. To provide a subcontractor materials list that had been reviewed and approved by the prime contractor
5. To review and approve all drawings and engineering orders before release

These materials were analyzed for compatibility with the oxygen environment as related to the hazards of flammability and toxicity. An example of the rigor used in controlling nonmetallic materials is the typical case shown in figure 85. At the Critical Design Review (CDR), the crew restraint harness was reviewed, and it was determined jointly by the contractor materials engineers and the MSC materials engineers that the best material available for that application at the time was Dacron. Dacron subsequently was tested, and the test data indicated a burn rate of 0.17 in/sec in 6.2-psia oxygen. Because the MSC flammability requirements for this application specified that the material be self-extinguishing, a deviation was required and was submitted by the contractor

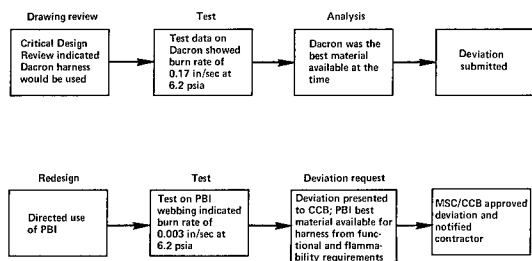


FIGURE 85.—Typical flow for material approval for use in crew restraint harness.

to MSC. In the meantime, another webbing, polybenzimidazole (PBI), had been developed that was reported to have a very low burn rate. Consequently, MSC directed the contractor to replace Dacron with PBI. The PBI subsequently was tested, and the test data indicated a burn rate of 0.003 in/sec in 6.2-psia oxygen. Because of this burn rate, it was still required that a deviation for the use of PBI be submitted for disposition by the MSC Configuration Control Board (CCB). The CCB, the chairman of which is the MSC Apollo Program Manager, consists of top level MSC management personnel. The CCB also is attended by contractor top management. The PBI deviation was reviewed by the CCB, and it was determined that PBI was the best material available with respect to function and flammability. Therefore, the deviation was approved, and the contractor notified officially.

Personnel at MSC continue to review new drawings from one vehicle to the next, and changes to existing drawings also are reviewed. In addition, contractor and MSC personnel review and approve all documents such as discrepancy reports, material reviews, and test preparation sheets to ensure that all materials added to the spacecraft are acceptable and properly documented.

Government-Furnished Equipment

A very important phase of the materials-control program was the Government-furnished equipment (GFE) in relationship to the major contractors. All the MSC organi-

zations supplying equipment were required to review nonmetallic materials in very much the same manner as the major contractors. All materials were identified on engineering worksheets and approved, changed, or deviated.

Ground-Support Equipment

Ground-support equipment used in closed-hatch, power-on tests also was examined in the same manner as flight equipment. The contractors also maintain a current list of approved nondeliverable items that can be used in and around the spacecraft during manufacturing and test, both at the manufacturing plants and at Kennedy Space Center (KSC).

DEVIATIONS

Material configurations requiring deviations are submitted to MSC personnel for processing. To support the request for deviation, the following data are required.

1. Drawings, photographs, and supporting illustrations
2. Material identification and location
3. Weight and surface data
4. Test data
5. Rationale for requesting and approving the material usage

Personnel at MSC review all data submitted with deviation requests and prepare recommendations for presentation to the MSC CCB for disposition.

TESTING

The three levels of testing that were implemented consist of individual-material-screening tests, configuration tests, and full-scale-mockup tests. Full-scale flammability and toxicity tests are performed at MSC. The objectives of these tests are to determine whether, in the event of a fire, the protective measures adopted on the basis of previous testing are sufficient to prevent flame propagation and to ensure that no toxicological hazard to the crew is present.

DATA SYSTEM

During the summer of 1967, a materials-configuration accounting-data system, called Characteristics of Materials (COMAT), was initiated. This data system, which was designed to replace several existing nonmetallic-materials data systems then in use, provides new data elements and flexibility not provided by the previous systems. The COMAT data system provides the following controls.

1. Inventory and status accounting system
2. Management aid in reviewing flammability and outgassing hazards
3. Material change and deviation control
4. Identification of material candidates for priority testing
5. Common data bank of materials test results

Inventory and Status Accounting System

The first consideration was a nonmetallic-materials inventory and status-accounting system. Serious confusion was avoided by implementing a central materials data-processing service at MSC to be used jointly by MSC and the spacecraft contractors. Therefore, it was not necessary for each prime contractor and GFE contractor to develop separate data systems. Also, this concept permits standardization of a coding technique. A typical computerized data print-out for one material usage is shown in table LIII. The trade name, manufacturer's designation, and detail part are self-explanatory. "Approval" and "Evaluation" refer to the overall approved code and evaluation code, respectively,

as shown in table LIV. Under the "Evaluation" heading of table LIII are eight possible tests that can be run.

1. Combustion rate
2. Odor
3. Carbon monoxide
4. Total organics
5. Flash point
6. Fire point
7. Electrical wire insulation and accessories
8. Configuration test

"Weight" and "surface area" designate the weight in pounds and the surface area in square inches of this material on this detailed part. "Usage" defines the usage category as defined in table LIV. Other available elements of information are shown in the footnote in table LIII.

The listings from the materials data bank provide a complete base line of spacecraft-materials applications. Applicable drawings are listed. Individual and total material weights and surface areas are summarized by spacecraft; and weight and surface-area changes are tracked from one spacecraft to another. New materials that are introduced on a spacecraft are pinpointed for detailed analysis and testing, if necessary.

The sorting capability of the computer is used to catch inconsistencies not apparent during an individual application review.

Management Aid in Reviewing Hazards

Before the implementation of the materials data bank, no systematic method existed for ascertaining which materials were ex-

TABLE LIII.—Sample Entry in the Central Data System ^a

Trade name	Manufacturer	Detail part	Approval	Evaluation	Weight, lb	Surface area, sq in.	Usage
Teflon, TFE	Du Pont	V36-571740-3	A	AAAA-C	0.052	8.1	B

^a Other data available include part name, major assembly drawing, general identification, quantity per spacecraft, specifications, test data, and evaluation rationale.

posed to the crew bays or knowing how hazardous these materials were. As mentioned previously, each contractor was required to perform a drawing review. Data work sheets were prepared to document all nonmetallic materials that were exposed to the atmosphere of the crew bays. Each material that was recorded on the work sheet was reviewed jointly by contractor and MSC personnel and evaluated in terms of flammability and outgassing acceptability. The work sheets then were submitted to MSC for encoding and processing in the MSC computer. The end product consisted of a set of computer indexes sorted in various ways for easy use by contractor and NASA personnel in the review of open problem areas (e.g., materials requiring deviations) and in the tracking of the final disposition of suspected hazardous applications.

Material Change and Deviation Control

The MSC has established a discipline that requires the materials-engineering organizations to join forces with the design organizations to report the exact materials being used, in addition to materials changes and deletions. Through the enforcement of the new discipline of requiring materials-engineering personnel to approve all design changes involving the use of nonmetallic materials and through the materials data-bank reporting and bookkeeping system, all changes are tracked. Special-materials data-bank listings sorted by evaluation/approval status are used to focus attention on applications requiring deviations. These methods provide assurance that management is aware of materials hazards.

Identification of Material Candidates for Priority Testing

The materials data bank made it possible to establish materials-testing priorities by providing a summary of the weight and surface area of a given material with cross-reference to evaluation status. Weights and surface areas are summarized by spacecraft

number (effectivity) and by subsystem. The subsystem report provides an indication of the materials location concentration, thereby indicating potential candidates for assembly flammability tests. Determination of materials locations also pinpoints the most critical materials requiring testing. An additional materials data-bank report also provides a materials comparison between spacecraft and identifies new materials being introduced into the design. In this way, attention is focused on new materials and the relative hazard of their use.

Common Data Bank of Materials Test Results

The COMAT data system is used as a common data bank to store flammability- and outgassing-test data. The test-data listing can be sorted in a variety of sequences. The two basic sorts are by generic identification and by manufacturer's designation, which are part of MSC-NA-D-68-1, "Nonmetallic Materials Design Guidelines and Test Data Handbook." At present, there are approximately 3200 different material entries that have some flammability testing and offgassing data printed in this report. An important benefit derived from these data is the prevention of duplicate testing, a situation that was known to occur before these data were available. The distribution of reports has served as a communications medium to appraise personnel of the availability of test data and to develop a cooperative program of data exchange.

HARDWARE VISUAL INSPECTION

Another important phase of materials configuration control at the contractor plants is visual inspection of the hardware during the manufacture of each spacecraft. The purpose of these inspections is personal observation of possible materials-usage discrepancies that result from using a previously untested material or from use in an untested configuration. Four planned hardware inspections cover the three major phases of manufacture and just before manned testing in a pure-ox-

TABLE LIV.—Code Keys Used in the Central Data System

Approval		Usage		Evaluation	
Code	Definition	Code	Definition	Code	Definition
A	Acceptable	A	Major exposed materials	A	Tested; meets requirements
D	Deviation requested for present use	B	Special applications and minor exposed materials	B	Tested to nonstandard test requirements; judged acceptable
E	Deviation requested for present use and future designs	C	Suit-loop materials	C	Not tested; established as acceptable by similarity or application
I	Insufficient data to judge acceptability	D	Material application in high-pressure oxygen system	D	Tested; does not meet requirements; deviation requested for present design
Q	Acceptability for use is questionable	E	Material applications in hermetically sealed containers	E	Tested; does not meet requirements; deviation requested for present and future design(s)
R	Rejected	F	Materials in vented containers	I	Tested; insufficient or inconclusive results; evaluation cannot be made
P	Conditionally acceptable pending results of test	G	Material applications in nonflight equipment	U	Tested; does not meet requirements
		H	Materials in uninhabited portions of spacecraft	W	Tested to nonstandard test requirements; judged unacceptable
				Y	Not tested; established as unacceptable by similarity

xygen environment at KSC. The discrepancies noted in these inspections are noted in the discrepancy logbook and corrected before the next inspection, which comes before any hazardous test. In some cases, materials-usage discrepancies result because manufacturing personnel deviate slightly from the drawings. Sometimes during the inspection of spacecraft, marginal configurations are detected that are not obvious at the time of the individual drawing review. In either case, the problem is corrected by reworking the discrepancy or by testing the new configuration for flammability. Each discrepant condition is documented by color photography, and a system is implemented that requires the contractor and NASA resident quality-control stamps as proof of correction. In addition, color photographs are made of the complete crew compartment at each of the manufacturing stages. These photographs are reviewed to ensure that proper manufac-

turing procedures and techniques have been used.

MAJOR MILESTONE REVIEWS

Major program milestones consist of three phases of Customer Acceptance Readiness Reviews and the Flight Readiness Review for each vehicle at these milestones. The Customer Acceptance Readiness Reviews are conducted in the following phases: before systems installation, integrated tests, and spacecraft delivery. The Flight Readiness Review is held before flight. The contractor furnishes a complete materials-summary acceptance document for these reviews, which contains the following:

1. A coded, indented parts list that identifies all parts that add nonmetallic materials to the spacecraft
2. A summary of all outstanding engineering orders
3. A list of all discrepancy reports that

add nonmetallic materials to the spacecraft

4. A summary of all deviations
5. A COMAT material-status print-out
6. A COMAT test-status summary

Personnel at MSC review this total package to assure that all materials have been reviewed, documented, and approved.

CONTROL AT KENNEDY SPACE CENTER

Materials control at KSC is another important aspect of the total materials configuration control. To continue maintaining nonmetallic-materials configuration control on the Apollo spacecraft during rework and testing at KSC, MSC placed a nonmetallic-materials engineer in residence at KSC. This step made possible the real-time review and approval or disapproval of nonmetallic materials for minor changes initiated at KSC for both contractor- and Government-furnished equipment. Major changes are submitted to the MSC CCB for disposition. The materials engineer coordinates his efforts with assigned contractor materials engineers for all material changes in the spacecraft. A log of all discrepancy reports, material reviews, and test preparation sheets with appropriate

approval is maintained, making possible the real-time evaluation of materials installed at KSC. This action is supported further by an approved materials list for controlling materials used in and around the spacecraft.

CONCLUDING REMARKS

Strict control over the nonmetallic-materials configuration of each spacecraft is exercised at every stage of production, from initial assembly through delivery and launch. This program was possible because a materials data system was designed and implemented to maintain the necessary degree of control. The results have produced significant material breakthroughs and benefits both to NASA and to industry. Perhaps most significant is the fact that a closed materials-configuration loop providing excellent materials control at all times is available for future program use by Government and industry. Some of the most significant benefits to be realized include sources of flammability and toxicological data, material-design-usage information, information applicable to safety improvement, and information on the use of new materials.

Apollo Spacecraft Nonmetallic Materials Applications

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Since the beginning of manned space flight, development of suitable nonmetallic materials has been a primary NASA concern. The advent of man in space initiated many new and stringent requirements for materials technology. The more significant applications of nonmetallic materials in the Apollo Spacecraft Program are discussed in this paper.

The Apollo spacecraft contains two crew compartments. The command module (CM) supports the complete crew during all mission phases except the lunar descent, the stay on the surface of the moon, and the subsequent rendezvous phase. The lunar module (LM) ascent stage houses two of the three-man crew during these critical mission phases.

COMMAND MODULE NONMETALLIC MATERIALS

In the Crew Compartment

The crew-compartment materials must not constitute fire hazards, outgas so as to cause objectionable odors, or pose toxic hazards to the crew in the relatively closed ecological system of the Apollo spacecraft living quarters. Crew-compartment materials must meet many special requirements related to odor, outgassing, and flammability because of the immediate proximity to the crew. Both special screening and vehicle-level tests were conducted to ensure the acceptability of the nonmetallic materials. A view of the CM crew compartment is presented in figure 86.

Electrical wire harness—The electrical-power wire harness (fig. 87) used in the CM

is enclosed in a metal cable tray. The purposes of the metal tray are to protect the wire harnesses from damage during the fabrication and operation of the CM and to en-

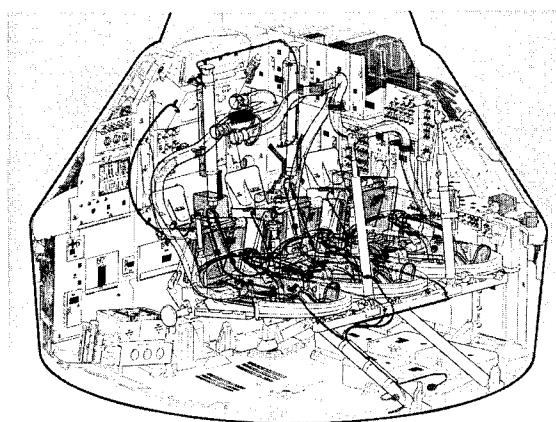


FIGURE 86.—Command module crew compartment.

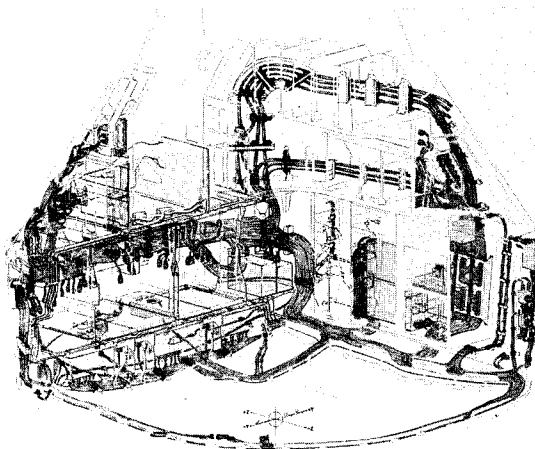


FIGURE 87.—Crew-compartment electrical harness.

close the nonmetallic materials and thus prevent the spread of fire in the event of a short circuit or other unforeseen electrical problem. Several special requirements must be accommodated. The tray must not present a chafing or short-circuiting hazard. As a result, the harness is enclosed entirely in a Teflon wrap. The wiring itself is Teflon coated and has various types of external coatings. The bundles are tied with Teflon-impregnated Beta-cloth spot ties. Beta cloth, a material used extensively in the crew compartment, is a fiber-glass cloth woven from a special type of glass thread. Because all fiber-glass thread is relatively frangible, most applications subject to crew use must be coated to improve the wear characteristics; thus, Teflon coating is applied to the spot ties. The ties are needed to bind the many wires in a tight bundle. The primary reason for using the Teflon cable and the Beta ties is the prevention of combustion; these materials are completely nonflammable in the 100-percent-oxygen atmosphere of the CM. The Beta-wrapped material is used both in the trays and in the wall clamps to constrain the bundle tightly. Such constraint is necessary because of the acceleration and vibration forces encountered during boost, entry, and landing. Because silicone rubber is flammable in oxygen, the Beta-cloth covering is used as a fire-protective shield to the silicone. The Beta covering made this application of silicone acceptable and permitted use of silicone, which has excellent resiliency, acceptable odor, and outgassing properties in the crew-compartment environment.

Display console—The main display console in the CM contains all controls and displays necessary to operate the spacecraft. Because the solar environment in space causes extreme glare and other lighting problems, good presentation and illumination of the controls and displays is essential to the success of the mission. To accomplish this function in the CM, electroluminescent panels (fig. 88) were developed to an extent not accomplished previously. The primary materials used in electroluminescent panels are plastic (Plexiglas in this case). Because

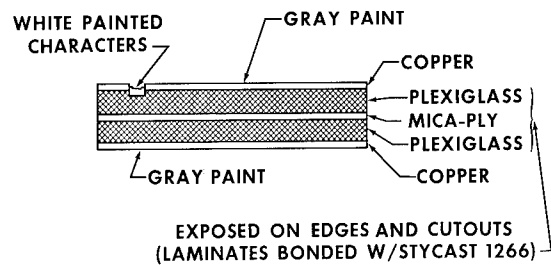


FIGURE 88.—Electroluminescent panel configuration.

Plexiglas is very flammable in oxygen, some special treatment was necessary to eliminate any potential fire hazard. The treatment selected for the CM was the bonding of a thin copper sheet to the Plexiglas. The area of the electroluminescence then was etched to allow the light to illuminate the nomenclature and controls. The entire assembly was painted to assure proper aesthetic and reflective characteristics to ensure readability.

The components used on electrical panels (such as switches and circuit breakers) generally are made of metal or plastic. The plastic is flammable, as are the conformal coatings and terminations on the panel. Rendering these configurations nonflammable without degrading the function was a challenging problem. Because nonflammable substitutes were not readily available, an overcoating process was developed. The overcoating material, which must be nonflammable, covers the combustible material, thereby preventing the access of oxygen and providing a heat sink so that the total configuration is made nonflammable. The coating material used in the CM is Ladcote, which is a combination of several inorganic salts and fillers that can be brushed over the conventional conformal coating or component. Some manufacturing improvements were incorporated in these coating techniques later. One technical improvement consisted of the substitution of a sleeve of nonflammable material around the component. This substitution resulted in a timesaving because only the top of the component must be coated with the Ladcote. Recent work with Fluorel/asbestos material has indicated that this material offers advantages over Ladcote for future applications.

Fluorel is completely nonflammable in air and is nonflammable in oxygen in many applications. Work is being done to develop nonflammable conformal and fire-barrier coatings for future spacecraft. Such coatings certainly have great potential, particularly in the aircraft industry.

Crew-associated components — Fabrics were considered to be a major developmental problem in the Apollo crew compartment. Many applications, such as couch pads (fig. 89), debris netting, stowage bags, and crew garments, require fabrics. A nonflammable substitute was necessary for the more conventional fabrics such as Dacron or nylon. Various forms of Beta cloth principally are used in the Apollo spacecraft. The cloth best suited for this application is a Teflon-coated Beta thread woven into a fabric (ref. 1). The primary problem with any glass fabric is durability, but the individually coated strands of this yarn offer the best available durability. Very-small-diameter fibers are necessary in the glass fabrics because thicker fibers, when broken, can prick and irritate the skin. Careful control of the manufacturing process of the strands is necessary to ensure that terminations of the yarn do not cause skin irritations.

Recently, Teflon fabrics have been used increasingly. These fabrics are softer and more durable against fiber breakage than Beta cloth. Teflon is flammable in some applications but is nonflammable when some slight heat sink is provided. Teflon is nonflammable

in air and certainly should be considered for such specialized nonspace applications as race-car drivers' and firemen's uniforms where nonflammability and durability are desired.

Early in the Apollo Program, a silicone-glass flexible laminate was used for the air ducts that provided postlanding ventilation. Later, a substitute Fluorel-glass flexible laminate was developed that is completely nonflammable and that affords essentially the same functional properties as the flammable silicone-glass laminate.

Rigid fiber-glass laminates were used for such items as food boxes, panel enclosures, wiring chafe guards, etc. The food box (fig. 90), which contains the crew's food, is molded to fit the contour of the spacecraft to make the maximum use of available volume. After an extensive evaluation of polyimide laminates, it was determined that careful control of resin content essentially would eliminate flammability while allowing good molding and structural properties to be retained. The polyimide fiber-glass laminate has the typical appearance and characteristics of any glass laminate. This material, however, is completely nonflammable (ref. 2). Several industrial firms have indicated interest in this material because a considerable reduction of fire hazards in the crew and passenger areas can be achieved for a relatively small difference in cost.

Another interesting CM application is also shown in figure 89. Early in the Apollo Program, a Dacron harness was used to restrain the crew in the couches during launch, entry,

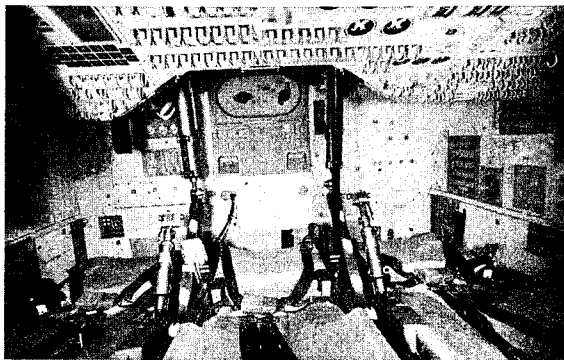


FIGURE 89.—Crew couch and restraint harness.

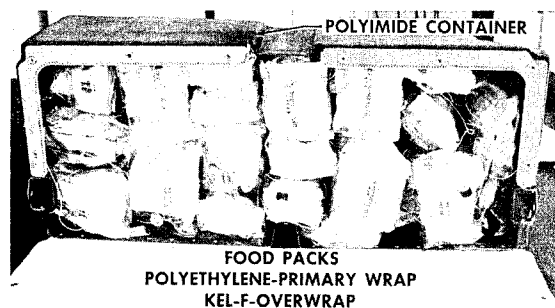


FIGURE 90.—Food container.

and landing. Because Dacron is very flammable, Beta cloth was considered as a substitute; however, the limited durability of Beta cloth and the high-strength requirement of the restraint system eliminated this candidate. Personnel of the U.S. Air Force developed a new material called polybenzimidazole (PBI), which was evaluated for this application. The PBI fabric is completely nonflammable in air and almost nonflammable in oxygen; only a smoldering combustion can be supported.

Velcro fasteners posed another problem. Since the inception of manned space flight, extensive use has been made of Velcro-type fasteners because of the zero-g environment. Velcro retainers allow the crew to stow and remove various personal items quickly. The conventional materials used for these fasteners (nylon and polyester) are, however, very flammable in oxygen. A new Velcro pile material, which consists basically of etched Teflon pile with a Beta-cloth backing, and a polyester Beta-cloth hook material were developed (ref. 3). The pile material is completely nonflammable in oxygen, and the hook material is almost nonflammable. Because of the slight flammability of the hook material, most applications are in items that normally are stowed in fireproof containers. These two new materials offer essentially the same functional properties as the more flammable predecessors and certainly should be considered for future industrial use.

Another interesting material used in the CM is a water-base gelatin contained in a portable fire extinguisher (fig. 91) developed by Manned Spacecraft Center personnel. This material is pressurized by Freon propellant and can be foamed in the CM equipment compartments in the unlikely event of an on-board fire. Unlike many other fire-extinguishing materials, this nonconductive foam can be used on electrical fires. The foam, which can be made in varying densities and with varying extinguishing properties to suit the specific purpose desired, could be manufactured in shaving-cream-type cans and certainly must be considered as having non-space applications.



FIGURE 91.—Command module fire extinguisher.

External to the Crew Compartment

The thermal insulation used on the CM is a fiber-glass compound that has extremely good thermal properties, is lightweight, and can withstand high temperatures. This material is used between the ablative heat shield and the aluminum pressure vessel of the CM. Silicone sealers are used to seal the edges. This material has been used in certain industrial high-temperature insulation applications. The shiny surface on the exterior of the CM ablator is a thermal coating. This coating was developed to provide for various critical thermal properties needed to maintain comfortable temperatures in the CM and to obtain the desired optical characteristics. Paint did not provide the required properties and posed certain problems; therefore, an

adhesive-backed tape was developed. This material is a Kapton substrate with vacuum-deposited aluminum to provide the thermal properties. This extremely reflective material offers potential advantages for dwellings and buildings in extremely hot or cold regions on the earth.

The superinsulation material used in the service module (SM) is shown in figure 92. This material, aluminized Mylar, is used in multilayer blankets in which the extremely reflective properties inhibit the heat flow and form a very efficient radiation barrier. Although relatively inefficient in a pressurized environment because of convective effects, the material has some application in earth-based cryogenic containers in which the material is used in evacuated enclosures.

Another interesting SM material is the white paint used on the radiators. This paint reflects incident heat in an extremely efficient manner. One problem with any white paint is stability in a continuous solar environment; however, considerable improvement has been achieved as a result of space research. This particular paint is an inorganic compound—zinc oxide and potassium silicate. Although the paint is extremely stable and can be air cured, the substrate preparation is

critical. Potential nonspace applications would include house paint in which cooling and heating requirements can be reduced substantially by proper coating of the building exteriors.

LUNAR MODULE NONMETALLIC MATERIALS

In the Crew Compartment

A view of the LM crew compartment is shown in figure 93, which depicts some distinctive nonmetallic-materials applications.

Electrical components—The LM wire harness does not require the large clamps, cover trays, extensive cushioning, and wrapping needed in the CM. Most LM electronic equipment is external to the pressurized compartment; therefore, considerably less wiring requires protection. In addition, because the LM is not required to survive the high g forces of entry and landing, the bulk of the wiring restraints can be lessened appreciably. Because the LM lands on the moon, the payload consists of a proportionately greater quantity of propellant, with the result that a much greater incentive for weight saving is realized. The LM wiring is similar to that of the CM, as are the tie cords. The LM, however, uses Kapton-coated wiring more extensively than the CM, in which Teflon insulation is used primarily. The two types of wiring are functionally very similar. The clamps, however, are small metal clamps with Teflon or silicone padding to prevent abrasion. The silicone will burn slightly. Although such a fire would be quite localized, it could propagate to adjacent areas. Most of

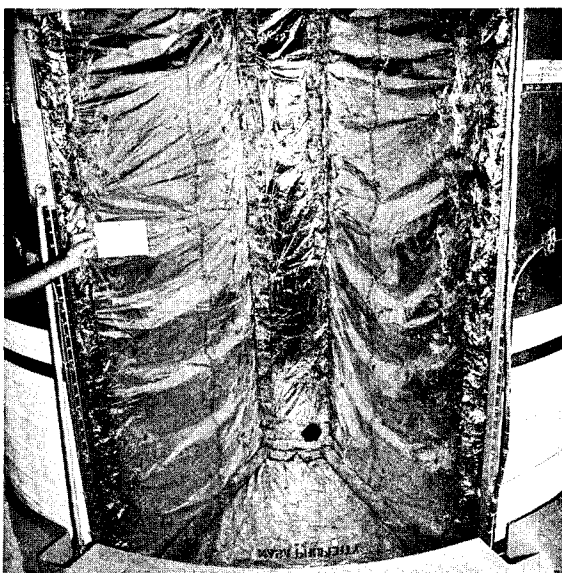


FIGURE 92.—Superthermal insulation in SM.

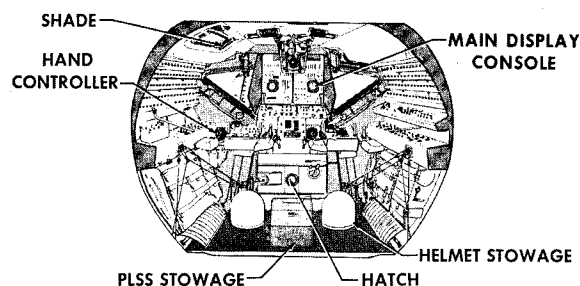


FIGURE 93.—Lunar module crew compartment.

the clamps in the current design of the lunar module are Teflon.

The LM electrical-panel design is physically different from that of the CM but essentially the same in concept. The humidity and contamination requirements for the LM are essentially the same as those for the CM; therefore, a conformal coating material similar to that previously discussed is used. Similar flammability problems also are encountered and can be solved in two ways. Flammable circuit breakers and switches are covered with Beta-cloth booties, which eliminate fire-propagation hazards. An inorganic coating called Melcoat IIA is applied over some conformal-coating applications when bagging is impossible. Although this material also effectively prevents flame propagation, it is brittle and, therefore, vibration sensitive.

Because of the presence of flammable Kynar-solder splices, some areas of the harness must be wrapped with a Teflon tape that has a silicone adhesive. The splices are needed to join individual electrical wires in the harness. As shown in figure 94, the flammable Kynar sleeve covers the solder to prevent electric shorts. Sintered Teflon tape also is used in certain areas where tighter conformance to the envelope of the wire bundle is necessary. Considerable work has been done in developing process techniques in the Apollo Program. Such process-development

techniques are certain to have future industrial applications.

Crew-associated components—Because the period of usage of the LM by the crew is shorter than that of the CM, more soft materials can be used. A typical stowage container consists of multilayer Beta cloth (used, in some cases, with Aclar stiffeners), is nonflammable, and protects the flammable contents.

A sleeping-bag hammock was developed for astronaut use during the lunar-surface stay. The hammock is made of Beta cloth, and the restraint straps are made of the higher strength, more durable PBI. As indicated previously, this material is only slightly flammable. Because the crew would be asleep when this material is exposed, the PBI must be protected from possible incipient fires. Therefore, the straps are covered with sleeves made of a nonflammable Teflon-coated fiber glass. Teflon tape also is used extensively in the LM. This tape is used not only for abrasion protection of the wiring harness but also for fire protection because the tape will not burn.

Large areas of debris netting are used in the LM in lieu of the metal closeout panels of the CM. The netting is needed to prevent the deposition and accumulation of trash in remote areas, a situation that could lead to the cutting or chafing of wiring and result in electric short circuits. Early spacecraft used an extremely flammable nylon-type netting that could propagate a fire. A substitute Beta-cloth yarn was found to be quite frangible and of limited endurance. Eventually, use of the super Beta- or Teflon-coated yarn resulted in far superior endurance. A Teflon filament that has been knitted to form lightweight netting has been developed recently and may be used in the future.

Another area of intense interest in Apollo materials development is paper for printed matter. A major breakthrough in flammability properties has been achieved recently with the development of a paper with writing and printing qualities comparable to any commercial paper. This material, however, is completely nonflammable in 100 percent oxy-

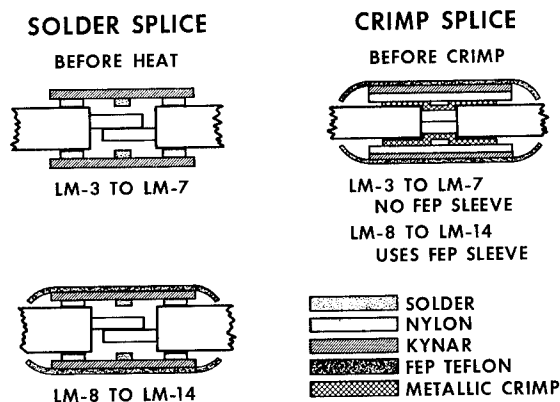


FIGURE 94.—Wire splices.

gen and in air. The paper is not completely qualified at the present time because of a primary deficiency—the brief shelf life. After qualification, the paper certainly will offer great potential for future commercial exploitation both for literary and structural use in which flammability might be a particular problem. Some commercial interest already has been shown in the use of this paper for fabricating building materials and for printing purposes. This material was flown on the Apollo 12 mission for evaluation and may be used more extensively in the future.

Extensive use of fiber-glass laminate panels also is made in the LM, in which a material designated as Trevaro F130 (a silicone-resin-impregnated fiber glass) is used extensively. Three-ply 30006 molded panels postcured for 30 min. at 700° F are nonflammable and have excellent functional properties. This material has potential applications in aircraft where the reduction of fire hazards is certainly feasible. The material also may be used for structural and nautical applications.

External to the Crew Compartment

Some typical wire-harness-insulation installations external to the LM crew compartment are shown in figure 95. Extensive use has been made of silicone-rubber conformal coating, which completely seals and protects all electrical connections and requires no fire protection in air.

The superinsulation material previously discussed is used extensively on the LM exterior. Although the fabrication of the LM structure is quite different from that of the heavier CM, the nonmetallic materials used in the spacecraft are basically very similar.

CONCLUDING REMARKS

Several material developments and design installations were accomplished for the Apollo Program in a relatively brief time with specific efforts to advance the state of the art of nonflammable, nonmetallic materi-

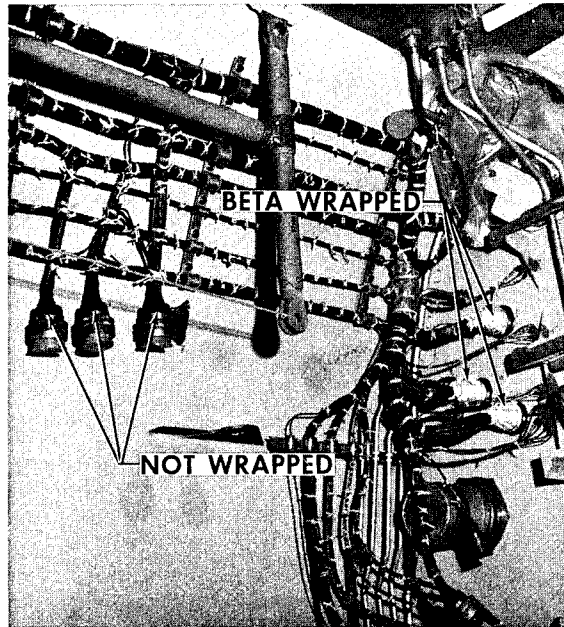


FIGURE 95.—Lunar module electrical connectors.

als. Advances have been realized both in new materials and in new fabricating techniques and materials applications. Several potential nonaerospace applications have been identified. A major byproduct of the Apollo Program is the technical expertise developed by the many dedicated people who have made this program successful. The effect of this knowledge will be realized in all types of industries as the influence spreads.

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The Effects of Gravity on Flammability*

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Until relatively recently, dealing with accidental fires was limited generally to extinguishing fires in the one-g environment of earth. However, the space program disclosed the need to deal with fires in the zero-g conditions of space and also under the conditions of acceleration and deceleration (greater than one g) associated with leaving and reentering the atmosphere of the earth. Thus, the necessity was established to investigate the effects of varying gravitational forces on the combustion characteristics of nonmetallic materials used in spacecraft. Inasmuch as there are many different atmospheric conditions encountered in space exploration, ranging from pure oxygen to oxygen/nitrogen mixtures at pressures of 3.5 to 16.5 psia, it was also necessary that the investigations include a range of atmospheric conditions.

The first zero-g tests were conducted in January of 1964 at Wright-Patterson Air Force Base using aircraft flying Keplerian parabolas, which allowed the flammability characteristics of several basic polymeric materials to be studied at zero-g and near-zero-g conditions for periods of a few seconds. Tests at accelerations of one g or greater can be accomplished much more readily in ground test facilities. During 1967 to 1970, such tests were conducted in a centrifuge at the NASA White Sands Test Facility (WSTF) for a broad range of spacecraft materials.

The purpose of this paper is to present briefly the gross effects of gravity and at-

mospheric conditions on material flammability as determined by the tests. Therefore, the aspects of gravity and atmosphere are considered herein. More detailed information is included in references 1 to 4.

INFLUENCE OF GRAVITY ON FLAMMABILITY

Effects of Weightlessness on Combustion

The effects of zero g on flammability are illustrated in figure 96 which depicts flames in normal gravity (one g) conditions and in weightless (zero g) conditions. As a material burns in one g, the material vaporizes and mixes with the surrounding gases. The resulting chemical reaction liberates energy that heats the unburned sample and the surrounding atmosphere. Convection forces induced by gravity cause the hot, lighter products of combustion to rise from the flame location and be replaced by a new supply of oxygen. The vaporized material mixes with the new oxygen supply and reacts; thus, a steady-state combustion process is maintained. In zero-g combustion, the flame reaches its maximum size and brilliance shortly after ignition. After initial reaction with the vaporized material, oxygen in the immediate surrounding atmosphere becomes depleted because of the absence of convection, and the flame diminishes.

Zero-g airplane flight tests—Beginning in 1964, a two-phase series of tests were conducted to evaluate experimentally the effects of zero g on flammability. These tests were conducted in specially equipped aircraft at Wright-Patterson Air Force Base. Approxi-

*This report was not presented at the conference.

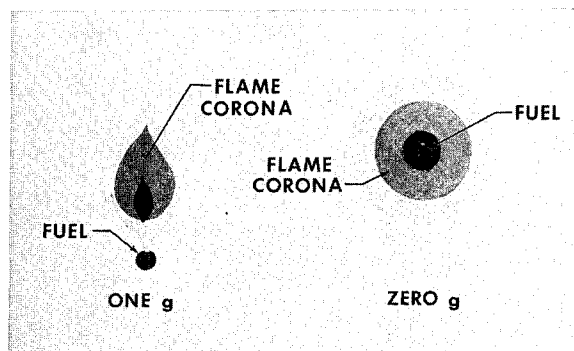


FIGURE 96.—Flames in one-g and zero-g environments.

mately 10 sec of zero-g conditions were available in each parabolic flight. In phase I of the program, tests were conducted with styrene, foam rubber, and paraffin fuels. Test atmospheres were 5 psia, pure oxygen; 14.7 psia, pure oxygen; 14.7 psia, 21 percent oxygen/79 percent nitrogen; and 10 psia, 50 percent oxygen/50 percent nitrogen. Motion pictures of the flames were taken.

In phase II, the burning rates of four polymeric fuels were investigated. Test materials were neoprene, silicone rubber, Teflon, and polyurethane. The test atmospheres were ambient air; 5 psia, pure oxygen; and 15 psia, pure oxygen. Ignition of the fuels in both phases of the tests was provided by a resistance wire closely wrapped around one end of the sample.

Zero-g test results—The ignition characteristics at zero-g appeared to be unchanged from those at one g. As solids burn in zero g, the flame becomes progressively darker and smaller with a spherical or dome-shaped corona after a short interval. Steady-state conditions do not exist after surface combustion has taken place. The flame tends towards self-extinguishment. Combustion propagates very slowly along a surface (approximately 0.1 in./sec for several materials in an oxygen-rich atmosphere), and the rate of propagation is independent of orientation.

Effects of High-Gravity Forces on Combustion

Because a spacecraft undergoes accelerations during launch and reentry, the effects

of such accelerations on combustion characteristics of nonmetallic materials must be considered. Because the convection forces necessary for natural circulation are increased during high-acceleration periods, two possible consequences, or a combination thereof, were anticipated: (1) material combustion may increase as increased circulation provides needed oxidizer at a faster rate, or (2) combustion may decrease as the increased velocity of circulation tends to "blow out" the flame.

To obtain the required data, tests were conducted at WSTF. Materials were subjected to accelerations of 1, 3, 7, 10, and 15 times that of earth gravity in three atmospheres—6.2 psia, 100 percent oxygen; 16.5 psia, 60 percent oxygen/40 percent nitrogen; and 16.5 psia, 100 percent oxygen. Samples were burned in both upward and downward directions, and data were collected.

Test materials—The following 13 materials were tested.

1. Neoprene elastomer
2. Viton-impregnated fiber-glass fabric
3. Urethane foam
4. Adhesive foil
5. Heat-shrinkable Teflon tubing
6. Polyurethane foam
7. Polyurethane coating
8. Silicone coating
9. Silicone-rubber potting compound
10. Polycarbonate
11. Methacrylate
12. Urethane potting compounds (two)
13. Polyester tape

Test description—The tests were performed in a 3.6-ft³ pressure vessel mounted on the 42-in.-radius arm of a centrifuge. The sample-holding fixture was designed to align the major axis of the sample with the acceleration resultant vector. Thermocouples, radiation calorimeters, and total-flux calorimeters were positioned about the test specimens. A pressure transducer and an ambient-air thermocouple were used to monitor the parameters of the test atmosphere. A 16-mm motion picture camera was used to obtain a visual record of the burn characteristics.

Test results at high-gravity forces—The results of testing 13 nonmetallic materials in three different atmospheres (6.2 psia oxygen, 16.5 psia oxygen, and 60 percent oxygen/40 percent nitrogen) at accelerations of 1 g, 3 g, 7 g, 10 g, and 15 g and for upward and downward propagation are presented in reference 3. Although considerable scatter is shown in these data, general trends may be summarized:

1. Flame temperature generally increased with increased acceleration level. In urethane foam, the temperature variation with acceleration was small but was approximately 500° F higher during upward burning than during downward burning. Also, for the urethane foam for 16.5 psia oxygen, the flame was approximately 300° F hotter than for 6.2 psia oxygen or 60/40 oxygen/nitrogen mixture. For aluminum adhesive tape and Teflon tubing, no distinct temperature trends were noted.

2. Propagation rates generally increased with increased acceleration level. For neoprene, the rate at 15 g was approximately twice that at 1 g. Upward burning rates for Teflon were generally very low. Urethane sheet-material rates increased with acceleration, but, unlike other specimens, these rates were higher for downward burning. Viton-impregnated fiber glass showed a decrease, however, in the case of downward burning. Teflon burned downward only in 16.5 psia oxygen at 1 g.

3. Total heat flux increased as flame temperature increased, usually as a function of acceleration and available oxygen, except that for Teflon, the flux varied inversely with acceleration.

4. Combustion products measured were carbon monoxide, carbon dioxide, and total organics. The scatter in the data precluded identification of any specific relationship of products of combustion to acceleration or atmosphere.

The flammability data for cotton cloth in oxygen and other atmospheres containing nitrogen or helium for a range of accelerations are included in reference 4. The results showed that the propagation rate increased with increased acceleration and available oxygen.

CONCLUDING REMARKS

Flammability testing of selected nonmetallic materials at weightless and high-gravity conditions has shown that combustion (propagation rate, temperature, and heat flux) generally increases with an increase in gravity (or acceleration equivalent) for the zero-g to 15 g conditions tested. Combustion is retarded by zero gravity and appears to be strongly influenced by available oxygen.

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Apollo Applications of Beta Fiber Glass

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In the news coverage of the Apollo flights, the terms Beta fiber or Beta fabric have been used in connection with various textile materials in the space suit and crew-bay areas of the command and lunar modules. Beta fiber is a unique material, the usage of which in the spacecraft far exceeds that of any other textile fiber. The purpose of this paper is to describe the physical characteristics of the fiber, to indicate the usages in the spacecraft, and to point out some potential applications in which the fiber may be used to enhance safety in everyday civilian life.

DESCRIPTION OF BETA FIBER

Beta fiber was developed by the Owens Corning Fiberglas Corp. in an effort to impart more durability and comfort to textile products that are made of glass. The chemical structure of Beta fiber is a lattice of inorganic oxides formed at temperatures at which no known organic material could exist. The formation of the fiber requires a great amount of thermal energy. The fiber cannot burn because it is already a product of the oxidation process. It is perfectly elastic. Even when stressed almost to the point of rupture, the fiber will return to its original length. To make a glass fiber yield, the fiber would have to be heated to 945° F. Because of these inherent properties, glass-fiber structures have outstanding dimensional stability—neither heat, moisture, nor physical stresses can cause shrinkage or stretching.

Beta fiber is unique among glass fibers because of its fineness. It is 0.25 denier per filament or 3.8 microns in diam. A compari-

son of cross-sectional areas of textile filaments is illustrative of the fineness of the fiber (fig. 97). Beta fiber is one-sixth the denier of common organic fibers. However, because glass has a much greater density than organic materials, the fineness of the filament is even greater than that indicated by the denier comparisons. For example, in actual area of cross section, a Beta filament would be nine times smaller than nylon, polyester, or viscose. Also shown in figure 97 is the relative stiffness of the fibers. It is known that the radius of bend at rupture varies with the diameter. The small diameter of Beta fiber provides low stiffness values and therefore, the fiber is more flexible, more pliable, and softer.

Some of the other physical characteristics of the Beta fiber glass are listed in table LV. The material exhibits high values of breaking tenacity and tensile strength; however, it should be noted that there are significant

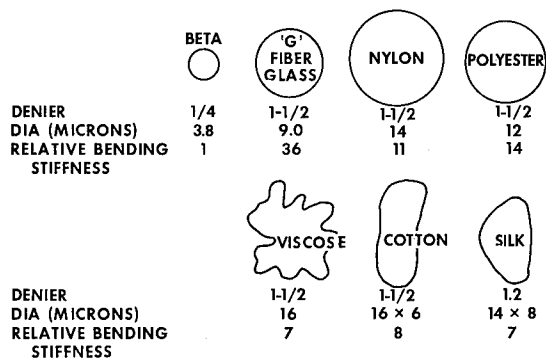


FIGURE 97.—Comparative size and relative bending stiffness of fibers.

TABLE LV.—*Physical Properties of Beta Fiber Glass*

Characteristic	Single filament	Multi-filament
Breaking tenacity, g/denier.....	15.3	9.6
Breaking elongation, percent.....	4.8	3.1
Tensile strength, psi.....	500 000	313 000
Elastic recovery, percent.....	100	100
Average stiffness, g/denier.....	320	310
Specific gravity, g/cc.....	2.5	2.5
Water absorbency, percent (70° F, 65 percent relative humidity)...	None	None

losses in the strength values of multifilament yarns compared with the values obtained with a single filament. This loss in strength is caused by interfiber friction and can be translated in practical terms to the biggest shortcoming of all fiber-glass materials: a relatively low order of resistance to surface abrasion.

SPACECRAFT APPLICATIONS OF BETA FIBER

Interest in Beta fiber started at NASA during the Gemini Program when the first experimental garments were made. At that time, several items for commercial dynamic applications were in various stages of development or evaluation. These items included bedspreads, mattress covers, mattress ticking, tablecloths, and some types of apparel. However, the available commercial finishes were flammable in pure oxygen atmospheres. To overcome this problem, a special silicone finish (F017A) that had low solids add-on was developed. This finish was nonflammable in the spacecraft 16.5-psia pure-oxygen atmosphere. Also, the finish had the same degree of fiber lubricity that was obtainable with the commercial finishes. By the end of February 1967, Beta fiber-glass yarns were selected as the prime textile material in an accelerated program to replace combustible textile materials in the spacecraft. To achieve these objectives, NASA entered into contract with the Owens Corning Fiberglas Corp. At the start of the program, the spacecraft included more than 150 different textile

configurations in the forms of fabrics, tapes, webbings, braids, sleeving, sewing thread, nonwoven pads, filters, and so forth. During the course of this program, the necessary items and configurations that had to be made of Beta fiber were defined, and participating contractors were made knowledgeable on the characteristics and methods of fabricating end-use items with Beta-fiber materials. The adaptation and successful fabrication of the majority of these items in Beta fiber glass is considered a major technical achievement.

A dense 90 by 65 Beta 150 1/0 fabric was engineered and was a good basic fabric for general use in the spacecraft. However, the surface durability of the fabric was not enough for dynamic and semidynamic applications. Therefore, coatings of carboxy nitroso rubber and Teflon were tried to improve this deficiency. Currently, this fabric, with a Teflon coating, is principally used in containers that are designed to hold flammable flight items.

In some instances, thermal protective multilayer covers were devised to protect susceptible items. One example of this protective system is the type of containers designed for the tissue dispenser (fig. 98) and medical kits. For these items, a composite was made that had an outer layer and lining of Teflon-coated Beta fabric, between which are sandwiched two layers of aluminum foil and two layers of asbestos fabric. Even when sub-

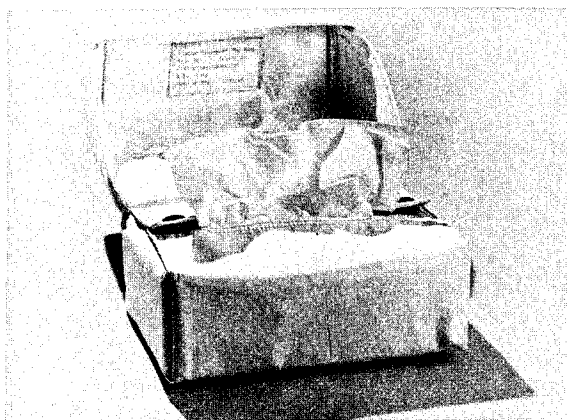


FIGURE 98.—Tissue-dispenser bag.

jected to a flame impingement of 1800° F in oxygen for 8 min., the tissues in the container remained intact.

The oxygen hoses in the spacecraft are made from silicone rubber to ensure the necessary low-temperature flexibility. Fire protection is provided by a covering sleeve that is made from the Teflon-coated Beta fabric. Similarly, bags made from this same material are used to cover circuit breakers and connectors in the electrical systems (fig. 99).

The Teflon coating improved surface durability, but this coating process immobilized the yarns, therefore reducing tear strength. Another special fabric was developed with a 65 by 62 construction in which the individual Beta yarns were coated with Teflon and then woven into a fabric. This process provided a material that had the necessary porosity and tear and puncture resistance to serve as the outer layer of the space suit and other applications.

Lightweight Beta marquisette, in an open-type weave, was developed for use as a spacer between the aluminized film layers that comprise the thermal insulation of the space suit.

Other Beta-fiber structures in the spacecraft include sleeping bags made from perforated Teflon-coated fabric. In addition, Beta-fiber-glass tapes, lacings, and nonwoven felts for pads and filters have been developed. Even the flag and mission emblems on the space suits are printed on a special Beta fabric that has an acrylic finish that is compatible with the print pastes.

The following illustrate the wide variety of end-items that were fabricated for Apollo.

1. Two-pass Beta (DuPont 95-049), Teflon coated

- a. Medical kit
- b. Rucksack
- c. Towel bag
- d. Tissue dispenser
- e. Helmet stowage bag
- f. Suit accessory kit
- g. Life vest assembly kit
- h. Backpack cover
- i. Oxygen hose cover

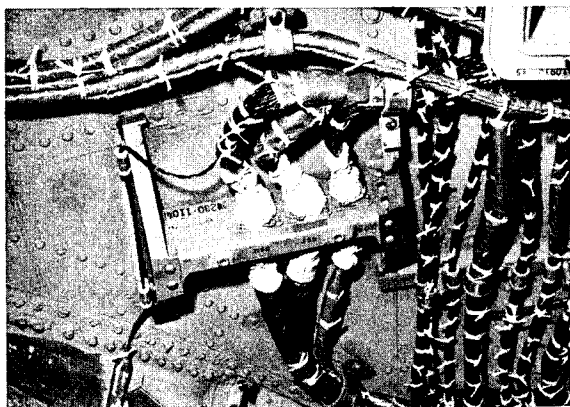


FIGURE 99.—Beta bags as electrical-connector protection.

2. X4484—Beta fabric, Teflon coated yarn
 - a. Outer layer of space suit
 - b. Spacecraft shades
3. Beta marquisette—spacer in superinsulation of space suit
4. Beta cord and webbing—accessories on crew provision and survival items
5. Beta knit (FG-104)—nonflammable spacecraft insulation
6. Beta screen prints
 - a. Mission emblems
 - b. NASA emblems
 - c. Flags
 - d. Nameplates

Beta fiber is also used as the ground weave in Astro-velcro.

CONCLUDING REMARKS

Efforts continue to improve Beta fiber for spacecraft use. Surface durability is adequate for the relatively short-term Apollo missions. However, improvement in this area is necessary to meet service-life requirements for long-term space missions as currently planned in the Skylab Program and future orbital space stations.

To provide increased durability, a finer and more flexible glass fiber is being developed. Also, active research and development programs to modify the chemical composition of the glass are in progress, to change the fiber manufacturing techniques, and to develop improved finishes, all with the objec-

tive of improving performance characteristics. Fabric geometry is being studied carefully, and the Beta fiber is being combined with other fibers to provide synergistic properties that are not obtainable by the use of the component fibers alone. These efforts should lead to more durable glass-fiber textiles for both dynamic and semidynamic use.

Beta textiles are being used as drapes and decorative hangings in homes, hospitals, institutions, public buildings, aircraft, and wherever total nonflammability is required. Fire-protective suits made from Beta are standard equipment at many airports in the United States and Canada. Many famous race-car drivers wear Beta coveralls. Beta fabric is used extensively as a roof material for inflatable buildings. A coated Beta-fabric roof has been erected for the United States Expo pavilion at Osaka, Japan. The U.S. Navy is considering a NASA-developed

fabric for use in decompression chambers for their deep submergence program. Beta fabrics are used for operating gowns and bedding in hyperbaric operating rooms. The development and use of glass fiber is expanding in the area of high-temperature filtration for air-pollution control. The temperatures required by this application make Beta fiber glass a leading candidate.

The use of Beta-fiber-glass materials is bound to expand. Some of the potential end uses that are visualized when durability is increased are: protective work clothing such as military flight coveralls; fuel and ammunition handlers' garments; fire-fighters' clothing; flameproof bedding for hospitals, hotels, and institutions; textile materials for overhead and wall coverings; upholstery and floor coverings for public transportation, and many fire-safe fabrics for use in the home and industry.

Apollo Space-Suit Materials

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The space suit constitutes a major part of the exposed nonmetallic materials in the Apollo spacecraft. Because potential ignition sources inside the suit are well understood and controlled, the principal effort in increasing the fire safety of the space suit has been directed toward the development and selection of materials exposed to external ignition. The three Apollo crewmen are provided with essentially the same basic suit configuration. However, the suits of the two crewmen who conduct the lunar exploration include certain additional features and materials adaptations necessitated by the more severe environment of the lunar surface. Therefore, a detailed discussion of the Apollo 14 lunar space-suit is presented in this paper.

LUNAR SPACE-SUIT DESCRIPTION

The Apollo lunar space suit consists of the identifiable subassemblies described in the following paragraphs.

Integrated-Thermal-Micrometeoroid Garment

The integrated - thermal - micrometeoroid garment (ITMG) is illustrated in figures 100 and 101. This garment forms the outermost portion of the space suit and, therefore, must protect against any potential ignition sources. Other functions of the ITMG are to protect the crewman from the thermal extremes of the environment, to protect against micrometeoroid bombardment, and to reduce wear on the pressure-retention portion of the suit. For these functions, a combination of

several materials is used. The outermost continuous layer of material is nonflammable Beta fabric, and this layer has patches of Teflon fabric attached to protect areas of high abrasion. The Teflon fabric is slightly flammable when used alone in pure oxygen;

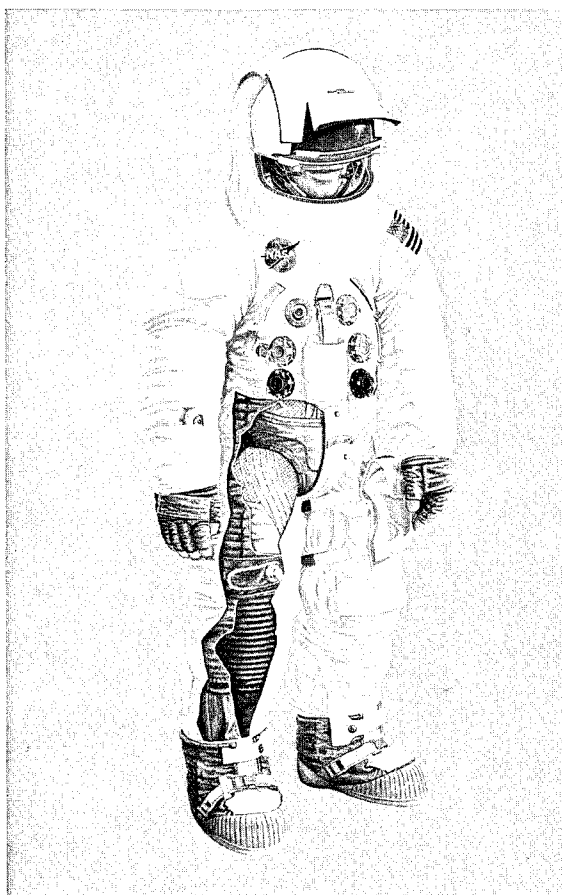


FIGURE 100.—Apollo lunar space suit.

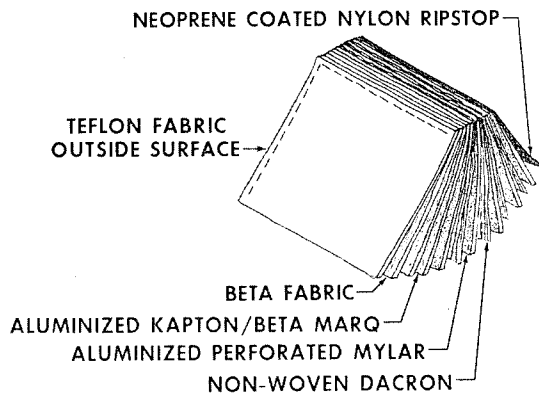


FIGURE 101.—Layup for integrated-thermal-micrometeoroid garment.

however, it does not present a combustion hazard when placed in small, isolated patches in direct contact with Beta fabric because the Beta cloth provides a heat sink and thus prevents continuous burning. The insulation requirement of the ITMG is satisfied by a multilayered composite called superinsulation. The first two layers, composed of 0.5-mil Kapton/Beta marquisette laminate, act as flame retardants as well as radiation shields. The remaining insulation layers are made of 0.25-mil aluminized Mylar radiation shields with nonwoven Dacron spacers. Dacron is more durable than the Kapton/Beta material but is more flammable. The aluminized Mylar can be used in this case because of the fire protection derived from the outer flame-resistant layers and because of the lack (or restricted supply) of oxygen between these insulation layers. The last layer of the ITMG layup, neoprene-coated nylon ripstop, when used in conjunction with the other layers, provides protection from micrometeoroids. This latter layer also is flammable, but it is protected from external ignition by the other layers of the ITMG.

Pressure Garment Assembly

The pressure-garment assembly (PGA) is the pressure-retention layer that encapsulates the torso, arms, legs, and feet. There are two major assemblies, one covering the

torso, arms, and legs and the other covering the feet. The torso, arm, and leg assembly is shown in figures 100 and 102, and the PGA boot, which completes the PGA, is shown in figures 100 and 103. The torso, arm, and leg assembly is fabricated from neoprene-coated nylon cloth, except for the elbows and knees, which have special dipped-neoprene convolutes with an integrated restraint system. The neoprene-coated nylon cloth that constitutes the pressure bladder is covered with a layer of nylon cloth to prevent the bladder from expanding under differential pressure. A Nomex liner is installed inside the assembly to prevent damage to the pressure bladder, to provide crewman comfort, and to facilitate donning of the suit. These three materials are flammable but are protected from external ignition sources by the ITMG. The PGA boots use the same cross section as the torso, arms, and leg assembly except that the bladder is dipped neoprene without cloth reinforcement. A layer of tricort is located in the sole and up one side between the bladder

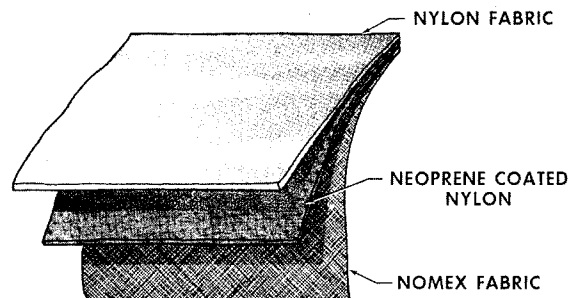


FIGURE 102.—Layup for pressure-garment assembly.

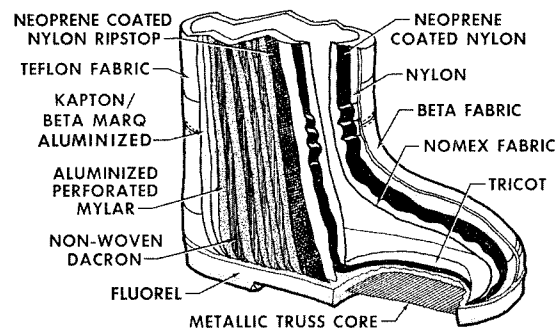


FIGURE 103.—Pressure-garment-assembly boot.

and liner to permit ventilation. The external sole is composed of a fluorocarbon elastomer with a metallic truss core to provide unidirectional flexibility. The external sole is flame resistant, and the other materials are protected in the same manner as the torso, arm, and leg assembly.

Liquid-Cooled Garment

The liquid-cooled garment (LCG), shown in figures 100 and 104 is a special set of long underwear covering the torso, arms, legs, and feet. The basic garment is made of Spandex, similar to foundation-garment materials, except for the socks, which are cotton. Spandex, although flammable, has no ignition source present and is used because of its elasticity. The primary purpose of the Spandex is to maintain direct contact of the Tygon-tube network (which circulates cooling water) with the body of the crewman. This garment covers the crewman's torso and limbs with cooling tubes and is lined with a very lightweight nylon fabric to assist in donning and to prevent interference between the cooling tubes and the limbs of the crewman.

Extravehicular Gloves

The extravehicular gloves, shown in figures 100 and 105, cover the crewman's hands and provide thermal protection, abrasion protection, limited flame protection, and pressure retention, with minimal restriction to the natural hand movement. The outer layer of the glove provides the abrasion and limited flame protection. Two of the three materials used in this layer, Beta cloth and Chromel-R metallic fabric, are nonflammable; the other material, silicone rubber, is flammable, but no other Silastic material is available that remains usable at temperatures for less than -100°F and continues to provide the desired tactility and dexterity. The silicone forms a very small portion of the glove and, therefore, presents an insignificant fire hazard. The insulation layup consists of Mylar radiation shields and

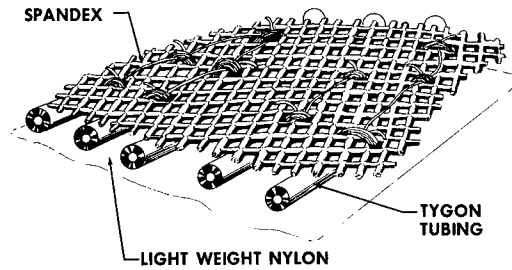


FIGURE 104.—Construction of liquid-cooled garment.

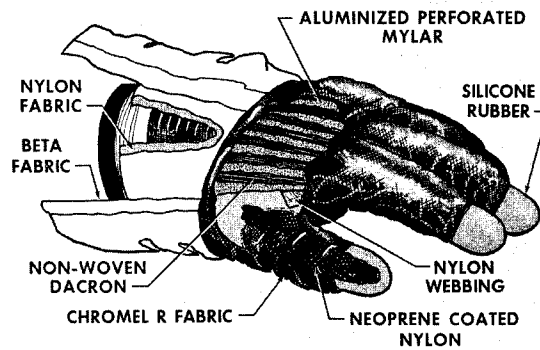


FIGURE 105.—Lunar extravehicular glove.

Dacron spacers. These materials are flammable but are protected by the covering materials. Kapton is not used in the glove construction because of its lack of durability. The glove pressure-retention bladder is constructed by dipping a mold into neoprene rubber, installing a thin nylon restraint layer shaped like the mold, and dipping again until approximately 10 mils of neoprene coating are applied over the form. This basic pressure-retention bladder then has a nylon restraint layer applied over the palm and a Beta snag layer installed over the wrist. There is a total of eight materials used in the glove, but only the outer layer is composed of nonflammable materials. Flame protection is provided in the same manner as in the PGA and ITMG. The gloves are attached to the pressure garment by an aluminum connector at the wrist.

Helmet

The Apollo helmet, shown in figures 100 and 106, is a one-piece shell shaped like an

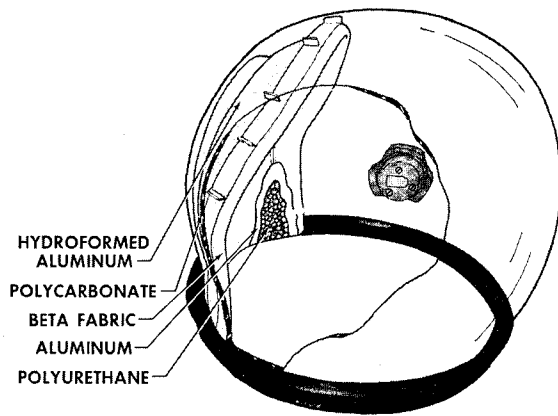


FIGURE 106.—Apollo helmet.

ellipsoidal section and made of polycarbonate. The helmet is attached to the space suit by an aluminum neck ring. An internal pad at the rear of the helmet provides ventilation and serves for impact absorption during splashdown. This pad is constructed of polyurethane and is flammable. To render this flammable material safe, it has been fully enclosed in a nonflammable covering. Between the polyurethane and the polycarbonate helmet shell, a covering of hydroformed aluminum is provided; and, on the front side of the pad, there is a layer of aluminum foil that is covered with Beta fabric to provide comfort. The assembled polyurethane pad is thus rendered flame resistant, leaving only the polycarbonate helmet that is flammable. In this instance, there is no acceptable material substitute that has the high impact resistance and good optical qualities of polycarbonate; and, hence, some risk is accepted in the use of this material. The risk is minimized because the helmet is little used in the spacecraft cabin environment and is stored in a nonflammable container when not in use.

Lunar Boots

The lunar boots are removable overboots that provide thermal protection and additional traction for the PGA boot while the space suit is used on the lunar surface. These boots are donned over the PGA boots just

before extravehicular activity and are not used inside the vehicle for any significant period of time. The outer layer of the boot is similar in concept to the outer layer of tennis shoes, as shown in figures 100 and 107. The toe, sole, heel, and lower sides are constructed of silicone rubber. This material, though flammable, is necessary to provide both abrasion resistance and flexibility at temperatures of less than -100°F . The rest of the exposed outer layer is Chromel-R fabric, which is both nonflammable and abrasion resistant. The insulation layers are identical to those of the ITMG except that there are two layers of 0.125-in. Nomex felt in the sole in addition to the superinsulation. The felt compensates for the loss of insulation effects of the superinsulation under compressive loads. The lunar boot also provides additional micrometeoroid protection for the pressure-garment boot. The lunar boot is lined with Beta cloth because this cloth is nonflammable and provides sufficient protection for the insulation.

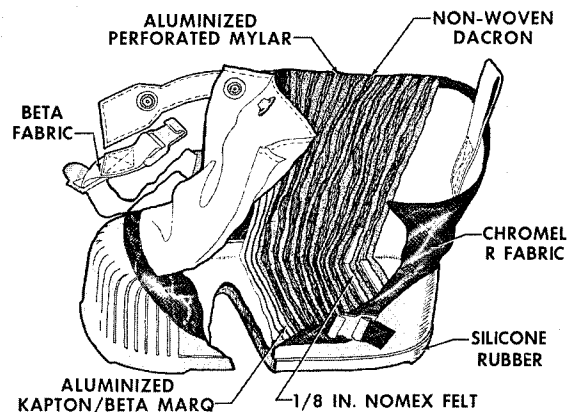


FIGURE 107.—Lunar boot.

Lunar Extravehicular Visor Assembly

The last major subassembly to be considered is the lunar extravehicular-visor assembly (LEVA), depicted in figures 100 and 108. The LEVA is a thin polycarbonate shell shaped to fit over the Apollo helmet. On the forward portion of this shell, two movable

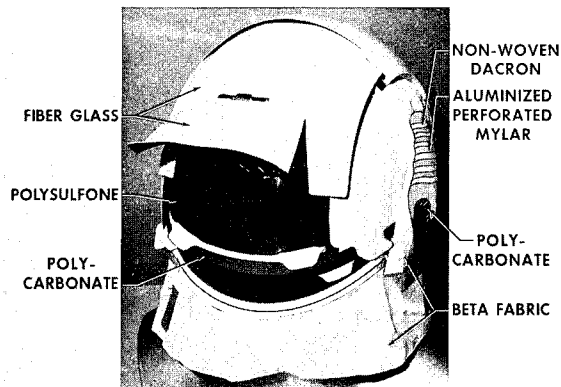


FIGURE 108.—Lunar extravehicular visor assembly.

solar-radiation-filtering visors are installed. Except for the visors, all of the LEVA is covered with a thermal insulation layup similar to that of the ITMG. The LEVA provides thermal, micrometeoroid, flame, and solar-radiation protection for the crewman. The outer visor is made of polysulfone, and the inner visor is made of polycarbonate. Both visors are specially coated to protect the crewman's eyes against solar radiation and still maintain visible-light intensity at an acceptable level. Most of the solar radiation is absorbed by the basic visor materials.

Many of the materials used in this assembly are flammable. The majority of these materials are protected, as is the polycarbonate shell; but some (for example, the visors) are not protected, and no acceptable substitute exists. Polysulfone was used in the outer visor because the temperature during an extended extravehicular activity is higher than the polycarbonate-forming temperature. The LEVA provides a complete solar-radiation and thermal-restricting envelope around the helmet.

CONCLUDING REMARKS

Flame-resistant materials have been used everywhere possible in the design of the Apollo lunar space suit to provide protection from burning materials falling onto the suit and from direct flame impingement. In some instances, where suitable nonflammable-materials substitutes were not available, some compromises in flammability requirements had to be made; however, in such cases, the problem was minimized by special design and procedural approaches. The Apollo lunar space suit has been demonstrated as a highly reliable and effective thermal protective device that satisfies lunar-surface operational requirements.

Fire Safety Design of a Mobile Quarantine Facility

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During the design phase of the Mobile Quarantine Facility (MQF), a primary consideration was fire safety. Therefore, appropriate criteria and ground rules were used in the design and construction of the facility. The fire codes and fire-requirement listings that are used by commercial airlines were supplied to the Manned Spacecraft Center (MSC) by the Federal Aviation Agency (FAA). After these codes were reviewed, a basic ground rule was adopted that flame protection for all combustible materials should be at least equivalent to or better than the standards for commercial aircraft.

Because the MQF was designed to operate with an interior atmosphere of air rather than with an oxygen-enriched atmosphere such as that of the Apollo spacecraft cabin, the requirements for MQF material were not as stringent as those for the spacecraft. Thus, other factors, such as cost and availability of materials, could be considered to a greater extent, and some materials that were unacceptable for use in the pure-oxygen atmosphere of the spacecraft were determined to be acceptable for use in the air atmosphere of the MQF.

During the construction of the MQF, commercially available materials that could be acquired readily (such as drapes, aircraft seats, floor tile, mattress ticking, and mattress foam) were purchased. However, the manufacturer of each item was required to submit certificates of compliance, as required by the Government. The items that were fabricated of wood, vinyl-on-wood, and fiberglass-reinforced plastic were required to be fireproofed.

Two types of flame-resistant coatings were evaluated to determine how to meet the FAA requirements for flammability. The first material to be evaluated was an inorganic silicate coating, which was selected initially because it was available as a clear paint. Thus, appearance of the walnut paneling that was used in the MQF could be retained. However, during the evaluation, it was discovered that in thicknesses greater than approximately 1.5 mils, the coating began to turn opaque and, in addition, began to crystallize and to flake from the surface to which it had been applied. The second material to be evaluated was a fluorinated hydrocarbon copolymer of hexafluoropropene and vinylidene fluoride (Fluorel). Because the application of Fluorel required neither much surface preparation nor a close tolerance on environmental control, this coating was chosen for all flammable substrates in the MQF. However, the original appearance of the walnut paneling could not be retained because Fluorel was not manufactured as a clear coating. For color contrast, pigments were added to this material before application inside the MQF.

MOBILE QUARANTINE FACILITY

The MQF (fig. 109) is a self-contained, transportable unit that is designed to isolate an Apollo crew of three men and a maximum of three support personnel after a lunar-landing mission. Adequate living facilities are provided for the occupants of the MQF while biological isolation is maintained during the transfer from the recovery area to the Lunar Receiving Laboratory at the MSC.

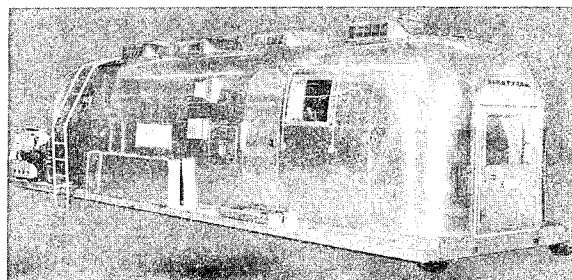


FIGURE 109.—Mobile Quarantine Facility.

The MQF includes sleeping quarters, a galley, a lounge, and lavatory areas. Three emergency exits are provided.

MOBILE QUARANTINE FACILITY MATERIALS

The statement of work for the design and construction of the MQF required that commercial trailer items were to be used, wherever possible, to prevent additional design and fabrication work and to reduce the total cost of the facility. After a review of the materials in a standard commercial travel trailer (table LVI), it was apparent that significant changes would be required, because

TABLE LVI.—*Standard Commercial Travel-Trailer Materials*

Item	Material
Bulkheads, doors, and framing materials	Walnut wood, oak wood, and vinyl-on-wood
Bathroom fixtures:	
Bathtub	Fiber-glass-reinforced plastic
Lavatory	Fiber-glass-reinforced plastic
Other moldings	Acrylonitrile butadiene styrene
Mattresses:	
Exterior ticking	Cotton
Interior	Urethane foam
Seats	Urethane foam
Curtains	Fiber glass
Interior end sections	Fiber-glass-reinforced plastic
Floor	Nylon carpet
Plumbing	Acrylonitrile butadiene styrene

TABLE LVII.—*Material Changes Made to Meet FAA Flammability Requirements*

Item	Material
Bulkheads, doors, and framing materials	Walnut with Fluorel, oak with Fluorel, and vinyl-on-wood with Fluorel ^a
Bathroom fixtures:	
Bathtub	Fiber-glass-reinforced plastic with Fluorel ^a
Lavatory	Fire-retardant PVC
Other moldings	Fire-retardant PVC
Mattresses:	
Exterior ticking	Fire-retardant polyethylene
Interior	Fire-retardant polymeric isocyanate foam
Seats	Covering: Casbah multi-point material (Bertchfield) Cushion: polyfoam sprayed with fire-retardant solution
Curtains	Combination of Verel modacrylic, saran flat monofilament, and viscose rayon
Interior end section	Fiber-glass reinforced plastic with Fluorel ^a
Floor	Asbestos-vinyl tile
Plumbing	Fire retardant PVC

^a 3- to 5-mil coating.

the majority of the materials did not meet the FAA flammability requirements. The primary changes would involve changing materials or coating the flammable substrates with a flame-resistant substance. The changes that were made to materials and the materials that were coated with a flame-resistant compound are presented in table LVII.

MATERIAL RESEARCH AND APPLICATION

In an effort to retain the appearance of the exposed wood in the MQF, a clear, flame-resistant coating (S-1001 clear silicate) was evaluated. Before the evaluation of this silicate, a two-pot, pigmented silicate paint had been used successfully. This paint previously had passed fire tests in a 100-percent-oxygen

atmosphere. The S-1001 clear silicate was only in the experimental phase.

Spray application of the S-1001 clear silicate onto various types of wood surfaces presented no problems until a thickness of approximately 1.5 mils had been applied. At this thickness, added silicate resulted in an opaque finish and crystallization of the coating. Past experience with silicate paints (two-pot system) indicated that a thickness of approximately 4 mils was needed on flammable substrates for flame-resistance purposes. Different application methods were attempted, but the crystallization problem could not be overcome. For instance, when small amounts of the S-1001 were applied and allowed to dry completely before the next coat was applied, the opaqueness was reduced somewhat, but not eliminated. Because of the MQF production-schedule requirements, the S-1001 evaluation program was terminated.

When the S-1001-clear-silicate tests were terminated, another flame-resistant compound, known as Fluorel L-3203-6, was being tested. This compound, which was not then fully developed, exhibited the best flame-resisting characteristics of any of the ambient-cured Fluorel compounds then known.

The beige color of Fluorel L-3203-6 also masked the surface finish of the substrate. To use this coating on materials inside the MQF, a color contrast was desired. The colors that were desired were achieved after experimentation with the coating and inorganic pigments. Application techniques were evaluated until a suitable technique was achieved for fiber-glass-reinforced plastic, wood, and vinyl-on-wood surfaces.

After application of approximately 3 mils of the Fluorel coating to various wood surfaces, fire tests were initiated. After a test, the vinyl surface was peeled back from the burned spot, and the wood was still in excellent condition. Additional tests were performed successfully on fiber-glass-reinforced plastic samples when Fluorel had been applied to the flammable substrates. The walnut panels and vinyl-covered bulkheads are

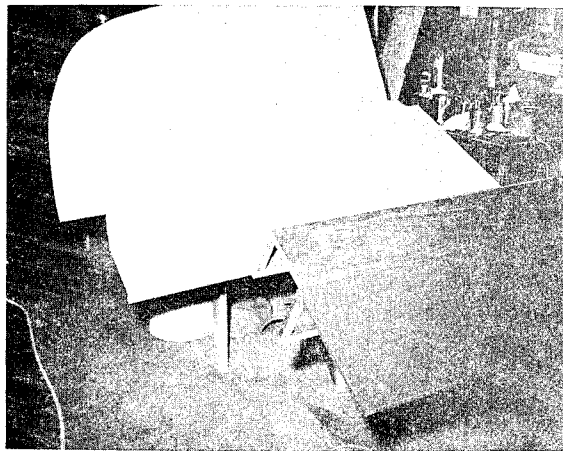


FIGURE 110.—Fluorel application on wood and vinyl-on-wood surfaces.

shown in figure 110 before and after the application of the pigmented Fluorel coatings. These coatings were applied to the panels with conventional painting equipment. If the coating were scratched or slightly damaged during installation of the panels, the coating could be touched up easily. Because Fluorel is dissolved by methyl ethyl ketone (MEK), the scratched surface could be smoothed out with small amounts of MEK and repainted with a small spray gun.

Throughout the interior of the MQF, special materials, coatings, and equipment were used to ensure fire safety. Esthetic factors were also considered. Because the appearance of the original walnut paneling in the prototype facility could not be retained, the Fluorel was pigmented to provide a pleasant color combination. A part of the plumbing was manufactured from fire-retardant polyvinyl chloride (PVC). This rigid PVC plumbing was adequate in terms of fire safety for this application. A microwave oven was used for meal preparation. With this unit, a possible ignition source was eliminated, and the meals were processed quickly. Several applications of the Fluorel compound were used in the laboratory area. These include the end section, tub liner, cabinets, and the molded PVC washbasin.

MOBILE QUARANTINE FACILITY SYSTEMS DESIGN

The MQF systems design included certain safety considerations in addition to the use of fire-retardant materials and flame-resistant coatings. These systems included the electrical system, the auxiliary power unit, and the fire-detection system.

In the electrical system, all major circuits were redundant and protected by circuit breakers. The primary circuit breakers, switches, and terminal boards were enclosed in junction boxes to contain any electrical fire. Additionally, the main power cables were routed behind shields to prevent accidental chafing or damage to the cable insulation.

In the auxiliary power unit, a metal shield was installed over the high-amperage batteries to protect the batteries from diesel-fuel spills. Also, for additional protection the auxiliary power unit was enclosed in a metal housing.

For active protection against fires, an automatic fire-detection system was installed in addition to portable fire extinguishers located inside and outside the MQF. This system used smoke detectors and audible alarms to provide an advance warning of fires. When the MQF is in storage during the quarantine period, this system is connected to the MSC fire-alarm system. Therefore, if a fire should start in the MQF, the master alarm at the MSC fire station would be acti-

vated and the personnel in the vicinity of the MQF would be alerted.

IMPLEMENTATION OF FIRE SAFETY PROCEDURES

When the MQF is operational, certain procedural guidelines are enforced to minimize fire hazards. First, flammable items that are required inside the MQF for medical or operational use are minimized. Next, the U.S. Air Force regulations regarding the air shipment of engines that have tanks containing fuel are followed. And, of course, no smoking is allowed inside the MQF during take-offs and landings of the aircraft that transports the MQF.

CONCLUDING REMARKS

The design of the MQF included practical applications of advancements in technology by the use of fire-retardant materials and flame-resistant coatings. Of particular interest is the use of Fluorel coating to protect materials from burning. This coating is flame resistant and can be applied readily to flammable substrates by the use of existing commercial painting equipment and techniques.

The Apollo 11 and 12 missions required biological isolation of the astronauts and, thus, use of this facility. Support of these missions with the MQF demonstrated operational application of the described materials, coatings, equipment, and procedures to ensure safety.

Fire and Safety Materials Utilization at the John F. Kennedy Space Center

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At the John F. Kennedy Space Center (KSC), two separate crews are required for hazardous and emergency-type duties in support of Apollo operations on the launch complex. The "spacecraft closeout crew" deals with fuel spillage, accidental fire, and astronaut rescue if the need arises during the pre-launch and cabin-closeout operations. This crew must wear special protective clothing to be ready to function under emergency conditions. In the interval between the departure of the closeout crew and the lift-off of the space vehicle, a second special crew, the "astronaut rescue team," becomes responsible for emergency rescue of the astronauts (including fire suppression). This crew is also on standby during the earlier operations to aid the closeout crew if needed. Again, special protective clothing is required. Some necessary operations at KSC are inherently hazardous. Before 1967, Dacron smocks or suits were worn for ordnance-handling operations and flameproof cotton overalls were worn for hypergolic-fuel-handling operations. The need to find improved and more flame-resistant clothing for emergency crews, and for other personnel engaged in dangerous occupations, led to an extensive investigation of new suit materials.

Thin plastic sheeting is used considerably at KSC as packaging to protect critical parts from contamination, dust, and humidity. It also is used to seal portions of the spacecraft against the weather. The criteria and the tests performed on several types of such

sheeting are discussed in the second part of this paper.

PROTECTIVE CLOTHING FOR RESCUE TEAMS

Approximately 3 hours before the launch of a Saturn-class vehicle, the astronauts enter the command module. They are assisted in their preentry preparations by the members of the close-out crew, who remain just outside the hatch door in an environmentally controlled area called the White Room. This room, located on the end of a mobile launcher swing arm, is a sealed compartment that is open to the spacecraft but not to the outside atmosphere. In early 1967, it was decided that personnel of the closeout crew would assume a new responsibility; the rescue of Apollo astronauts if they became incapacitated while the closeout crew was in the launch tower. It also was decided that an astronaut rescue team, composed of personnel highly trained in rescue and fire-suppression techniques, would be available nearby for astronaut rescue after the closeout crew left the launch tower. After launch, rescue would be accomplished by U.S. Air Force personnel. The astronaut rescue team also would be available to aid the closeout crew if needed.

Clothing Requirements

The closeout crew required clothing that could be worn in reasonable comfort with

negligible fiber-shedding characteristics to prevent contamination of the White Room. The material also had to provide a high measure of protection under most emergency conditions to allow the wearer sufficient time for rescue work.

The astronaut rescue team, on the other hand, required clothing that was lightweight, durable, self-extinguishing, waterproof, and also provided satisfactory protection against contamination by propellants. Because this team would not have to maintain the standard of cleanliness required in the White Room, the low fiber-shedding characteristics were not required. This factor made it possible to adopt the aluminum reflective-coating technique used in present-day aircraft-rescue proximity suits (fig. 111).

Conventional aircraft-rescue proximity suits are heavy and bulky, weighing 28 lb or more. These suits would severely restrict the movements of a man effecting the rescue of

an astronaut. These suits are not well ventilated and body temperature rises quickly. Under such conditions, the small self-contained air supply quickly becomes exhausted. These limitations make the standard fire-suppression clothing unacceptable at KSC.

Both the closeout crew and the astronaut rescue team require self-contained breathing apparatus and radio communication with the launch test supervisor. In addition to being lightweight, the equipment must have a low profile to be usable within the Apollo command emergency-egress. The particular types of breathing apparatus that were selected will not be discussed; but both suits use air rather than oxygen as the breathing medium. The decision to use air was based primarily on reducing the complexity and eliminating the additional hazard inherent in the use of an oxygen system in a fire environment.

The visor assembly of both the closeout-crew suit and the astronaut-rescue-team suit is made of a gold-coated Kapton material that is commercially designated as Kydex 100.

Use of Nomex in Protective Garments

So-called "flame retardant" cotton has long been a standard material from which to prepare garments for personnel exposed to fire hazards. However, at KSC, the closeout crew needed an improved garment that could be used in any emergency situation. The search for an adequate and reasonably low-cost garment led to a material called Nomex.

A member of the nylon family of fibers, Nomex was developed by the Du Pont Company for applications requiring good dimensional stability and excellent heat resistance (ref. 1). Nomex can be used for such items as electrical insulation, gas filter bags, ironing board covers, tires, race car driver and plant worker coveralls, pajamas, upholstery, pillows, general work coveralls, and children's clothing.

Nomex does not melt in the manner of ordinary nylon. However, at temperatures above 700° F, the fiber will char, providing



FIGURE 111.—Conventional proximity fire-suppression suit.

an insulating effect but also causing rapid degradation of the material. Nomex does not readily transmit heat but will burn in an oxygen-enriched environment (refs. 2 and 3). The material is unaffected by changes in humidity and has a higher resistance than ordinary nylon to acids, beta and gamma radiation, X-rays, and high-temperature water and steam.

This material is compatible with most hypergolic propellants used in the Apollo/Saturn vehicle. (However, nitrogen tetroxide used in the service module, will slowly dissolve the aluminum coating added to the Nomex suits worn by the astronaut rescue team.) This material is self-extinguishing in air and has acceptable particle-shedding characteristics in the coverall form.

Nomex is available in yarn, staple or tow fiber, and paper. The natural color is off-white; color-sealed yarns of olive green, sage green, and international orange also are available. The abrasion resistance is superior to that of cotton, wool, or acrylic fibers.

Test Program and Results

The properties and characteristics discussed, which meet KSC safety requirements, were verified at KSC by laboratory tests. Tests also were conducted elsewhere by the Thiokol Chemical Corp.; complete details are given in reference 4. These tests involved exposure of various garments to high temperatures. The results, which are summarized in this report, influenced the KSC closeout crew in selecting Nomex. However, other acceptable materials now have become available for this application.

The tests were conducted as follows. A manikin, exposed to the atmosphere and equipped with temperature-measuring thermistors at various locations, was placed in an open test cell. The thermistors recorded the effects of a burning ordnance pellet capable of generating approximately 5000° F. In each test, the pellet was taped to the right hand of the manikin and released to fall after 0.6 sec. When the pellet fell, it hit a slanted steel plate, causing it to roll away

from the manikin and thus simulate a person running from the ignition. The tests also measured blister and pain thresholds for human tissue protected by the different garments. The criteria used were developed at the U.S. Naval Air Defense Center, Johnsville, Pennsylvania (ref. 4).

The results of the tests were:

1. The flameproof cotton coveralls worn over Nomex underwear flamed and burned extensively on the right side (fig. 112). Although the 7-oz/yd² Nomex underwear protected the manikin for approximately 9 sec. it finally charred through and the heat flux increased to a point beyond the pain threshold.

2. The flameproof cotton coveralls worn over cotton underwear (fig. 113) burned quite extensively (fig. 114) and continued to smolder until extinguished. The heat flux extended beyond the blister threshold.

3. The 7-oz/yd² Nomex underwear worn beneath the 5-oz/yd² Nomex coveralls showed only light scorch marks on the outside of the material in the area of the right chest and hip (fig. 115). The heat flux versus time to pain and blister threshold indicated that the heat flux did not approach the point at which pain would have occurred.

4. The aluminized coat on the treated garments remained intact with the exception of a slight rip across the right chest (fig. 116). Tests showed the aluminized coating to be satisfactory because the heat flux remained.



FIGURE 112.—Results of test on flameproof cotton coveralls over Nomex underwear.



FIGURE 113.—Flameproof cotton coveralls over cotton underwear.

The clothing chosen for the closeout crew is antistatic treated and consists of a 5-oz/yd² Nomex coverall outer garment over one layer of Nomex underwear and Nomex gloves and socks (fig. 117). The clothing selected is very similar to that worn by race car drivers. The price is approximately \$60 per set. Members of the astronaut rescue team wear a specially constructed aluminum-over-Nomex jacket, bib coverall, hood, gloves, and boots (fig. 118). Ordinary thermal underwear is worn under the protective garments. The price of a rescue-team suit is approximately \$275. The specifications for this suit are given in reference 5.

The needs of KSC have been met effectively by using Nomex in the two different types of protective garments. The tests that have been performed and the operational uses to which KSC has put Nomex indicate that it also can be used in other ways. The

use of Nomex as protective clothing for firemen is obvious. It can be used as clothing for hospital patients, as seat covers in vehicles, as protection against many types of chemical hazards, and in a variety of other applications in the safety field. Nomex presents no physiological problems under normal usage conditions, including having an acceptable degree of outgassing.

THIN PLASTIC SHEETING

This plastic sheeting (film) is used extensively at KSC. Critical parts that must be kept clean and particle free from the time of arrival through installation on the space vehicle and finally launch are packaged in several different plastics. Moreover, plastic sheeting protects certain spacecraft openings and sensitive areas from the weather. Some plastic sheets provide a completely controlled



FIGURE 114.—Results of test on flameproof cotton coveralls over cotton underwear.



FIGURE 115.—Results of test on Nomex coveralls over Nomex underwear.

environment around critical vehicle/spacecraft sections.

An ideal plastic film for KSC must meet these criteria:

1. High transparency so that the status of a part or item of equipment may be checked without disrupting a clean environmental seal.
2. Noncombustible.
3. Antistatic, permitting no buildup of electric static charges.
4. Compatible with all propellants likely to contact the material.
5. Low particle-shedding characteristics.

Laboratory tests developed at KSC (ref. 6) to verify the listed properties have checked these qualities:

1. Degree of transparency.
2. The flame resistance, as determined in accordance with the best specifications currently available, which are:

ASTM D 568-61, Method of Test for Films Under 0.05-in. Thickness



FIGURE 116.—Results of test on aluminized coat.

ASTM D 635-63, Method of Test for Films Over 0.05-in. Thickness

ASTM D 1692-67T, Method of Test for Cellular Films

ASTM D 1692-59T, Method of Test for Plastic Foams and Sheeting

3. Static charge formation, as determined by Pan American Environmental Health Laboratory Method 6-703, Measurement of Static Charge Formation on Materials. This method consists of applying friction against rotating disks of wool or Teflon at approximately 50 percent relative humidity. The charge and decay time are recorded on a stripchart recorder.

4. Effects of propellants, as determined by visual observation of the effects of contact and by measurement of any temperature increase.

5. Particle count, as determined in accordance with specification FED-STD-209.

More than 20 different types of plastic film have been tested to date. Some of these ex-



FIGURE 117.—Closeout-crew Nomex protective clothing.



FIGURE 118.—Astronaut-rescue-team aluminized-Nomex fire-suppression suit.

hibited excellent antistatic properties and low fiber-shedding characteristics but proved to be combustible. Others are noncombustible but accumulate static charges and shed fibers. Some of the films lost antistatic and self-extinguishing properties with age or after exposure to sunlight and a salt air atmosphere. Table LVIII lists some of the films that have been tested and the results obtained from the tests. Even though there is no single sheeting material that satisfactorily meets all the safety requirements for a given application, considerable use has been made of a number of the available materials. The need exists for further development of sheeting materials that will have all the desired properties.

CONCLUDING REMARKS

This paper has discussed some of the special needs of Kennedy Space Center in the area of protective garments for personnel engaged in hazardous emergency operations, and the safety requirements for thin plastic sheeting used to protect critical components from the environment. After thorough testing, Nomex was chosen as the material from which to make protective clothing for rescue and firefighting crews for use in air atmospheres. It should be noted that there are now available several recently developed materials with improved performance characteristics that can be used for firefighting and rescue-clothing.

Extensive use has been made of several thin plastic sheeting materials; however, no currently available material entirely satisfies all the safety requirements of the KSC. The need exists for further development of sheeting materials that can more adequately meet all requirements for the various uses of these materials.

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TABLE LVIII.—*Plastic Film Test Results*

Film	Advantages	Disadvantages	Use
Velostat 1010 (Custom Materials, Inc.)	Antistatic ^a Propellant compatible Nonburning	Sheds particles Opaque	Can be used where neither clean-room environment nor transparency is required.
Velostat RFC ^b (Custom Materials, Inc.)	Antistatic Propellant compatible Nonburning ^c	Sheds particles Opaque	Can be used where neither clean-room environment nor transparency is required.
RC-AS-1200 FR (Richmond Corp.)	Flame resistant ^d Minimal particle shedding Propellant resistant	Opaque Losse antistatic properties with age	Satisfactory for use in clean rooms where antistatic properties are not required.
RC-AS-1200 (Richmond Corp.)	Propellant resistant Minimal particle shedding Fairly transparent	Loses antistatic properties with exposure to light Melts and burns to completion	Can be used where antistatic and nonflammable characteristics are not required.
RC-AS-2400 (Richmond Corp.)	Antistatic (see disadvantage) Self-extinguishing ^e Particle count satisfactory Transparent	Loses antistatic properties with age Dissolves in nitrogen tetroxide	Can be used in clean-room environment around space and launch vehicles.
Velostat 1705 (Custom Materials, Inc.)	Propellant compatible Antistatic	Burns to completion Excessive particle count	Suitable for use where clean-room environment and flammability are not major concerns.
Fluorglas M-385-10 (Dodge Ind.)	Antistatic Propellant compatible Particle count satisfactory Nonburning	Opaque	Acceptable for use where antistatic nonflammable material is required.
Aclar (Allied Chemical Co.)	Self-extinguishing Propellant compatible Transparent	Builds static charge	Can be used where antistatic characteristics are not required.
Polyethylene (Various manufacturers)	Most are propellant compatible Most are transparent	Most burn to completion Most build static charges	Not recommended for use around spacecraft.

^a Does not build or hold static charges.^b Reinforced fluorocarbon conductive.^c Incapable of burning.^d Resistant to degradation caused by flame impingement.^e Stops burning when ignition source is removed.

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Fire Extinguishment in Hypobaric and Hyperbaric Environments

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The operation of the Apollo spacecraft involves an assortment of special atmospheres and situations. Oxygen content in the spacecraft ranges from 60 percent at 16.5 psia on the ground to 100 percent at 5 psia in flight. Pure oxygen at a pressure of 15 to 19 psia is used in space suits on the ground, and 3.5-psia oxygen is used in the suits during extra-vehicular activity (such as on the lunar surface). In contrast to space vacuum conditions, hyperbaric atmospheres at pressures greater than 105 psia must be available for therapeutic treatment of dysbarism. Gravitational variations range from zero g in special aircraft flights and spacecraft to 1/6 g on the moon and to 5 g or 6 g during centrifuge testing or spacecraft entry. Each of these conditions affects flammability and must be considered in dealing with accidental fires.

This paper summarizes the results of work that has been performed to provide information on the effects of various extinguishants in special atmospheres. Data used in the development of both equipment and techniques for manned spacecraft and related equipment are discussed. Equipment includes a hypobaric chamber suitable for low-pressure use and a hyperbaric chamber for high-pressure operation.

Several test programs are briefly described in this report. First, with respect to hypobaric-oxygen environments, the evaluation of a specific agent, Halon 1301, is given on the basis of recommendations in the literature. Second, a broad screening program is described in which extinguishants are com-

pared. These tests were conducted in a 5-psia-oxygen atmosphere, and a selected material was used as the fuel. Third, high-expansion foam is described. Finally, extinguishment with water and Halon 1301 in a hyperbaric atmosphere is described. The same fuel was used in these tests as in earlier ones. In addition, applications of these findings to nonaerospace usage are discussed.

EXTINGUISHMENT IN HYPOBARIC-OXYGEN ATMOSPHERE

Halon 1301

Tests were conducted at the NASA Manned Spacecraft Center (MSC) to determine the effectiveness of Halon 1301 for extinguishing fires in an oxygen-enriched atmosphere. The primary fuel used in these tests was 1-ft² of flexible, open-cell polyurethane foam 2 in. thick. Halon 1301 was evaluated in 100 percent oxygen at 5 psia and at various oxygen concentrations at 14.7 psia. All tests were performed in a 400-ft³ Apollo boiler plate to give results relevant to the spacecraft.

The results of applying Halon 1301 (directly, by hand-held means) to open fires of polyurethane, polystyrene, and combined fuels in various oxygen concentrations at a pressure of 14.7 psia are given in table LIX. Although the fires were extinguished when the oxygen content was 21 to 33 percent, they were not extinguished when the oxygen content was greater than 77 percent.

TABLE LIX.—*Halon 1301 Tests in Apollo Boilerplate*

[Pressure = 14.7 psia]

Amount Halon 1301, lb	Fuel	Oxygen, percent	Extinguished
Ignited in open-top container			
1.7	(a)	21	Yes
1.7	(b)	24	Yes
1.7	(b)	33	Yes
1.7	(b)	82	No
1.7	(b)	78	No
1.7	(b)	79	No
Ignited on flat board			
1.7	(b)	82	No
1.7	(b)	83	No
3.5	(c)	81	No
3.4	(c)	81	No
4.0	(c)	80	No

^a Polystyrene foam.^b Polyurethane foam.^c Composite assortment.

In every case (both at 5 and 14.7 psia) in which there was a high oxygen percentage, motion pictures showed that the extinguishment attempt appeared to intensify the burning. Apparently, the effects resulting from the entrained oxygen flow and from the removal of combustion products are worse than the various beneficial effects that the extinguishing agent can provide. Previous investigations indicated that typical flammables self-extinguish in air when the local oxygen content is reduced from 21 percent to approximately 16 percent. With 80 to 100 percent oxygen available, it is particularly difficult to reduce oxygen concentration to 16 percent in the vicinity of the flame.

The polyurethane foam is a good worst-case fuel because it traps a significant quantity of oxygen in its cells and because it has a broad range of flammability rates. As shown in figure 119, the horizontal burning rate for this fuel varies from approximately 0.1 in/sec in air to nearly 20 in/sec in 100 percent

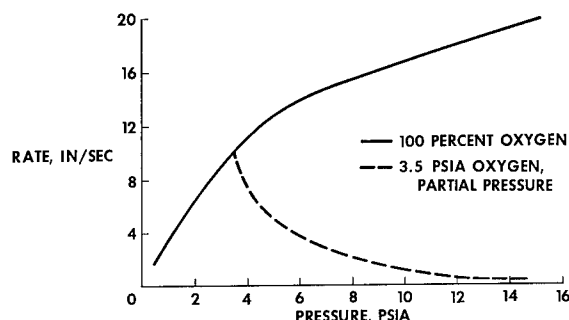


FIGURE 119.—Horizontal flame-propagation rate with open-cell polyurethane foam as fuel.

oxygen at the same total pressure of 14.7 psia.

Screening Test

Screening tests were done with the same chamber and fuel as the Halon 1301 tests. The test atmosphere was 100 percent oxygen at 5 to 16.2 psia.

The results of the extinguishant tests, for which much of the information was obtained through motion-picture coverage (and post-test inspection), are summarized in table LX. All the gaseous agents listed in this table were rated as detrimental in that they intensified burning. The solids tested were ineffective, and water and water-based compounds were rated best. The effect of venting to remove the oxygen also was investigated. During venting, the fuel continued to burn until the pressure dropped to 0.12 psia. This method of extinguishment was rated ineffective for manned spacecraft because a man could not remain conscious in such a low-pressure environment even while breathing through an oxygen mask.

The water required to extinguish fires in an oxygen atmosphere can best be expressed in terms of quantity rather than rate. The "virtual" water depth expressed as a function of the oxygen pressure is shown in figure 120. Virtual water depth is defined as that quantity of water applied directly onto the surface of the material and is expressed in terms of the average thickness of an applied layer of water (as in measuring rain-

TABLE LX.—*Rating of Extinguishing Agents*
[Polyurethane-foam fire in oxygen (5 to 16.2 psia)]

Agent	Effectiveness
Gases	
Halon 1301.....	Intensifies burning
Helium.....	Intensifies burning
Nitrogen.....	Intensifies burning
Argon.....	Intensifies burning
Carbon dioxide.....	Intensifies burning
Solids	
Sodium bicarbonate.....	Ineffective
Potassium bicarbonate.....	Ineffective
Liquids	
Water.....	Good
Foam.....	Good
Ethylene glycol solution..	Poor
Gel solution ^a	Excellent
Vent	
Pump down to 0.12 psia in 2 min	Ineffective

^a Water containing gel (0.25 percent), 300 to 350 centipoise.

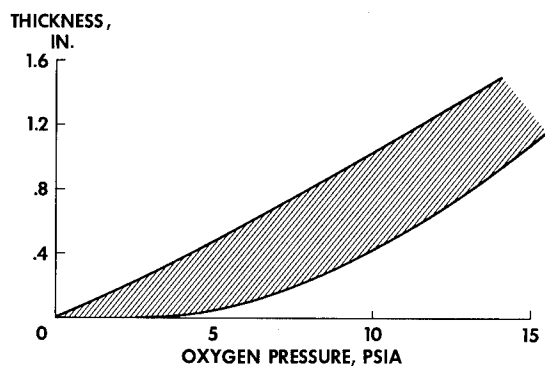


FIGURE 120.—Average thickness of water applied to extinguish polyurethane-foam fire in oxygen.

fall). The rate of application of the water appeared not to be a significant factor. Consideration of the flammability of the test fuel and the difficulty of using water efficiently by the remote means required in these tests in-

dicated that the values are probably realistic for the design of extinguishers. In this regard, the quantity is applicable to all burning surfaces rather than to a net wetted area.

High-Expansion Foam

Under contract to MSC, the E. W. Bliss Co. conducted a study to evaluate a high-expansion foam extinguishing agent. In this study, the ambient gas inside the test chamber was used to generate a liquid-type foam that was applied to the standard polyurethane-foam test fuel. Results, given in reference 1, show extinguishment with a mixture of approximately 300 parts gaseous oxygen to one part water-based solution. The foam is breathable. There is insufficient liquid to inhibit lung action; and, with adequate oxygen, occupants could remain immersed in this mixture without harm for much longer than the time required to escape the fire area. This application seems to be suited to many future requirements. The extinguishment mechanism appears to be one of blanketing; once the burning material has been enveloped in foam, the oxygen adjacent to the fuel is consumed and is replaced by gaseous products of combustion. Thus, the supply of oxygen is quickly cut off because convection is inhibited. That the same blanketing phenomenon does not inhibit breathing is evidenced by tests performed by the Danish Government in which it was shown that dogs immersed for as long as 90 minutes in foam made with air undergo no physiological change (ref. 2).

HYPERBARIC FIRE EXTINGUISHMENT

Extinguishment in high-pressure atmospheres was evaluated with a U.S. Navy 180-ft³ diving chamber outfitted for conducting fire tests. As described in reference 3, a large number of closely spaced nozzles throughout the interior of the chamber released the extinguishing agent uniformly. The same standard fuel used in the two previously discussed programs was used for the test fire.

Slightly enriched air (27.5 percent oxygen) was used. Tests were conducted at 15-psi increments from 30 to 105 psia. The fuel was placed on the floor of the chamber.

Water

Water-expulsion pressures studied were 50, 80, and 90 psi greater than chamber pressure. Both the time of application and the total water flow were measured. After a pre-burn interval of 10 sec, the water was turned on and the flow was continued until the fire appeared to be extinguished. As in other experiments, the oxygen content was measured before and after testing. The quantity of water required for extinguishment is shown in table LXI (tests 1 to 18) along with the

duration of flow and an estimate of fuel remaining after extinguishment.

The amounts of water required for extinguishment at various atmospheres are shown in figure 121. It should be noted that the lowest water pressure, 50 psi greater than chamber pressure, resulted in the lowest total amount of water used and gave the most consistent results. Furthermore, the quantity of water needed for extinguishment increased only slightly with an increase in pressure. The chamber pressures and temperatures before and during the tests are given in table LXII.

Halon 1301

Halon 1301 also was evaluated for use

TABLE LXI.—*Water Fire-Extinguishment Tests in Hyperbaric Atmospheres*

Test	Chamber pressure, psia (a)	Water pressure		Agent used		Duration of flow, sec	Fuel remaining, percent
		psia (a)	Head, ΔP	gal	lb (b)		
1	30	80	50	12.5	104	4.7	65
2	45	95	50	17.5	146	7.9	25
3	60	110	50	14.5	121	6.6	15
4	30	120	90	16.0	134	5.6	40
5	45	125	80	18.0	150	6.8	15
6	75	125	50	17.0	142	7.5	1
7	45	135	90	38.5	321	13.7	40
8	60	140	80	33.0	275	13.2	25
9	90	140	50	(c)	(c)	8.3	1
10	90	140	50	18.0	150	8.3	1
11	60	150	90	21.0	175	7.5	20
12	75	155	80	25.0	208	11.3	10
13	105	155	50	25.0	208	^d 3.8	0
14	75	165	90	25.0	208	8.3	25
15	90	170	80	20.0	167	5.6	20
16	90	180	90	17.0	142	4.9	5
17	105	185	80	34.0	284	^d 7.5	0
18	105	195	90	18.0	150	5.6	0

^a Pressures are ± 0.5 psi.

^b Weights are ± 5 lb, test 1 to 18.

^c Quantity of water used not recorded.

^d Additional water used to extinguish secondary fire.

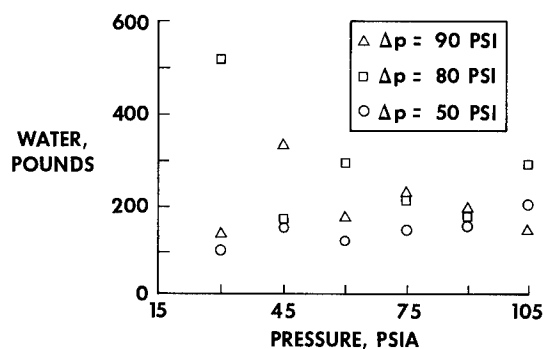


FIGURE 121.—Water extinguishment in 180-ft³ hyperbaric chamber using 27.5 percent oxygen.

under hyperbaric conditions. The same chamber, fuel, and piping system used in the tests with water were used in the evaluation of Halon 1301. In each case, the fire was extinguished by fuel exhaustion regardless of the extinguishant flow rate. The amounts of Halon 1301 used are given in table LXIII.

Chamber pressures and temperatures before and during Halon 1301 tests are given in table LXIV. No evaluation was made of the effects on electrical equipment or of the hazards from powered equipment. Such effects are discussed in reference 4.

APPLICABILITY OF FINDINGS FOR NONAEROSPACE USE

The National Fire Protection Association Subcommittee on Hyperbaric Facilities has published a tentative standard, 56D-T, which contains many construction and usage recommendations (ref. 5). This standard should be applicable to manned hyperbaric facilities, either in hospitals or in oceanographic installations. The findings presented are related to fighting fires in oxygen-enriched atmospheres and can be applied on a broader scale. Such fires are likely to occur

TABLE LXII.—*Hyperbaric Chamber Pressure and Temperature Before and During Tests With Water as Extinguishant*

Test	Pressure, psig			Temperature, °F		
	Initial	Maximum	ΔP	Initial	Maximum	ΔT
1	15	17	2	70	220	150
2	30	34	4	50	155	105
3	45	50	5	50	130	80
4	15	18	3	55	145	90
5	30	35	5	60	192	132
6	60	67	7	65	190	125
7	30	32	2	65	145	80
8	45	49	4	60	168	108
9	75	82	7	70	190	120
10	75	82	7	65	185	120
11	45	50	5	60	155	95
12	60	66	6	55	163	108
13	90	97.5	7.5	55	204	149
14	60	64	4	50	97	47
15	75	81	6	60	127	67
16	75	81	6	60	150	90
17	90	* 99	>9	65	247	182
18	90	* 99	>9	67	253	186

* Pressure-relief valve actuated at approximately 100 psig.

TABLE LXIII.—*Fire-Extinguishment Tests in Hyperbaric Atmospheres With Halon 1301 as Extinguishant*

Test	Chamber pressure, psia	Quantity extinguisher used, lb	Duration of flow, sec	Fuel remaining, percent
1	30	22.5	22.5	0
2	45	21.0	19.8	0
3	60	26.5	26.0	0
4	75	33.0	33.0	0
5	75	28.0	23.5	0
6	105	40.0	37.6	0

TABLE LXIV.—*Hyperbaric Chamber Pressure and Temperature Before and During Test With Halon 1301 as Extinguishant*

Test	Pressure, psig			Temperature, °F		
	Initial	Maximum	ΔP	Initial	Maximum	ΔT
1	15	21	6	60	148	88
2	30	40.5	10.5	65	200	135
3	45	59	14	55	270	215
4	60	72	12	55	290	235
5	60	72	12	45	210	165
6	90	99	>9	60	220	160

in hospitals, industrial installations, and transportation vehicles because more oxygen tends to be used in these facilities as design becomes more complex with technological advances. The proposed application of pure oxygen to treat raw sewage is an example of this increasing usage brought about by new technology. Gaseous oxygen is still the most typical form of oxygen used, and liquid oxygen is becoming more common (e.g., for military and research aircraft). Solid oxygen has many attractive characteristics but is not yet commercially available. The use of solid oxygen will require special safeguards in handling and stowage; both liquid and solid oxygen require venting to release boil-off gas, for example.

The case histories of fires in oxygen-enriched atmospheres are difficult to interpret. Many fires were extinguished by fuel exhaustion. In some cases, the percentage of oxygen in the atmosphere was unknown. It is important to consider rating a fire also according to the atmosphere rather than only by the type of fuel, as is currently the case. Also, additional classes of fires, based on physical and chemical properties of the fuel and on many environmental factors, are recommended in reference 6. Extinguishers provided for use in various oxygen-enriched atmospheres should be evaluated in these atmospheres, and those that intensify burning should be eliminated. This point is emphasized as a result of the tests reported herein.

CONCLUDING REMARKS

In oxygen-enriched environments (more than 35 percent oxygen), water or water-based foam was found to be the most effective extinguishant for all the fuels tested. All gases tested intensified the burning if indiscriminately applied at high flow rates.

In hyperbaric environments, water is effective in extinguishing fires. If fixed nozzles are used, they should be spaced uniformly throughout the chamber, including shielded areas such as those beneath decking, to provide one nozzle for each 6-ft² of wall surface area. For a 180-ft³ chamber, 90 to approximately 200 lb of water (10.8 to 23.9 gal) will extinguish an open fire in atmospheres with pressures as high as 105 psia if a delivery pressure 50 psi greater than the chamber pressure is used.

In the chamber used in these tests, a water-delivery system was shown to be suitable for extinguishing a hyperbaric-chamber fire 4.7 to 8.3 sec after system activation. This water caused a relatively small pressure rise of 2 to 10 psi. Water offsets most thermal effects of a fire and can reduce the quantities

of potentially toxic products by scrubbing them out of the atmosphere.

Halon 1301 was not effective when released at a rate of 1 lb/sec in a 180-ft³ hyperbaric atmosphere. A distribution system suitable for water at 50 psi greater than chamber pressure is not adequate for Halon 1301 liquefied at 215 psia.

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Session IV

SPECIAL TESTS

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Manned Spacecraft Electrical Fire Safety

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Many of the papers presented at this conference discuss the techniques of improving safety through the selection of optimum materials and through rigorous configuration control to minimize quantities of flammable materials. The word "minimize" is important because the goal of totally eliminating combustibles will never be attained in practice. The fire hazards of manned space flight, although significantly reduced in magnitude, will remain as long as operations are performed in habitable atmospheres and in the presence of potential ignition sources.

This paper discusses the goal of minimizing these ignition sources. Ultimate fire safety depends upon optimum attainment of both of the following goals:

1. Minimum quantities of combustibles
2. Minimum number of ignition sources

SOURCES OF IGNITION

Combustion must be initiated by some type of ignition source with sufficient energy and temperature to develop a self-sustaining or self-propagating flame. The generally recognized sources of ignition are:

1. Electrical sources
2. Hot surfaces
3. Open flames
4. Heated gases
5. High-energy impact (i.e., meteoroid penetration, pressure-vessel rupture, valve-seat impact, etc.)
6. Chemical sources
7. Electrostatic sparks

Of these seven possible ignition sources,

electrical initiation is considered to be the most probable ignition source in spacecraft and space-flight-related activity. Four major accidental fires have occurred in oxygen-atmosphere test chambers related to the development of the present manned space-flight technology. Three of these fires occurred in manned chambers. There was also, of course, the catastrophic Apollo fire. The most probable cause of all five fires was an electrical malfunction, and four of the five fires have been attributed to overheated electrical wiring (table LXV).

Electrical wiring is considered to be the most difficult ignition source to eliminate because:

1. Despite the complex manufacturing processes required to produce consistently high-quality electrical wire, the user often treats the wire as "raw material." Wire is received as spooled by the manufacturer and may be neither visually inspected nor subjected to dielectric tests before stockpiling.

2. Wiring is vulnerable to damage during manufacturing, installation, and actual service. As a result, shorted wiring is one of the most probable ignition sources.

3. The integrity of the completed wiring in a complex spacecraft is difficult to verify. Overstress dielectric tests are not practical in every situation because of sensitive electronic installations. A 100-percent visual inspection is not possible because of large wire bundles, complex installation geometry, and high density of installed components.

4. If a short circuit occurs, circuit protective devices cannot always be relied upon to trip before dangerous wire overheating

TABLE LXV.—*Space Program Fires*

Location	Date	Environment	Most probable cause
Brooks Air Force Base, 2-man space-cabin simulator (2 subjects)	1962	5-psia oxygen	Unknown electrical anomaly—PVC wire insulation was major fuel for fire.
Air Crew Equipment Laboratory, Philadelphia, Pennsylvania (4 subjects)	1962	5-psia oxygen	Incandescent bulk fixture arced, igniting wire insulation.
Apollo Environmental Control System chamber, Torrance, California (unmanned)	Apr. 28, 1966	5-psia oxygen	Short circuit of PVC-insulated strip heater (nonflight), igniting polyolefin shrink tubing and PVC cable jackets.
Apollo Spacecraft 012, Cape Kennedy, Florida (3 astronauts ^a)	Jan. 27, 1967	16-psia oxygen	Electrical-wire short circuit /anomaly.
Brooks Air Force Base, 2-man environmental simulator (2 subjects ^a)	Jan. 31, 1967	7.3-psia oxygen	Extension-light-cord short circuit.

^a Fatalities.

occurs because of the finite trip times of these devices and the electronic design engineers' tendency to slightly oversize the devices when circuit integrity demands no "nuisance" trips.

5. Many commonly used wire-insulating materials and electrical-system accessory materials ignite and propagate flame when exposed to current overloads in oxygen-rich atmospheres.

REDUCING ELECTRICAL-WIRE/CABLE IGNITION HAZARDS

The following approach has been applied by NASA to minimize electrical-wire/cable ignition hazards.

1. Special efforts have been implemented at the manufacturing facilities of the spacecraft contractors to ensure that adequate emphasis is placed on required wire and cable quality-control. The contractors also have initiated rigorous quality and test requirements at the wire suppliers' facilities.

2. "Tender loving care" programs have been invoked by spacecraft contractors for all phases of in-plant wire handling, fabrication, installation, and checkout. Wiring bundles are protected by chafe and scuff guards to preclude in-service damage.

3. Dielectric testing is conducted after fabrication processes that may degrade wire integrity (i.e., hot stamping, connector termination, etc.). Maximum in-process visual inspection is required, and automated air dielectric (DIT-M-CO) tests are conducted after harness fabrication and after spacecraft installation but before connection of sensitive electronics, when possible. Not all wire can be tested, however, and DIT-M-CO tests cannot find all faults because detection is a function of fault geometry in a DIT-M-CO test.

4. Continuing research in the field of circuit breakers and more definitive design requirements have improved confidence in the circuit-protection capabilities of circuit breakers. Solid-state breakers have more rapid response times than the presently used thermal breakers. The designer can achieve near-optimum circuit-protection compatibility by specifying tighter breaker-trip tolerances and by sizing breakers for the minimum wire gage.

5. A new and more realistic wire/cable electrical overload test procedure has been developed by NASA to screen out candidate wire insulations and electrical-system accessory materials to minimize flame propagation in the event of a short circuit.

WIRE/CABLE FLAMMABILITY TEST PROCEDURE

Commercial wire flammability testing typically consists of subjecting a short length of the test specimen to a Bunsen-burner flame with the specimen oriented either vertically, horizontally, or at some intermediate angle (60° or 45°). A 30-sec burner-flame exposure is specified in the standard Underwriters' Laboratories (UL) horizontal test. If the insulation does not propagate flame faster than 1 in /min and does not release burning particles, the construction is rated "flame retardant" and is approved, through application of the familiar "UL Listed" sticker or nameplate, for use within appliances in the home, plant, or office. These UL flammability tests are not conducted on lamp cords or appliance power cords, even though these cords are normally powered at all times and are subject to handling damage and abuse that easily can result in short circuits.

In the UL vertical test for thermoplastic-insulated conductors within jacketed building wiring, five separate burner applications of 15 sec each, with 15 sec between each application, are required. The insulation is rated "flame retardant" if it does not propagate a flame more than 10 in. or burn for more than 1 min after the last application.

Airframe wiring is tested for flammability in a similar fashion, although recent Federal Aviation Administration flammability requirements probably will upgrade the severity of the test in the near future. In the flammability test in military specification MIL-W-22759C, for example, a specimen oriented 60° from the horizontal is exposed to a burner flame for 15 sec for small-gage wires and for 60 sec for the larger, more commonly used sizes. The duration of the after-flame is measured. The burned section of the wire must pass a dielectric test for certain constructions.

These test procedures are not considered by NASA to be adequate to ensure optimum spacecraft electrical safety because:

1. The Bunsen-burner test assesses only the flame-propagation tendencies of insulating materials if a fire already has started

somewhere else. The test is not strictly realistic even in this context because it is conducted at room temperature, whereas wiring exposed to a general conflagration would be at a significantly elevated temperature.

2. The heat-sink effect of the cold copper conductor helps even a highly flammable jacket material to self-extinguish. Thus, although large-gage wires represent a more serious ignition source than small-gage wires in the event of a large current overload, the large-gage wires will pass a burner exposure test more easily.

3. The Bunsen-burner exposure times are so short that actual fire conditions are not simulated realistically.

4. Any significant open-flame propagation should constitute grounds for disapproval because this propagation represents a secondary ignition source for proximate combustibles, thereby violating the flame-retardant rating.

In National Fire Protection Association (NFPA) Bulletin HS-6, it is pointed out that grouped electrical cables, even though rated flame retardant and installed to conform in every respect to the National Electrical Code, represent a significant fire hazard. Flame propagation within wire trays is a notable problem. The NFPA suggests wrapping each flame-retardant wire with 1/16- by 2-in. asbestos tape with a 50-percent overlap and then saturating the tape with sodium silicate to render the insulation truly nonflammable. The weight and space penalties associated with such an approach are significant and are not considered acceptable for spacecraft application. The NFPA reports that in 1968, over 131 000 fires in the United States were caused by electrical malfunctions with total losses exceeding \$210 million.

Commercial aircraft electrical fires are particularly hazardous because of long unbroken runs of wire bundles and the close proximity of highly combustible trim and upholstery materials. Polyvinyl chloride (PVC) wire insulation commonly is used, although the smoke from burning PVC is a

serious toxic hazard in the close confines of an aircraft cabin. The "wet wire fire" phenomenon has caused PVC ignition in galley and washroom wiring without sufficient current being drawn to trip the circuit breakers.

In an attempt to overcome some of these deficiencies, NASA developed the present Electrical Wire Insulation and Accessory Flammability Test Procedure, test number 4, as specified in Manned Spacecraft Center (MSC) documents D-NA-0002 (for future programs) and MSC-PA-D-67-13 (for the Apollo Program). This test consists of applying an electrical current overload to a single candidate wire in a symmetrical bundle of seven wires. The test is conducted in a chamber filled with oxygen or oxygen and nitrogen at the applicable spacecraft cabin pressure (fig. 122). Initially, a current overload, approximately 80 to 90 percent of the fusion current for the gage of wire being tested, is applied for 1 min. The amperage is increased in 5-A increments each minute until ignition occurs or until the wire fuses. Approval for use in the spacecraft is withheld if the insulation on the overloaded wire propagates flame or if the insulation integrity on adjacent wires in the bundle is destroyed. Electrical-system accessory materials (i.e., spot ties, tubing, tape, clamps, etc.) that are used in close contact with wiring also must demonstrate nonflammable characteristics when installed over the 7-wire test bundle.

IMPACT OF NASA WIRE/CABLE FLAMMABILITY TEST RESULTS ON SPACECRAFT CONFIGURATIONS

The NASA wire flammability test was conceived in late 1963 and has evolved to the present level based upon the experience gained from conducting many hundreds of tests during the last 6 years. It has been concluded that many commonly used electrical insulating and accessory materials are not suitable for use in spacecraft cabin oxygen atmospheres.

Insulations such as irradiated modified polyolefin, PVC, polyvinylidene fluoride (PVF₂), and silicone rubber have been

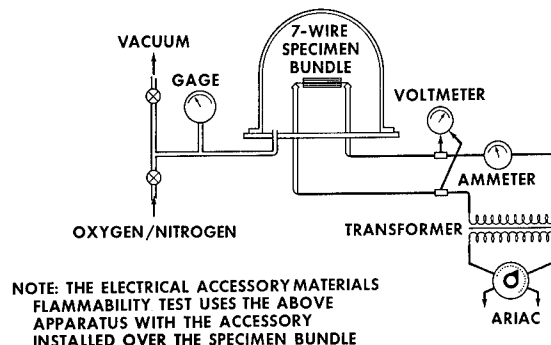


FIGURE 122.—Schematic diagram of apparatus for the NASA wire-insulation flammability test.

tested and found to be unacceptable for use in oxygen atmospheres. The materials ignite well below the fusion current and continue to burn violently even after the overload current is removed. In these tests, all insulation on adjacent wires was consumed entirely. If this situation were to occur in service, additional arcing and short circuits would increase the severity of the fire.

A number of electrical-system accessory materials were found to be equally deficient. Nylon wire-bundle spot ties, polyolefin and nylon sleeves and/or heat-shrinkable tubing, vinyl and silicone electrical tape, silicone rubber liners and spacers, and silicone rubber chafe-guard material failed the overload flammability test in simulated installed configurations.

The results of tests conducted during the last 6 years indicate that the following generic classes of electrical-wire/cable insulating materials will withstand the stringent current-overload test in spacecraft cabin oxygen atmospheres (fig. 123).

1. Extruded or tape-wrapped polytetrafluoroethylene (TFE)
2. Polyimide-coated extruded Teflon (TFE/ML)
3. Polyimide film/fluorinated ethylene propylene (Kapton/FEP) (not acceptable as a jacket material for shielded electrical cables)

The following electrical-system accessory materials meet the NASA current-overload flammability test requirements.

1. Teflon-coated Beta-cloth wire-bundle spot ties

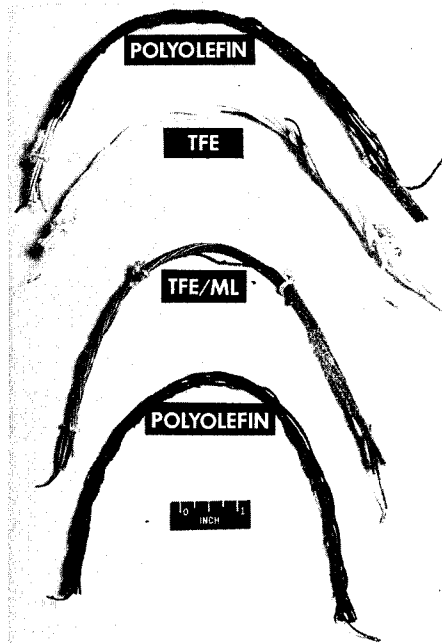


FIGURE 123.—Post-test comparison of four types of insulation.

2. Teflon/FEP heat-shrinkable tubing
3. Teflon liners for cable clamps
4. Fluorel sponge rubber clamp spacers
5. Unsintered Teflon tape with no adhesive
6. Teflon-sheet chafe guard
7. Fiber-glass laminate with polyimide bonding resin for molded applications (i.e., circuit-breaker housings, wire-bundle scuff guards, wire ways, electrical-panel closeout covers, etc.)

The results of the NASA wire/cable flammability test have influenced spacecraft changes as follows:

1. The Gemini cabin wiring insulation was changed from polyolefin to Teflon.
2. The early contractor decision to use polyolefin insulation for the Apollo command module wiring was reversed. The insulation selected for the Apollo Block II command module cabin wiring was TFE/ML or TFE.
3. The lunar module weight constraints forced the contractor to consider only thin-wall wiring insulations. Favorable flammability characteristics influenced the contractor decision to specify lightweight Kapton/FEP insulation, even though it was a relatively

new and untried construction at that time. Although the Kapton/FEP wire-insulation construction meets the NASA current-overload test requirements, shielded electrical cable with Kapton/FEP as the shield jacket exhibits a "burning reaction" when one of the underlying primary conductors is subjected to a current overload in an oxygen-enriched environment. This burning reaction consists of flame propagation over varying lengths of the test cable and results in total destruction of the affected portion of the cable, including the copper shield and conductor. The burning is accompanied by the dripping of molten copper, which provides a serious potential secondary ignition hazard. This burning reaction occurred only during electrical-overload tests in spacecraft oxygen atmospheres and was not repeated with external ignition sources or during overload tests in air or in a vacuum.

Working closely with the insulating-materials suppliers and wire makers, NASA personnel developed a number of alternative constructions with the goal of producing a safe cable construction while retaining the desirable lightweight and exceptional physical properties of the Kapton/FEP cable. A prototype cable has passed the current-overload test successfully, with no burning reactions noted. The new cable has a TFE/FEP fire-barrier tape over the shield and a thin Kapton/FEP tape as an outer protective jacket.

4. Numerous significant safety improvements in electrical-system accessory materials have accrued. The new Teflon-coated Beta-cloth wire-bundle spot ties are nearly as strong as the previous nylon spot ties and are noncombustible. Teflon heat-shrinkable tubing is now available. The new generation of Fluorel high-density and sponge rubbers has direct electrical applications, as do the nonpropagating fiber-glass/polyimide laminates.

5. MSC design and procedural standards define flammability requirements for wiring and accessory materials and wiring inspection criteria.

SUMMARY AND RECOMMENDATIONS

Even though the maximum use of available technology can minimize combustibles and ignition sources, the finite possibility of fire initiation caused by an electric-current overload remains. To minimize the hazards in the event of such a short circuit, NASA developed the electrical-wire/cable current-overload flammability test. The results of this test have been applied to spacecraft design, configuration, and application decisions with a resultant increased confidence in the safety of manned space flight.

The technological advances accrued during this concerted NASA effort are considered to be directly applicable to the advancement of electrical safety in commercial, residential, and airframe applications. The following recommendations are made:

1. The materials and insulating systems that have been accepted by NASA as safe in spacecraft oxygen atmospheres should be considered for use in commercial, residential, and airframe applications.
2. The presently utilized Bunsen-burner tests should be considered for replacement with an electric-current-overload flammability test similar to that described herein.
3. Electrical-system accessory materials should be tested for flammability in their installed configuration over a wire-bundle current-overload test specimen.

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Special Flammability Test Techniques

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The test methods developed by the military and by industry, although highly satisfactory for the intended applications, are inadequate for evaluating the flammability hazards in the space program. Therefore, a series of special test methods was developed to determine the flammability parameters of aerospace materials. The purpose of this report is to describe four of these test methods.

TEST OBJECTIVES

Two types of tests are conducted. The first type consists of formal tests in accordance with a prescribed set of specifications or procedures to qualify materials for flight use (refs. 1 to 3). These tests, conducted under rigid quality control inspection, are a necessary prerequisite for placing a material in a flight status. The Apollo Program materials-qualification requirements are contained in reference 4.

The second type of test, the subject of this report, consists of the development and design verification tests that are used to provide engineering data before or during the fabrication of an end-item. These tests, which precede the qualification tests, do not follow a fixed preestablished format because each test is designed to investigate a different performance parameter.

The test methods described in this report serve the following purposes:

1. Provide design engineering data on dielectric and thermal properties of nonmetallic materials

2. Provide backup flammability data used in reviewing materials that exhibit marginal

performance in the formal qualification tests

3. Permit prediction of end-item performance from flat-sample testing

The test methods are simple in theory and operation, and the equipment can be fabricated inexpensively.

Three special test apparatus will be discussed and a fourth apparatus will be described briefly. The performance and environmental parameters that were considered in designing the special test equipment are described below.

Spacecraft Environment

The large differences between the flammability properties of materials in air and in oxygen necessitate a major reorientation in thinking when materials for space flight are tested and considered. Many materials that are totally nonflammable in air will burn vigorously in the Apollo environments (table LXVI). For example, fabrics made from pure steel or from a nickel-chromium alloy burn intensely when ignited in pure oxygen,

TABLE LXVI.—*Gaseous Environment of the Apollo Spacecraft Interior*

Spacecraft	Total pressure, psia	Gas	Percent
Command module:			
Prelaunch.....	16.5	Oxygen	60
		Nitrogen	40
Postlaunch.....	6.2	Oxygen	100
Lunar module.....	5.8	Oxygen	100

even when the manufacturing lubricants have been removed before the test.

Nonmetallics in the Spacecraft

In addition to the problem of the enriched-oxygen environment is the fact that approximately 1700 lb of nonmetallics are used in the command module and 450 lb are used in the lunar module for a typical Apollo mission. As shown in table LXVII, the nonmetallics are potting compounds, insulations, space suits, and crew-provision equipment. Tests must include not only the flammability of end-item materials, but also the interaction of the effects between materials. For instance, the dripping from a burning polycarbonate meter face may be the ignitor for an end-item not otherwise exposed to an ignition source. The exterior of a soft-goods container may be required to be nonflammable, but the facial tissue that is stowed inside might not have to be flame resistant if the container provides sufficient protection.

Types of Ignitors

Potential spacecraft ignition sources typically originate from electrical system failures (which result in short-circuit arcing or system overheating), mechanical overheating caused by friction, and chemical interactions. When a material ignites in the spacecraft, that material can in turn become an ignitor for the adjacent materials. For specialized flammability testing, the worst-case ignition source must be analyzed for each component being tested, and this ignition source must be simulated with an appropriate safety factor. Different ignition sources, such as electrical overloads, other burning and dripping materials, and a constant flame source, are described below.

Specialized Test Criteria

The test criteria for the standard Apollo flammability tests are described in reference 4. However, for special test methods, the criteria must be generated separately for each

TABLE LXVII.—*Typical Apollo Nonmetallic Materials*

Elastomers	Plastics	Fibers
Hoses:	Wire insulation	Space suit
Oxygen and urine	Windows	Restraint harness
Cushions:	Wire tray liners	Lunar transport tether
Headrest, stowage, and mirror	Helmet	
Potting compounds	Electroluminescent panels	Couch fabric
Space-suit bladder cloth	Waste-disposal bags	Stowage containers
Conformal coatings	Wire splice shields	Survival equipment
Sun shade	Urine plenum chamber	
Clamp filler	Heat shrink sleeving	
Adel clamps	Chafe guards	
Sealant	Meter faces	
Fire barrier sealer		
Wire and cable clamp liners		
Handholds		
O-rings		
Window seals		
Fire dams (wire tray)		

test. The establishment of criteria requires an analysis of the application and function of the materials with respect to the operation and the total spacecraft environment. For those tests that are conducted only to generate engineering-design information, frequently it is sufficient to determine only the relative flame resistance of several materials; formal criteria of acceptability are not necessary.

SPECIALIZED TEST EQUIPMENT

Numerous special tests have been developed that supplement the formal screening and final selection test requirements. Some of the most frequently used pieces of equipment, as well as the associated special applications and test criteria, will be described.

Flame-Impingement Tester

The flame-impingement tester (figs. 124 and 125) is used principally to evaluate the adequacy of a thermal layup in protecting a stowed flammable material from a fire in an oxygen-enriched environment. This apparatus consists of a Bunsen-burner-like barrel that is supplied separately with natural gas and oxygen, a method for lighting the burner remotely, a method for applying the flame remotely to the sample after test conditions have been established, and instrumentation

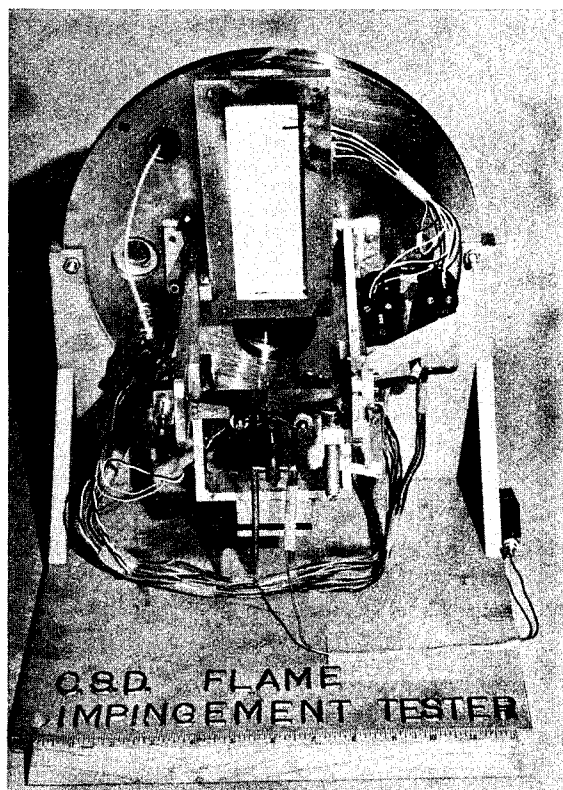


FIGURE 124.—Flame-impingement tester.

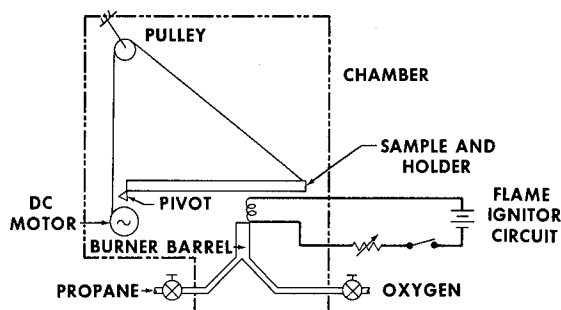


FIGURE 125.—Schematic of flame-impingement tester.

for monitoring temperatures. When a flame of the desired temperature impinges on the sample layup, thermocouples located between each layer of the layup (centered directly over the flame) supply information to a data-acquisition system that provides a time-temperature plot. This plot shows not only the temperature reached by the "cold side" of the layup as a function of time, but also the temperature drop provided by each layer in the layup. The information on differential temperature (Δt) across each layer permits layup optimization by trade-off of thermal performance as a function of other considerations such as weight and flexibility.

The factors relating to the acceptability, used in conjunction with the flame-impingement tester, vary with the application. The layups that are used to protect "life and limb" end-items are required to maintain a cold-side temperature that is lower than the degradation-threshold temperatures of the materials being protected for the maximum time established for extinguishing a fire. The layups that are designed to protect noncritical end-items are required to maintain a cold-side temperature below the ignition temperature of the material being protected.

This equipment was used to design and qualify the thermal adequacy of the Apollo integrated space suit. A typical experimental space suit layup is shown in figure 126. This layup maintained the temperature of the pressure-retention layer below the 300° F degradation temperature of the bladder layer for about 150 sec as shown in figure 127.

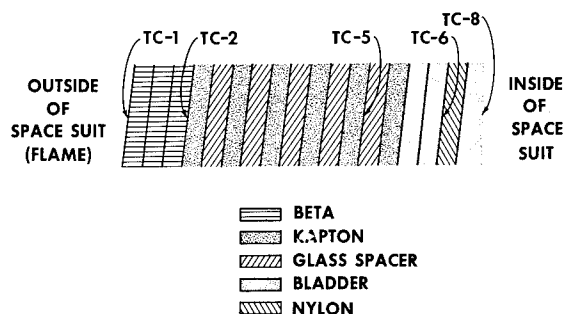


FIGURE 126.—Experimental space-suit layout.

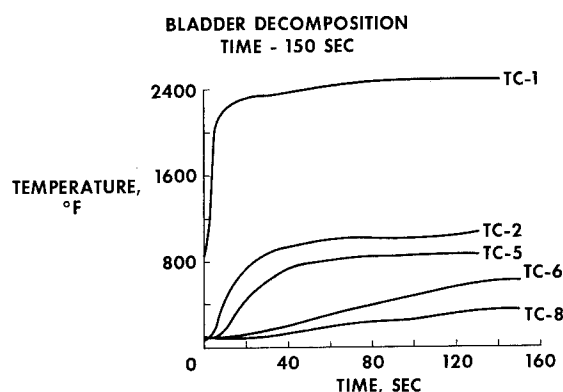


FIGURE 127.—Time-temperature plot from flame-impingement tester.

Short-Circuit Ignition Tester

The short-circuit ignition tester (fig. 128) is used to evaluate the possible hazard when a flammable material must be used adjacent to an electrical system and to evaluate the hazard of static discharge associated with the dielectric end-item materials. The apparatus consists of a movable chamber feed-through mechanism with an electrically isolated needle electrode and a stationary flat copper disk. This apparatus was used to qualify the cotton undergarments for use inside the space suit.

The cotton underwear is, of course, flammable in oxygen. The flame-impingement tester described previously was used to verify that the cotton was protected sufficiently by the space suit against a fire outside the space suit. The remaining question is whether a possibility exists that the cotton

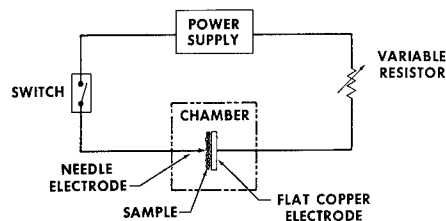


FIGURE 128.—Schematic of short-circuit ignition tester.

could be ignited by some ignition source inside the space suit. The only possible ignition source inside the space suit is the communications and bioinstrumentation electrical equipment, which is powered by 28 V direct current. The procedure imposes this voltage, at various current levels, across the cotton sample in pure oxygen. The needle electrode is scraped across the flammable material to simulate the action of a broken wire, and the resulting arc is observed to determine whether sufficient energy exists to ignite the flammable material. In this manner, the minimum current capable of igniting the flammable material at any preestablished open-circuit voltage can be determined. The minimum ignition currents for several typical materials are shown in table LXVIII. After the minimum ignition current has been determined, a circuit analysis is made to deter-

TABLE LXVIII.—Test Results, Short-Circuit Ignition Tester

[95 percent oxygen, 28-V dc open circuit]

Material	Chamber, pressure, psia	Resistance, ohm	Minimum current, A
Unwashed cotton knit (green)	19	21.5	1.3
Clean cotton knit (green)	6	15.5	1.8
Unwashed cotton knit (white)	19	25.5	1.1
Human hair	6	10.8	2.6
Bioinstrumentation insulation	19	21.5	1.3
	—	—	—
	19	10	2.8
	6	7.8	3.6
	19	8.25	3.4
	6	4.3	6.5

mine whether, under any failure mode, these levels could be obtained in the flight configuration. If this current level can be achieved, appropriate design features such as current limiters are included as required.

Polycarbonate-Drip Ignition Tester

A small localized fire could occur in a spacecraft, building, or aircraft without catastrophic results. However, flaming embers from the localized fire could ignite other non-metallic materials in the area. The polycarbonate-drip ignition tester was designed to simulate this source of ignition on test materials under laboratory-controlled conditions. Polycarbonate was selected as the most severe source of several ignitors tested because the molten substance clings to whatever it contacts and continues to burn. The polycarbonate-drip ignition tester is shown in figure 129.

The prime consideration in designing the polycarbonate-drip tester was to obtain repeatability in the size of the molten droplets. Uniformity was obtained by establishing a uniform ignitor size, by notching the ignitor to ensure uniform droplets, and by attaching the ignitor mount to a low-speed vibrator that can shake the ignitor at 1-sec intervals. This apparatus, although simple in design, successfully predicts how an end-item such as the space suit will perform in full-scale-mockup flammability tests and eliminates expensive prototype hardware buildup.

Occasionally, this tester is used in conjunction with a silicone ignitor to evaluate the

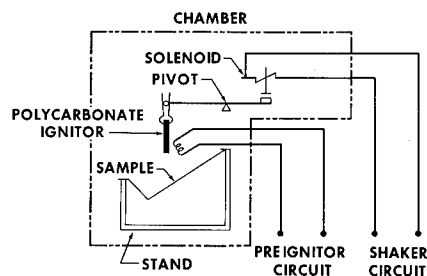


FIGURE 129.—Schematic of polycarbonate-drip ignition tester.

performance of the test specimen under simultaneous exposure to multiple ignition sources.

Flash-Point and Fire-Point Tester

The flash-point and fire-point tester (fig. 130) is used to predict the temperatures at which a material constitutes a flammability hazard if overheated accidentally in the spacecraft. The following five definitions are relevant:

Flash point—The flash point is the lowest temperature at which a heated material will emit flammable vapors in such quantities that these vapors will result in a nonsustaining flash or flame when mixed with oxygen and exposed to an electric spark of a preselected energy level (usually 100 m μ at 10 000 V).

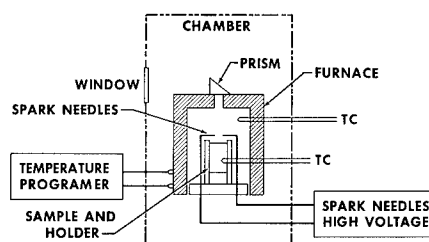


FIGURE 130.—Schematic of flash-point and fire-point tester.

Fire point—The fire (ignition) point is the lowest temperature at which a heated material will emit sufficient flammable vapors to result in a self-sustaining fire when the vapors are mixed with oxygen and exposed to an electrical spark of a preselected energy level (usually 100 m μ at 10 000 V).

Autoignition point—The autoignition point is the lowest temperature at which a material will emit flammable vapors that will, when mixed with oxygen, self-ignite.

Combustion-rich limit mixture—The combustion-rich limit mixture is the vapor-to-oxygen ratio above which combustion cannot occur.

Combustion-lean limit mixture—The combustion-lean limit mixture is the vapor-to-ox-

xygen ratio below which combustion cannot occur.

The flash-point and fire-point tester consists of a furnace and associated temperature programmer equipment, a test stand, needle electrodes with associated spark-producing equipment, and a vacuum chamber with associated equipment for supplying oxygen or a gas mixture.

The apparatus heats a sample at a desired rate and exposes the offgassed volatiles to a spark of a predetermined energy level. The material is rejected if it flashes or ignites (as defined previously) before reaching a preselected upper temperature (usually 450° F). The sample is monitored, either visually by means of a prism on top of the furnace or by the use of thermocouples or photocells mounted in the furnace.

One additional refinement is used to ensure good test results. A small tube is plumbed between the outside of the chamber and the interior of the furnace so that oxygen can be supplied to the furnace cavity. This oxygen is used to prevent the material from going through a sudden phase change in which the gaseous composition of the furnace cavity changes from the combustion-lean limit mixture to the combustion-rich limit mixture between sparks. To ensure that this change has not occurred, the furnace is turned off at the end of the test, and oxygen is supplied slowly into the cavity while the spark equipment continues to operate. If the gas mixture exceeds the combustion-rich limit, the pure oxygen that is being supplied will force the mixture into the combustible range. If combustion does occur, the process is repeated at lower temperatures until the minimum flash-point or fire-point temperature is obtained.

To determine the acceptability of the material being tested, the minimum temperature is adjusted by a suitable safety factor and compared with those spacecraft temperatures that are attainable under various failure modes.

The test results from a sample of cotton fabric are shown in figure 131. In this test,

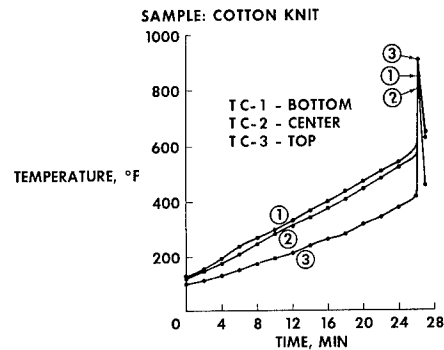


FIGURE 131.—Test results, flash-point and fire-point ignition test on knitted cotton fabric.

the sample was heated at a rate of rise of 18° F/min and exposed to a 10 000-V, 100-m μ spark at 18° F increments. The sample ignited at 600° F and would be acceptable from a flash or fire test viewpoint.

Autoignition-Point Testing

The flash-point and fire-point equipment also is used to measure the autoignition point of materials. The procedure used for autoignition-point determination is similar to the procedure used for flash-point and fire-point measurement, with the following exceptions: (1) the spark equipment is not used, and (2) the sample is brought to some maximum temperature and maintained at that temperature for a prescribed time (usually 30 min). If self-ignition does occur, the procedure is repeated at lower temperature levels until the lowest level at which ignition does not occur is determined.

POTENTIAL COMMERCIAL APPLICATIONS OF SPECIALIZED TEST EQUIPMENT

The approach and the equipment described previously should be applicable, with appropriate modifications, for meeting many commercial test needs. More specifically, the rationale consists of studying the end-item environment (such as airplane interiors, building interiors, or deep-sea submersibles) and the possible ignition sources and develop-

ing test equipment that can simulate these conditions on flat samples. This approach permits screening numerous materials economically and expeditiously and predicting the performance of the materials in full-scale mockup tests. Possible applications of this equipment are discussed in the following paragraphs.

The flame impingement tester could be used to evaluate paneling or ceiling materials for building interiors or paneling materials for aircraft. Temperatures would be monitored in a fire in a mockup of a room or aircraft, and the worst-case temperatures would be simulated by the impingement testers. Other parameters, such as convective air-current velocities and temperatures, would be measured and simulated by means of heaters, fans, and baffles.

The test results could be compared with preestablished absolute standard burn rates or burn-through times for acceptance or rejection. In those instances in which all available materials are combustible, the test results could be compared with each other to permit selection of the best material. Similarly, the short-circuit ignition tester could be used to simulate building or aircraft electrical systems and to evaluate insulation, structural materials, and paneling used adjacent to this wiring.

The flash-point and fire-point tester could

be used to qualify materials, such as packing or insulation materials, that can be exposed to high temperatures in various applications. The drip ignition tester could be used to evaluate aircraft seat covers where the most probable ignitor would be flaming material that drops from the wall or overhead.

Each application would require the simulation of a different environment and of different acceptance criteria. However the rationale would be the same—to determine the actual worst-case potential fire condition under various failure modes and to select a test apparatus that can simulate that condition realistically.

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Specialized Testing and Evaluation of Space-Suit Materials

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Selection of nonmetallic materials used in the Apollo space suits and in the crew-bay areas of the spacecraft was made from results of physical testing conducted according to applicable American Society for Testing and Materials (ASTM) and Federal specifications. Although standard testing equipment satisfied the test specification in most instances, several unique requirements necessitated the design of specialized testing fixtures and facilities.

Because of the stringent flammability requirements for nonmetallic materials used in the interior cabin areas of the spacecraft, flammability performance has been a prime consideration in the selection of materials for such applications. On the other hand, requirements such as wear, durability, and comfort also are vital and hence strongly influence the selection of materials in many instances. Therefore, because of the fundamental importance of the physical-performance characteristics of materials used in the cabin areas, it is appropriate to discuss some of the specialized physical tests, other than flammability, in the selection and application of nonmetallic materials for the Apollo Program. This paper therefore describes the specialized test program, with emphasis on the equipment used to test and qualify the space-suit materials and subassemblies for operation in the deep-space environment. Such variables as temperature, pressure, and radiation—typical of space and lunar-surface conditions—were applied to determine

the changes in the physical and mechanical properties of space suit materials. In addition, in situ dynamic testing was used to verify performance.

SPECIALIZED TESTS

The primary criterion in the design of a pressurized space suit is the maintenance of pressure integrity. Because of the severity of the lunar-surface environment, materials for the Apollo extravehicular space suit were subjected to either failure or degradation tests in several categories. The data obtained from these exhaustive materials evaluations allowed the establishment of realistic design limits and positive safety margins. As a result, actual space suit pressure leakage has been well within acceptable rates for all Apollo flights.

To assure reliability, special test requirements were imposed. Where standard testing apparatus was inadequate, these requirements were fulfilled through the development of specialized testing equipment that permitted dynamic testing under precisely simulated environmental conditions.

Tensile and Compression Testing

The equipment used for conducting tensile and compression tests under simulated space conditions consists of a tensile-testing machine integrated with a space-environment simulator. The simulator is capable of pro-

ducing a vacuum of 1×10^{-8} torr and a temperature range from -300° to -1800° F and accommodates an external solar simulator that irradiates the sample being tested.

A series of tests to determine the effects of ultrahigh vacuum and high temperature on the breaking strength and elongation of aluminized Kapton was performed with the tensile/simulator array using specially fabricated jaws. Apollo extravehicular space-suit thermal-protective-cover-layer samples of aluminized Kapton served as specimens for basic materials tests. In addition, seam strengths between sections of aluminized Kapton bonded with Kapton adhesive tape were evaluated. Satisfactory test results qualified both materials for use in the intended application.

Folding-Endurance Testing

The folding-endurance tester (fig. 132) is used to determine the endurance of materials to repeated folding in the simulated environment of space. The oscillating heads are designed for continuous operation until the specimen fails under applied loads of 1.5 kg or less. The oscillating head rotates through a 135° angle centered on the vertical position at speeds as high as 200 double folds per min. Breakage of the test specimen disconnects the counter to terminate the test. The

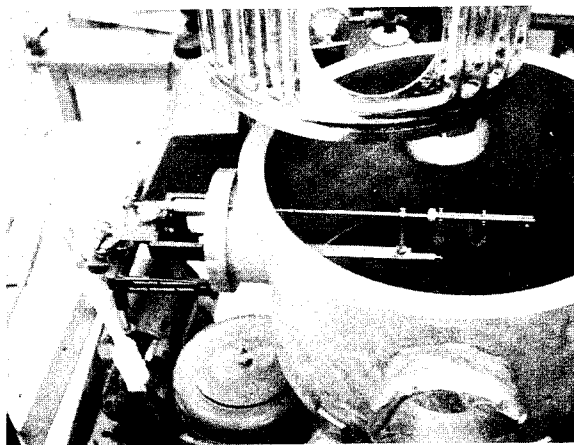


FIGURE 132.—Folding-endurance tester.

folding-endurance tester is being installed in a vacuum test chamber in figure 132.

All individual material layers as well as the multilayered integrated thermal-micrometeoroid garment (ITMG) cover garment of the space suit, exterior to the pressure bladder, were tested using this equipment. Single layers were considered satisfactory if they withstood 5000 or more cycles using a 1-kg load. For the composite multilayer cover garments consisting of 14 individual pieces, withstanding 50 000 or more cycles was considered satisfactory performance. However, withstanding more than 100 000 cycles is not unusual. When testing multilayered composites, an inspection of the individual layers is made each 5000 cycles.

Abrasion and Wear Testing

The abrasion and wear tester (fig. 133) performs abrasion and wear tests separately. In the abrasion test, a specimen of space-suit material is rubbed against an abrasive material in a reciprocal or rotational motion; in the wear test, the specimens are rubbed against each other. A static load of 0.25 to 2.0 lb can be applied. The specimens used in these tests are disks of space-suit material mounted in the testing jig so as to form a diaphragm. The vacuum of the test chamber is maintained on the outside surface of the diaphragm while the internal pressure of the diaphragm is controlled. The tests are continued for a specified period or until failure of the specimen. The term failure means that either an abrupt increase of pressure occurs within the test chamber or a constant leak develops. The testing is terminated automatically if a failure occurs, and the number of cycles is recorded. The internal pressure of the diaphragm is maintained at 3.7 psig, the normal operating pressure of the space suit.

To evaluate the outermost fabric layer of the space suit for abrasion resistance, fine-grit sandpaper was used as the abrasive medium. The motion was reciprocal and the load was 2.0 lb. This fabric, Beta fiber glass 4484, withstood 500 ± 50 cycles before wearing through.

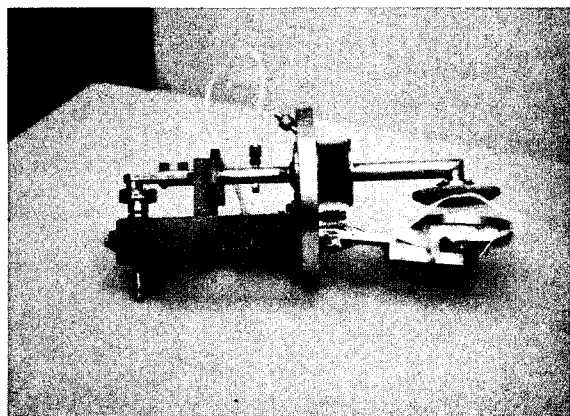


FIGURE 133.—Abrasion and wear tester.

To evaluate the wear resistance of the multilayered ITMG cover garment, the disk of material, which consisted of the composite layup, was rubbed against a piece of the outermost layer; that is, Beta fiber glass 4484B. The motion was reciprocal and the load was 2.0 lb. Values of more than 1000 cycles were obtained repeatedly.

The abrasion and wear tests are more useful as a relative comparison of materials than as a measure of absolute performance.

Finger/Wrist and Boot/Ankle-Flexure Testing

The finger/wrist-flexing tester (fig. 134) is used for simulating the flexing of a hand in a space suit glove. The external surfaces of the glove are exposed to the vacuum and temperature of the chamber while the internal pressure is controlled at 3.7 psia, the operating pressure of the space suit. The test objectives are to determine (1) the number of flexing cycles to failure of the finger joints at an arc-flexing range up to 180° and (2) the number of flexing cycles to failure of the wrist joints. These tests are conducted in a vacuum test chamber at an internal pressure of 3.7 psia while the chamber pressure is maintained at 1×10^{-5} torr.

The boot/ankle-flexing tester (fig. 135) simulates the motions of the foot and ankle in a boot. The tester simulates a 90° ankle flexure. These tests are conducted in the

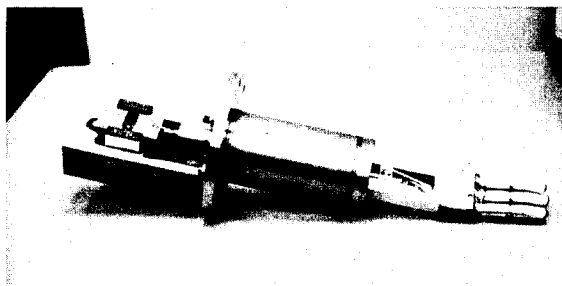


FIGURE 134.—Finger/wrist-flexing tester.

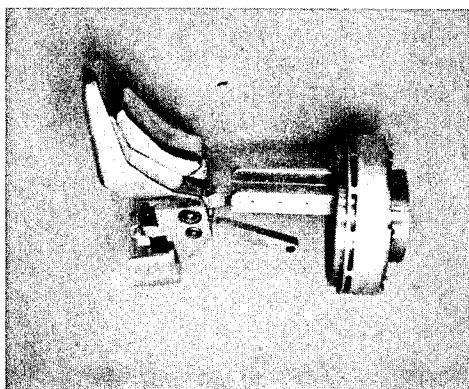


FIGURE 135.—Boot/ankle-flexing tester.

same manner as the flexure testing of the glove and wrist.

In both the finger/wrist and boot/ankle tests, a test component is considered failed when the leakage rate increases significantly. This failure is observed by recording the time of pressure loss of the test component after it has been isolated from the oxygen supply. This measurement usually is made after each 1000 cycles. The mode of failure usually is not a gradual degradation but rather a very noticeable increase in the leakage rate. For these space suit components (i.e., gloves and boots), withstanding more than 100 000 flexure cycles before failure is not uncommon.

Other Tests

Other mechanical testing devices have been designed to impose "in-use" simulated

wear on other space-suit components such as the entrance pressure-sealing slide fastener, the helmet and neck-ring disconnects, and the elbow and knee bellows.

Deep-Space-Simulation Materials Testing

One of the most complex pieces of materials test equipment is the deep-space environmental-simulator chamber (fig. 136). This chamber is unique in that materials can be exposed simultaneously to the following conditions.

1. Vacuum
 - 10^{-12} torr (clean and dry)
 - 10^{-10} torr (typical test)
2. Temperature, $\pm 250^{\circ}$ F
3. Electromagnetic radiation:
 - Near infrared, visible, and ultraviolet
0.25 to 2.5 microns (xenon lamp)
 - Extreme ultraviolet
1050 to 2000 Å (Lyman-alpha source)
 - Soft X-ray
10 to 500 Å (X-ray generator)
 - Solar-wind particulate flux, electron and proton
3 to 150 keV energy at 5×10^8 particles/cm²/sec flux density (linear accelerators)

The simultaneous exposure to all conditions allows the study of possible synergistic degradative effects on materials; thus, samples can be examined both for changes under test conditions and for physical-property degradation after a test. Many space-suit materials and nonmetallic materials from the portable life-support system (PLSS) have been tested in the simulator.

MATERIALS FOR IMPROVED FIRE SAFETY

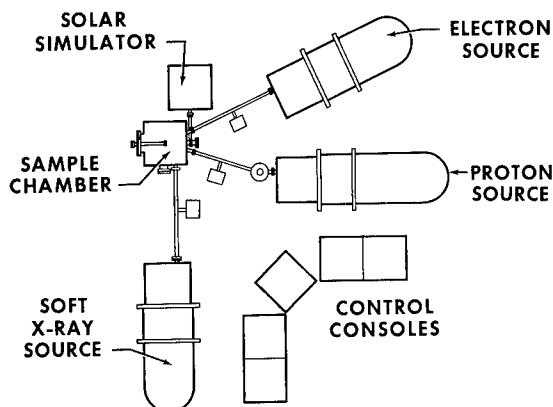


FIGURE 136.—Combined-environment-simulator schematic.

CONCLUDING REMARKS

The tests described in this report are representative of those required to ensure satisfactory performance of the nonmetallic materials used in the Apollo Program. Not only were specified materials qualified through such testing, but the experience gained through materials testing has aided in the selection of particular materials for particular applications. Test results also have suggested advantageous combinations of materials for the fabrication of specific functional end-items.

Although the Apollo specialized test program culminated in the successful lunar-landing missions, its role continues to be an active one. The constant search for new nonmetallic materials for even more rigorous applications requires a creative testing capability. Testing materials for improvements in existing suit designs, based on flight-crew recommendations, is accomplished in much the same manner as for new suit designs and is of equal importance.

Development of an Oxygen Impact-Testing Method

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Many materials burn, often catastrophically, if subjected to external stimuli in the presence of oxygen. The aerospace industry, with its widespread use of both liquid oxygen and gaseous oxygen, is particularly concerned with this problem, and much effort has been expended in attempting to define the degree of hazard associated with the various materials under various types of external stimuli. This hazard is also of considerable interest to many nonaerospace industries and institutions because the use of liquid and gaseous oxygen is widespread. Many spacecraft accidents are attributed to the use of non-compatible materials in oxygen-system-regulator diaphragms, valve seats, and so forth.

One of the initial problem areas to receive significant attention was that of severe mechanical-impact conditions in liquid-oxygen systems. Consequently, considerable effort has been expended in the development of a liquid-oxygen impact-test method to aid in the selection of materials for these systems; and, from this effort, a partially standardized liquid-oxygen impact-test technique has evolved. The data accumulated with this procedure are substantial.

In contrast to the effort that has been expended in the development of a liquid-oxygen/materials compatibility test method, relatively little attention has been given to the problem of developing a test for gaseous-oxygen/materials compatibility, and no proven test methods exist in this area. As a result, designers selecting materials for use in pres-

surized gaseous-oxygen systems have relied on the rather indirectly applicable results of liquid-oxygen impact tests. In view of the physical differences between liquid and gaseous oxygen, this obviously is undesirable.

In an attempt to provide a more appropriate method for determining gaseous-oxygen/materials compatibility, the Manned Spacecraft Center (MSC) recently began a program to develop a reliable gaseous-oxygen impact-test method for use in selecting materials for pressurized gaseous-oxygen systems employed in ground facilities and spacecraft. The purposes of this paper are to summarize the background information upon which the gaseous-oxygen impact-test development plans were formulated and to describe the present status of this program.

BACKGROUND AND PRESENT STATUS

Liquid-Oxygen Impact Test

In the late 1950's, the Marshall Space Flight Center (MSFC) devised a drop-weight impact tester and a test method for measuring impact sensitivity of materials in liquid oxygen (LO_2) (ref. 1). Considerable effort has been expended in refining and standardizing this technique, and these efforts have resulted in the adoption of standard impact-sensitivity-test methods in the form of U.S. Air Force (USAF) Specification Bulletin 527 (ref. 2) and NASA specification MSFC-SPEC-106B (ref. 3). More recently, the sim-

ilar characteristics of these two methods have been combined in the American Society for Testing and Materials (ASTM) Test Method D2512 (ref. 4). The same basic drop-weight-type tester is used in all these test methods, with only minor variations in test procedures and in the handling of the test materials. In all instances, the test material is placed in an aluminum specimen cup in the presence of LO_2 , and a stainless-steel striker pin is placed upon the test material. A plummet is released from a selected height, and observations are made as to whether or not a reaction has occurred. In all three methods, the basic concept used is that of attempting to measure the "threshold value" of a material by finding the highest drop height at which the material under test will withstand 20 consecutive test drops without reaction. The threshold value thus obtained is used as the relative sensitivity rating for the material. In the USAF and NASA methods, described in references 1 and 2, a variation of the threshold-value technique is used to qualify materials for service. In this variation, 20 or more drops are made from a fixed height, and the materials are accepted or rejected on a go/no-go basis.

Unfortunately, the methods discussed in references 1 and 2 have been limited from the beginning because of rather poor repeatability and reproducibility, as discussed in the precision statement published in reference 4. However, in spite of poor precision, until recently, this method was the primary test by which materials were chosen by the aerospace industry for use in oxygen systems. Insofar as is known to the writer, all the LO_2 impact-test facilities in this country except one are set up in adherence to this procedure. This one facility is at the Southwest Research Institute, San Antonio, Texas. This facility originally was installed under USAF contract in the late 1950's and, for several years, was operated in accordance with the procedure in reference 2. Generally, the research program followed during this period was similar to the programs of other organizations in the field; the program was a

systematic investigation of the effects of various equipment adjustments in an attempt to determine the cause or causes of the poor precision of the threshold-value method. In the mid-1960's, however, both the Southwest Research Institute and the USAF concluded that the prime cause of the inconsistency was not the equipment but the procedure. This conclusion resulted from reviewing impact-sensitivity research in the field of condensed-phase explosives and liquid monopropellants. It was learned that, at first, these researchers had followed the threshold-value approach but later abandoned it as unworkable. A much more acceptable method was adopted that involved measurement of the "50-50 go/no-go point," which is the drop height at which 50 percent of the drops cause reactions. The fundamental principles of probability mathematics were applied in establishing this point. It was concluded that LO_2 impact-sensitivity testing had encountered the same problem and possibly could benefit from the same solution. It was only after a considerable period of trial-and-error redesign of the striker pin and specimen cup that the new technique could be used. Once operational, however, the new technique, which is known as the "up and down" or Bruceton method, proved to be quite efficient and very repeatable.

It was learned that the precision with which sensitivity could be rated by the up-and-down test was much improved over that of the previous test methods. However, with improved precision, it also was noted that the sensitivities of the materials tested were so nearly the same that significant distinction between them was difficult. Moreover, as would be suspected intuitively (from the types of materials tested), some of the materials reacted violently while others yielded, at worst, only small char marks—no flash or sound resulted. Clearly, the violent reactors would be more hazardous in an LO_2 system than the mild reactors; nevertheless, sensitivity measurements alone did not define the obvious difference quantitatively.

The next logical step was the development

of some means for making quantitative measurements of reaction intensity during impact tests. The equipment subsequently developed for this purpose at the Southwest Research Institute proved quite satisfactory, and the results of an extensive test program using this apparatus were published in a USAF Technical Rept. (ref. 5) in December 1967 and in the American Society of Mechanical Engineers Transactions in July 1968. The method also appears in the ASTM Standards, Part 18, October 1969.

Briefly, the reaction-intensity-measuring system consists of a probe device that makes a relative measurement of the peak air-shock pressure generated by a reaction. For the test drops, two probe devices are placed adjacent to the specimen cup. The highest individual peak-pressure reading obtained is defined as the maximum peak pressure and is taken as the reaction-intensity rating of the material under test.

Even under the most favorable conditions, the impact testing of materials in LO_2 sometimes gives anomalous results. These anomalies are caused by a lack of precise control over certain parameters, particularly sample temperature. Sample temperature is a function of the LO_2 boil-off and of the conduction of heat out of the equipment and the atmosphere into the sample. Another factor that produces lack of precision in the LO_2 impact-test system is frictional loss to the rails that guide the falling plummet; this loss prevents the plummet from producing precise energy levels. Because of these observable problems, plans were made early in the Apollo Program to develop a testing method whereby these problems would be solved. It was concluded that these problems would be largely corrected by changing from an LO_2 test medium to a gaseous-oxygen (GO_2) test medium. Furthermore, these plans included the means for maintaining predetermined temperatures in the sample region by employing a heat medium circulating through a jacketed vessel. It also was decided that frictional loss to the guide rails could be circumvented by using a free-falling plummet.

From these early concepts, steps were taken to produce a system free of some of the old problems. This system later became known as the GO_2 impact-test method.

Gaseous-Oxygen Impact Test

Because the use of oxygen, either liquified or pressurized, is hazardous and demands discreet selection of associated system materials, the necessity for having dependable screening techniques for these materials is self-evident. Whereas the LO_2 impact test has been improved significantly during the past few years and is considered satisfactory for screening materials to be used in LO_2 systems, it has shortcomings for screening materials to be used in GO_2 systems. The significant differences between LO_2 and GO_2 require that different test methods be used. Some of these differences are temperature (-183°C compared with ambient), pressure (some GO_2 systems operate at a pressure under several thousand psi), extent of oxygen permeation into the sample, and physical effects upon the sample. For this reason, development of a GO_2 test system was undertaken.

The specific objectives for the new system were:

1. To develop new equipment using variable high-pressure GO_2 instead of LO_2 as the medium for testing materials
2. To develop a useful procedure for qualifying spacecraft materials used in an oxygen atmosphere
3. To make initial test runs using standard materials and Apollo flight materials for comparison
4. To determine the extent to which transducer readout data could be used to verify visual observations of tested samples or actually to increase the sensitivity and precision of the test interpretation
5. To work toward the standardization of the test

With these objectives in mind and with the desire to circumvent the problems of existing test systems, work was begun on equipment

design. Though some existing problems would be solved, it was obvious that new problems would develop because the planned system would involve the use of pressurized oxygen in quantities sufficient to cause considerable hazards. It also was obvious that a pressurized-oxygen system would have the potential of becoming a "flaming blowtorch," feeding on itself for fuel, should a hot spot develop in the system. (It is known that iron will burn vigorously in oxygen when sufficiently heated.) These concerns were taken into account in the design of the GO_2 test equipment and in the establishment of the GO_2 test procedures.

Gaseous-Oxygen Test Equipment

The test equipment developed at the MSC consists of three identical instrumented and remotely controlled impact-test chambers designed for a working pressure of 7500 psig at 450° F and a test pressure of 15 000 psig at 70° F. A schematic drawing of the test chamber illustrating the various chamber components is shown in figure 137. This illustration depicts the system pressurized and ready for the drop test. The specimen-prepa-

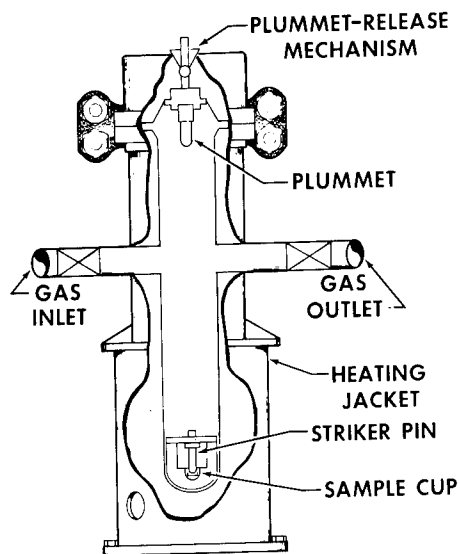


FIGURE 137.—Schematic drawing of test chamber.

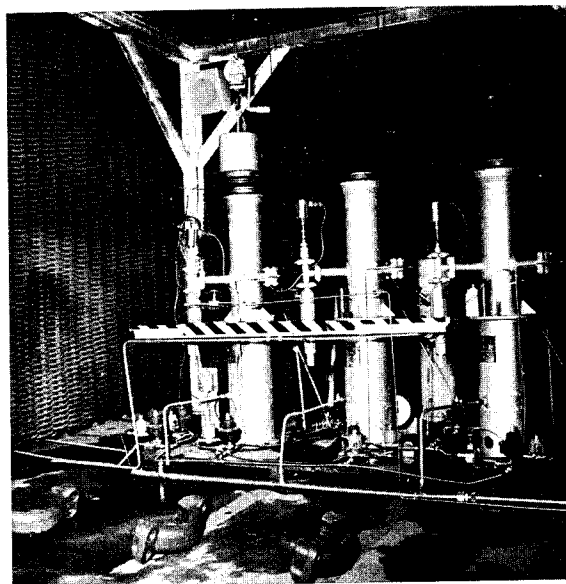


FIGURE 138.—Specimen-preparation equipment.

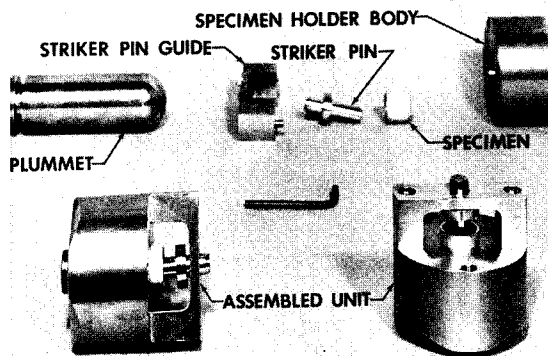


FIGURE 139.—Specimen-holder assembly and plummet.

ration equipment is shown in figure 138. (Sample preparation details are discussed in the subsequent section, entitled "Test Procedure.") The impact-test specimen-holder assembly with a solid sample in place under the 0.5-in. diam impact pin (striker pin) is shown in figure 139. Also shown in figure 139 are the disassembled parts of the assembly, the specimen cup, and the plummet. Under test conditions, the plummet is dropped onto the striker pin to impart a predetermined quantity of energy to the specimen.

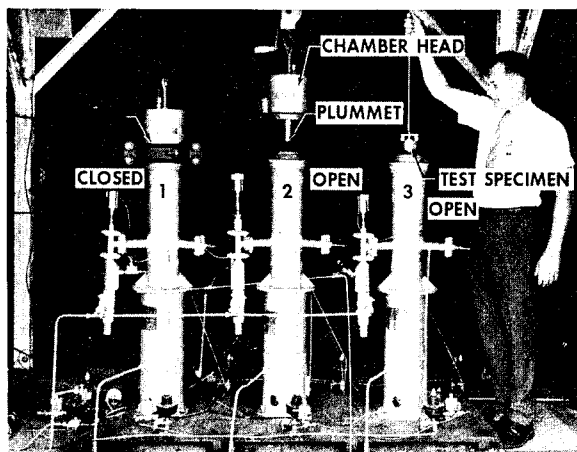


FIGURE 140.—Impact-test chambers.

Three identical test chambers in which impact tests were made under oxygen pressure are shown in figure 140. The chamber at the left is closed and ready for the impact test. In the center chamber, the plummet is shown suspended in the head before the head is clamped in place. At the right, a specimen in the specimen-holder assembly is shown being lowered to a precise position at the bottom of the chamber. The extension at the bottom of the holder fits into a slot at the bottom of the chamber. Also shown in this figure are the valves and manifold systems for creating the desired test conditions for each test chamber. Each chamber can be purged with nitrogen, pressurized with oxygen, or evacuated, as desired. Also, the desired preimpact (initial) temperature is established with a circulating heat medium, and the plummet is dropped by remote control. The test-chamber area is isolated from the control and recording area by concrete walls lined with blast safety mats.

The test-control and data-recording systems consist of two consoles. Each console is connected to each test chamber individually and independently. One console controls the systems for chamber evacuation, oxygen and nitrogen flow, chamber temperature, and solenoid release of the plungers. This console also includes temperature and pressure indicators for each chamber. The other console

records shock waves on a high-speed oscillograph and records the temperature and pressure on a strip chart. Thermocouples are used for temperature measurement, while Taber transducers are used for pressure pickups. Kistler 603-A transducers are used to identify high-frequency shock waves.

Early results showed that the electronic measurements of the sample reactions were of little benefit as compared to visual inspection after the test, because no shock wave above the background noise was measurable; therefore, only visually observed results are recorded. The lack of shock wave apparently was caused by the fact that the tested samples exhibited "burning" characteristics as opposed to detonation. In contrast, the LO_2 impact test often produces very loud reactions.

Test Procedures

Because the testing of combustible materials in chambers containing several cubic feet of highly pressurized oxygen constitutes a significant fire hazard, stringent safety precautions were enforced. All test equipment was cleaned and dried thoroughly. Subsequently, the specimen cup, striker pin, measuring cup, specimen-cup holder, plummet, and so forth were handled with tongs or chemically clean gloves. Also, appropriate precautions were taken to prevent contamination of test specimens.

Solid materials were cut into disks approximately 0.70 in. in diam and approximately 0.050 in. thick. The disks then were washed in detergent and dried before being placed in the specimen cup for testing. Semisolid material was measured in the 0.050-in. deep measuring cup, and the measuring cup containing the specimen then was placed in the specimen cup. Liquid material was weighed or measured volumetrically to produce a calculated 0.050-in. deep volume of material in the specimen cup. The specimen cup then was placed in the cup-holder assembly with the striker pin resting on or in the specimen. After the measurement, the assembly con-

taining the specimen was placed in the test chamber. At that time, the plummet was placed in the test-chamber head, and the head was clamped onto the chamber. By remote control, the test chamber was flushed with oxygen twice to reduce air contamination to acceptable limits before pressurization with oxygen for the test. Also, from the remote-control console, the temperature was stabilized by circulation of a uniform-temperature fluid through the test-chamber jacket. At the appropriate time, the plummet was dropped onto the striker pin, thus imparting the desired (impact) energy to the specimen under oxygen pressure. The recording console recorded the test-chamber conditions before, during, and after the plummet drop.

A fresh striker pin was used for each test, and a microscopic inspection of the striker-pin head was made after each test to locate the plummet imprint. When the inspection showed that the plummet landed outside a 3-mm radius measured from the center of the striker-pin head, the test was invalidated. This precaution was taken to ensure the delivery of a true and constant quantity of impact energy in each test.

RESULTS AND DISCUSSION

Although the newly developed GO_2 impact-test system was patterned partially after the LO_2 impact-test system (similar energy sources from a falling plummet, similar striker-pin assembly, and similar sample cups), the evaluation of the system was not straightforward. No valid criteria for selection of impact-energy values for standardization existed. (The attempt always could be made to duplicate the use condition for the sample material being tested, but this procedure has disadvantages in that standardization of testing parameters is prevented.) It might seem logical to choose 72 ft-lb as the standard value, because 72 ft-lb is the energy figure generally used in the LO_2 test system; however, using 72 ft-lb as the standard was impractical because of the need to keep the

system small in the interest of safety. Also, the choice of 72 ft-lb apparently has no absolute scientific basis. Furthermore, it is known that a given energy may yield drastically different results if the velocity of the plummet fall is varied, even if the plummet weight also is changed in the proper ratio to produce the same energy level. This result is caused by the production of a more or less effective transfer of energy to the sample. The amount of energy transfer is affected greatly by the rate of energy release. This factor, along with the observed fact that small changes in sample-cup material or striker-pin surface area greatly affect the results, demonstrates the problems involved in establishing suitable standard test parameters for an impact test system. Because of these considerations, a series of plummets was used varying from 1 to 20 ft-lb. Finally, 10 ft-lb was selected as a standard value except for those tests calling for reproduction of test-material-use conditions. The 10 ft-lb level was selected because the equipment responded best with this plummet.

The probable reasons for the previously discussed observations may be found by examination of the generally accepted theory of the impact-ignition mechanism. This theory suggests that impact produces ignition through concentration of energy into hot spots, not rough general compression of the bulk sample material. However, because much of the total impact energy delivered does produce deformation of the sample and sample cup, it follows that only a portion of the delivered energy is manifested at a hot spot site as an ignition stimulus. Therefore, it can be seen that the amount of actual ignition stimulus delivered depends not only upon the gross impact stimulus applied but also on how efficiently that stimulus is localized into hot spots. The efficiency obtained in localizing hot spots is a function of the test method. Therefore, it is clearly misleading to conclude from an impact test that a certain material is safe if it passes tests at a given energy level in the service system, because a much smaller energy input might cause igni-

tion through better localization. Impact sensitivity, in other words, is a highly system-dependent phenomenon. This dependence of the sensitivity, then, suggests that some materials may need to be qualified over a spectrum of conditions overlapping the use conditions for the sample being studied, as opposed to adopting an arbitrary set of conditions contained in a standard test method.

The experimental work consisted essentially of subjecting materials to mechanical impact while under various GO_2 pressures. The test materials in the following list were supplied by various manufacturers from their commercial stocks.

1. Adhesive tapes
2. Adhesives with activators
3. Chewing gum
4. Chlorinated products
5. Cloth materials
6. Coatings
7. Dry-film lubricants
8. Fluoridated products
9. Greases
10. Insulating materials
11. Liquid hydrocarbon lubricants
12. Paints
13. Plastics
14. Rubber products
15. Silicones
16. Petroleum waxes

Testing of these materials resulted in both evaluation of the flammability of the materials and validation of the test equipment.

Catastrophic oxidation of the noncompatible materials was detected readily by visual observation, because this type of reaction consistently resulted in a rapid burn, leaving highly oxidized byproducts (ashes). It is significant that, in every instance in which the sample ignited, it continued burning until totally consumed. However, with the LO_2 test system, the ignited samples self-extinguished before complete combustion in many cases. This difference apparently was caused by rapid cooling of the heated portion of the sample directly under the striker pin once the fire zone was in direct contact with the

cold LO_2 and the frozen outer perimeter of the sample disk. The indication is that pressurized oxygen may present a greater fire hazard on a sustaining basis than does LO_2 .

The results obtained in 10 standard-materials tests and 33 test-material tests are shown in tables LXIX and LXX, respectively. Test results from the standard samples indicated that the test conditions were in the range of practicality; therefore, similar conditions were used to test the Apollo materials. Although these results indicate that some noteworthy correlation is found in comparing LO_2 test data with GO_2 test data, some samples deviated considerably in that they passed the LO_2 test but failed the GO_2 test, even though the impact energy for the two systems varied sevenfold (72 ft-lb compared with 10 ft-lb).

Although the impact energy was controlled precisely under the test conditions, the effect of the impact energy seemed to be influenced by the physical as well as the chemical properties of the samples. The data summarized in tables LXXI and LXXII show that liquid and semisolid lubricants were relatively stable (compatible with oxygen) under test conditions; 91 percent of the tests showed no combustion. The liquids exhibited good stability, probably because it was not possible to create sufficient impact heat in the sample for ignition to result. Therefore, liquids may have shown better compatibility than would be expected from noting only the chemical composition of the liquids. All fluorocarbons tested (Viton-A and -B, Teflon, Kel-F and Krytox 240) showed complete stability while all others showed mixed results.

Poor repeatability for certain samples was attributed to nonuniformity of test materials, slight variations in test conditions, and numerous other unknown factors. However, the GO_2 impact test, as it was conducted, is a worthwhile method for screening materials for stability in an atmosphere of pure oxygen.

Because of the widespread use of LO_2 or pressurized oxygen by almost every major industry and institution, the nonaerospace

TABLE LXIX.—Summary of GO_2 Impact-Test Data for Standard Materials

Test number	Material	Manufacturer	Test date	Test pressure, psia (^a)	Test temperature, $\pm 10^\circ$ F	Impact energy, ft-lb	Number of runs	Number of failures
1	Polyphenylene oxide	General Electric	Sept. 24, 1968	2000	75	20	22	None
2	Lexan 1100 series (polycarbonate)	General Electric	Sept. 26, 1968	2000	80	20	22	None
3	Vespel (polyamide)	Du Pont	Sept. 28, 1968	2000	75	20	38	2
4	Vespel (polyamide)	Du Pont	Oct. 9, 1968	2000	75	10	42	None
5	Teflon	J. L. Dore	Sept. 30, 1968	2000	80	20	21	None
6	Nylon	Du Pont	Oct. 1, 1968	2000	80	20	21	None
7	Fluorel 1059	General Electric	Oct. 7, 1968	2000	75	20	12	None
8	Silicone 5537	General Electric	Oct. 15, 1968	2000	75	10	16	7
9	Silicone 5537	General Electric	Oct. 8, 1968	100	80	20	9	3
10	Silicone 5537	General Electric	Oct. 8, 1968	20	75	20	21	None

^a Oxygen, aviator's breathing grade, specification MIL-Q-2710C.TABLE LXX.—Summary of GO_2 Impact-Test Data for Test Materials

Test number	Material	Manufacturer	Test date	Test pressure, psia (^a)	Test temperature, $\pm 10^\circ$ F	Impact energy, ft-lb	Number of runs	Number of failures
1	Astronauts' chewing gum	NA ^b	Sept. 21, 1968	20	80	20	5	None
2	Astronauts' chewing gum	NA	Sept. 21, 1968	2000	80	20	6	None
3	Viton EMS-338	Precision Rubber Products	Oct. 16, 1968	2000	80	10	20	None
4	Silicone elastomer 342	Precision Rubber Products	Oct. 17, 1968	2000	70	10	20	4
5	Ethylene-propylene rubber (EPR) elastomer EMS-388	NA	Oct. 18, 1968	2000	75	10	9	8

6	EPR elastomer EMS-388	NA	Oct. 18, 1968	100	75	10	21	None
7	Teflon EMS-372	J. L. Dore	Oct. 21, 1968	2000	80	10	21	None
8	Loctite grade C		Oct. 22, 1968	2000	70	10	20	None
9	A-2 Adhesive/activator A	Armstrong	Oct. 23, 1968	2000	70	10	20	4
10	A-2 Adhesive/activator A	Armstrong	Oct. 24, 1968	100	70	10	22	None
11	Invelco 33F grease	NA	Oct. 24, 1968	2000	70	10	20	None
12	Epibond 123/hardener 931	NA	Oct. 25, 1968	2000	75	10	9	5
13	Epibond 123/hardener 931	NA	Oct. 28, 1968	100	75	10	21	None
14	Dow Corning 33 grease	Dow Corning	Oct. 28, 1968	2000	75	10	20	None
15	Silicone elastomer SE-550	NA	Oct. 29, 1968	2000	75	10	9	5
16	Krytox-240 AC grease	Du Pont	Oct. 29, 1968	2000	75	10	20	None
17	Andox-C oil	Humble Oil	Oct. 30, 1968	2000	80	10	21	None
18	Viton-B	NA	Oct. 31, 1968	2000	80	10	21	None
19	Viton-A HS 757-A	NA	Nov. 1, 1968	2000	80	10	20	None
20	Electrofilm 2006	NA	Nov. 4, 1968	2000	80	10	21	None
21	Viton cement and coating material	NA	Nov. 5, 1968	2000	80	10	20	None
22	Silicone rubber primer A-4094	Dow Corning	Nov. 6, 1968	2000	80	10	21	None
23	Scot-weld structural adhesive	3M	Nov. 8, 1968	2000	75	10	19	2
24	Silicone primer SS 4004	General Electric	Nov. 13, 1968	2000	75	10	6	3
25	Room-temperature vulcanizing (RTV) adhesive	NA	Nov. 13, 1968	2000	75	10	4	4
26	Teflon tubing	J. L. Dore	Nov. 15, 1968	2000	75	10	21	None
27	Electrofilm 3406	NA	Nov. 18, 1968	2000	75	10	20	None
28	Kel-F, bar stock	NA	Nov. 19, 1968	2000	80	10	18	None
29	L-3203-6	Raybestos-Manhattan	Nov. 20, 1968	2000	80	10	20	None
30	L-3217-1	Raybestos-Manhattan	Nov. 21, 1968	2000	80	10	20	None
31	L-3217	Raybestos-Manhattan	Nov. 25, 1968	2000	75	10	8	None
32	QED 65 oil	NA	Nov. 28, 1968	115	135	10	20	None
33	Houghton safe oil 1120	E. F. Houghton Co.	Nov. 28, 1968	115	145	10	20	None

^a Oxygen, aviator's breathing grade, specification MIL-Q-2710C.

^b Not available.

TABLE LXXI.—Characterization by Chemical Designation

Item number	Product name	Chemical designation	Physical state	Number of tests	Compatibility with GO at 72° F under 2000 psia and 10-ft-lb impact, in percent of tests showing no combustion
1	Viton EMS-338	Fluorocarbon ($-\text{CF}_2-\text{CF}_2-$) _n	Solid	20	100
2	Silicone elastomer 342	Silicone ($-\text{SiR}_3\text{O}-$) _n	Semisolid	20	80
3	FPR elastomer EMS-388	($-\text{CH}_2-\text{C}_6\text{H}_4-\text{CH}=\text{CH}_2-$) _n	Solid	9	10
4	Teflon elastomer EMS-372	Fluorocarbon ($-\text{CF}_2-\text{CF}_2-$) _n	Solid	21	100
5	Loctite grade C	Polyester cement ($\text{COOH}-\text{C}\equiv\text{CH}-\text{CO}_2-\text{CH}-\text{CH}_2-\text{CH}_2-\text{OH}$) _n	Liquid	20	100
6	A-2 adhesive/activator A	Epoxy (without activator) $\begin{array}{c} \text{Q} \quad \text{O} \quad \text{Q} \\ \text{Q} \quad / \quad \text{Q} \\ \text{Q} \quad / \quad \text{Q} \\ \text{Q} \quad \text{CH}-\text{CH}_2-\text{O}-\text{R} \quad \text{R}-\text{O}-\text{CH}_2-\text{CH}-\text{CH}_2\text{Q}_2 \\ \text{Q} \quad \text{I} \quad \text{I} \\ \text{Q} \quad \text{HC}-\text{CH} \\ \text{Q} \quad \text{I} \quad \text{I} \end{array}$ where R is C ₆ H ₄	Solid	20	80
7	Invelco 33F grease	Fluorosilicone	Semisolid	20	100
8	Epibond 123/hardener 931	Epoxy (without activator), same as in item 6	Solid	9	40
9	Dow Corning 33 grease	($-\text{SiR}_3\text{O}-$) _n	Semisolid	20	100
10	Silicone elastomer SE-550	($-\text{SiR}_3\text{O}-$) _n	Solid	9	60
11	Krytox 240 AC grease	Fluorocarbon ($-\text{CF}_2-\text{CF}_2-$) _n	Semisolid	20	100
12	Andox-C oil	Complex sodium grease (C ₁₇ H ₃₅ -COONa) plus long, branched hydrocarbon	Liquid	21	100
13	Viton-B	Fluorocarbon ($-\text{CF}_2-\text{CF}_2-$) _n	Solid	21	100
14	Viton A HS 757-A	Fluorocarbon ($-\text{CF}_2-\text{CF}_2-$) _n	Solid	20	100
15	Electrofilm 2006	Unknown	Liquid	21	100
16	Viton cement and coating material	Fluorocarbon ($-\text{CF}_2-\text{CF}_2-$) _n	Solid	20	100
17	Silicone rubber primer A-4094	($-\text{SiR}_3\text{O}-$) _n	Solid	21	100
18	Scot-weld structural adhesive	Epoxy (without activator), same as item 6	Solid	19	90
19	Silicone primer	($-\text{SiR}_3\text{O}-$) _n	Liquid	6	None
20	RTV additive	Unknown	Semisolid	4	None
21	Teflon tubing	Fluorocarbon ($-\text{CF}_2-\text{CF}_2-$) _n	Solid	21	100
22	Electrofilm 3406	Unknown	Solid	20	100
23	Kel-F bar stock	Fluorocarbon ($-\text{CF}_2-\text{CF}_2-$) _n	Solid	18	100
24	QED 65 oil	Hydrocarbon	Liquid	20	100
25	Houghton safe oil 1120	Hydrocarbon	Liquid	20	100

TABLE LXXII.—*Characterization by Chemical or Physical Designation*^a

Item number	Chemical or physical designation	Number of designated types tested	Total number of tests	Compatibility with GO ₂ at 72° F under 2000 psia and 10-ft-lb impact, in percent of tests showing no combustion (^b)
1	Fluorocarbon.....	9	181	100
2	Silicone hydrocarbons.....	5	76	78
3	Common hydrocarbons.....	7	117	83
4	Greases and lubricants.....	6	108	91

^a Summary of data in table LXXI.^b Average of percentages in table LXXI.

applications of these testing concepts should be numerous. Those producers, vendors, and users of equipment such as oxygen regulators containing polymeric diaphragms and solenoid valves with combustible seat materials are affected directly by the availability of reliable materials for these applications; this reliability can be improved greatly by better screening techniques. The user of oxygen-handling equipment, whether he be a welder, a hospital patient, an astronaut, or a high school chemistry student, should be protected by the proper combination of materials. This protection can be provided only by knowledgeable materials specialists within the production industry.

At this time, neither the equipment nor the procedure for the GO₂ impact-test method is considered to be standardized. In fact, the equipment configuration and procedures are now in the second generation of development. These changes are intended to improve the testing repeatability, to reduce the cost and size of the equipment, and to lessen the time required for testing samples. Hopefully, a simplified, relatively safe, automated system soon will be developed, permitting rapid testing of samples under conditions varying from vacuum to perhaps 10 000 psi oxygen and over a wide range of temperatures. Such a system would represent a vast improvement over existing equipment.

CONCLUDING REMARKS

The program to develop a gaseous-oxygen impact-test method proved that a mechanism totally enclosed in a high-pressure vessel consisting of a drop plummet for delivering precise impact to a sample through an impact striker pin could be developed for screening samples for flammability in high-pressure oxygen. The procedures used and the results obtained with these procedures indicated that acceptable repeatability could be obtained by using the described system. Examination of the data indicates that the fluorocarbon solids showed complete repeatability; all fluorocarbon solids passed the tests, showing no flammability. The least repeatable sample types were the semisolids and liquids because of the inability of the mechanism to deliver finite quantities of energy to the samples in a repeatable manner. When compared with solids of similar chemical composition, the liquids showed considerably better stability.

The use of carefully selected standard materials typical of the Apollo flight materials enhanced the interpretation of the data obtained from the test results, because the character of like substances could be compared easily. Results from the testing of the standard samples generally were comparable to results from the testing of the Apollo samples. For example, the fluorocarbon samples

showed complete stability in all tests, and all other types showed mixed results.

Though considerable effort was expended in establishing the capability of transducer readout for detection of test results through measurement of shock waves set up in the gas phase, the results were not conclusive. Because of this unreliability and because of the ease and precision with which visual observations were made after extraction of the exposed samples from the test chambers, the attempted use of instrumental readout of reactions was abandoned.

Standards of operation for the gaseous-oxygen impact-test system were established for testing specific materials. Although these standards were adequate for that specific task and, in fact, form a good basis for establishing future standards, further refinement and standardization are required.

The liquid-oxygen impact-test system, though useful for screening materials to be used in liquid-oxygen conditions, does not appear adequate for screening materials to be used in gaseous oxygen. The test method, being based on liquid oxygen, deviates to an extreme extent from gaseous-oxygen use conditions.

It should be emphasized that the gaseous-oxygen impact-test system is not fully devel-

oped as a standard test method; therefore, the data are to be used with discretion. Hopefully the continued development of the system will produce sufficient data for writing standard-use procedures. Because industry, in general, has never had a test system for screening materials under mechanical impact in pressurized oxygen, the testing concepts presented should be applicable to a wide variety of industries around the world.

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Odor Test

L. A. SCHLUTER AND D. L. PIPPEN

White Sands Test Facility

Mankind is beginning to recognize the need for reducing environmental pollution. A corresponding major problem of manned space flight is the buildup of objectionable, nauseating, and hazardous gaseous contaminants released from nonmetallic materials such as paints, adhesives, insulation, and fabrics. The spacecraft unlike earth, contains no "fresh morning breeze." Buildup of odors from nonmetallic materials in the spacecraft cabin could become nauseating and jeopardize a mission.

To prevent the use of material that would outgas objectionable or nauseating odors, an odor test was developed. This test provided a means whereby candidate spacecraft materials were subjected to a particular environment and the outgassed products were evaluated by an odor panel. This panel was comprised of individuals with acute olfactory senses. The test results of the odor panel provided design engineers with data regarding potential material-odor problems. The odor-test procedure, panel-member selection, and odor scoring methods are described and typical test results are presented in this paper.

TEST CONSIDERATIONS AND GUIDELINES

One of the major considerations of an odor test by a panel is panel-member safety. It would be hazardous to subject panel members to unidentified gases of unknown concentrations. Prior analysis of the gas and medical examinations of panel members be-

fore and after odor testing were thus required. These precautions gave reasonable assurance that members were subjected under medical surveillance to low-concentration levels of gaseous products. A separate analysis was conducted on each candidate material before the odor test. In this analysis, the offgassed products were examined by gas chromatography for carbon monoxide and total organics and also were subjected to an infrared scan for hydrogen cyanide, hydrogen sulfide, and other highly toxic substances. The odor panel conducted the odor test only when the analysis showed that the total organics level was below 250 ppm (by volume) and only when no toxic gases were present in detectable concentrations by infrared analysis. A nose and throat examination was given each panel member immediately before and after odor testing. This examination was essential. For example, after odor testing six materials (four Fluorels, one Beta fabric, and one Aclar), the medical examination revealed small, clear blisters in several of the members' throats. It was surmised that one of the Fluorel specimens may have been cured insufficiently. This was later found to be the case. In any event, immediate action was taken to limit the number of Fluorels tested by a panel to two materials. This limited the number of "sniffs" by each member to six. (Each candidate material is "sniffed" at three different concentrations by each panel member.) As a result of this action, no more blisters developed during testing. Some

2900 individual post-test medical examinations of odor-panel members at the NASA White Sands Test Facility (WSTF) have shown:

Nose irritation	133
Throat irritation	5

Panel members themselves report:

Lingering aftertaste	10
Headache	5

These figures are the results of testing approximately 1150 candidate spacecraft materials during 1968 and 1969. In all cases, the symptoms disappeared within 24 hours. Blisters that had developed disappeared with 5 days with no further complications.

A complement of 10 panel members has been used since extensive odor testing began in 1967. However, panel membership is permitted to vary from five to 10. The WSTF initiated a study to determine the effect of the size of the odor panel on odor-test results. This study used 20 panel members testing 33 samples. The results indicated that 10 members is the minimum number that should be used on a panel and that the decrease in standard deviation is quite small as the panel size is increased from 10 to 20. One of the most difficult aspects in developing the odor test was finding a sufficient number of qualified volunteers. This problem was overcome by forming an elite "Sniffers' Club" with fringe benefits of a periodic steak dinner and special awards for having participated in a certain number of tests.

To obtain "calibrated noses," a calibration or qualification procedure was used. The procedure essentially was to subject each odor-panel member periodically to a set of standard odors of various concentrations. The panel member was required to detect (but not necessarily identify) seven out of 10 standard odors of fixed concentration. The member was not informed which standard was being administered to him, and "blank" samples were intermixed with the standards. The standard or calibration odors used in qualifying odor-panel members are:

<i>Primary odor</i>	<i>Standard compound</i>
Ethereal	1,2 dichloroethane
Camphoraceous	1,8 cineole
Musky	15-hydroxypentadecanoic acid lactone
Floral	1-methyl-1-ethyl-2-phenylpropanol-1
Minty	methone (dl)
Pungent	formic acid
Putrid	methyl dithiomethane (methyl disulfide)
Blank	distilled water

These solutions were prepared freshly as required to assure good standards. No solution was used for more than a month. Panel members were qualified at 3-month intervals; also, a qualified member was required to pass the nose and throat medical examination as well as detect three randomly chosen standard odors before qualifying for a particular test sequence. The odor-test room was controlled; that is, no smoking was allowed in the area at any time, and other odoriferous materials were not permitted in the area.

TEST METHOD

Before the odor test, each material to be tested was subjected to a carbon monoxide, total-organics, and infrared analysis as previously described. The odor test then was initiated by preparing the material to the proper size, surface area, volume, or weight; it was then placed in a clean desiccator, which was evacuated and backfilled to 5 psia oxygen. The desiccator then was placed in a temperature chamber at a temperature of $155 \pm 5^\circ \text{F}$ for 72 hours. After 72 hours, the desiccator was removed, allowed to cool, and then charged with pure oxygen to ambient pressure.

Each panel member was given the nose and throat examination and then seated in a semiprivate booth where he was required to detect three of the standard odors. After this, each member was subjected to three randomly selected gas samples of specified dilutions of each test specimen. These dilu-

tions were: no dilution, 1:9, and 1:29 parts oxygen. The panel member recorded his score for each dilution tested. The score of each member was recorded on the total score card from which the final test-specimen average grade was obtained. A post-test nose and throat examination was then given each member. The scoring was based on the panel members' reaction to the test-specimen gas. The scoring system used was:

<i>Members' reaction</i>	<i>Score</i>
Undetectable	0
Barely detectable	1
Easily detectable	2
Objectionable	3
Irritating	4

An average rating of 2.5 or lower of any candidate material by the panel members signified that the material passed the odor test.

RESULTS

Typical odor-test results are shown in table LXXIII. Odor-test results for materials tested to date are tabulated in the document "Nonmetallic Materials Design Guidelines and Test Data Handbook," MSC-NA-D-68-1F. An indication of odor score distribution for 1000 randomly selected odor-test results is shown in table LXXIV. It is interesting to note that, of the total assortment of 1000 materials in this distribution, only 8 percent (80) of these materials were rejected as a result of the odor-panel evaluation (i.e., score greater than 2.5).

CONCLUDING REMARKS

The odor test is relatively simple to set up and administer. The test-scoring system provides a reasonable means for evaluating candidate spacecraft materials. For panel-member safety, effort must be expended on gas analysis and medical surveillance.

The odor test can be used by numerous

TABLE LXXIII.—*Typical Odor-Test Results^a*

Material generic name	Dilution		
	None	1:9	1:29
Alumina cement	1.4	0.4	0.1
Potting resin	2.0	1.2	.6
Kapton film	.7	.0	.0
Ion exchange resin	3.5	2.1	2.0

^a The above figures are average scores of a 10-member panel for the dilutions shown.

TABLE LXXIV.—*Odor Score Distribution for 1000 Candidate Materials*

Score range	Percent in score range
0 to 0.4	6.3
0.5 to 0.9	13.6
1.0 to 1.4	26.5
1.5 to 1.9	29.9
2.0 to 2.4	15.7
2.5 to 2.9	6.7
3.0 to 3.4	.7
3.5 to 4.0	.6

industries. Anyone who has entered a new automobile undoubtedly has noted a "new car smell" (not necessarily pleasant). Certain plastic toys have odors that frankly are irritating to nauseating. Some plastic shower curtains may be attractive to the eye but possess an objectionable odor. It is difficult to imagine an industry or product that could not benefit from a quantitative odor test in some way. We even judge a city on the basis of odor—the smell of the packing houses, the oil-refinery odor, and so on. Indeed, the current concern in regard to environmental pollution may give rise to test methods that are "people oriented" as well as instrument oriented. One such people-oriented test is the odor test described herein.

The American Society for Testing and Materials currently is evaluating a test procedure that eventually may serve as a national standard for odor evaluation.

Toxicology of Spacecraft Materials

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Nonflammability is of primary importance in selecting materials for spacecraft use. Also, it is essential that the materials selected not contribute noxious components to the atmosphere, thereby endangering the lives or performance of the crew. To meet these selection criteria, a multifaceted testing approach was used for candidate spacecraft materials. The first step in this approach was the routine testing of spacecraft materials for offgassing characteristics; arbitrarily established criteria were used. It was assumed that no qualified material would offgas a single component of very high toxicity and that, even if a qualified material did offgas a toxic component, the material would not be present in the spacecraft in a quantity sufficient to constitute a potential hazard. The second step of this approach was to analyze the atmosphere of test vehicles during manned and unmanned tests at the Manned Spacecraft Center (MSC). The third step was to verify the results and to establish that materials added to the spacecraft since the test-vehicle evaluation did not contribute excessively to atmospheric contamination. The atmospheres of three flight vehicles were evaluated during manned and unmanned altitude-chamber tests at Kennedy Space Center. These tests resulted in the establishment of an estimate of the safety of the atmospheres based on a chemical evaluation. In all cases, the analyses seemed to confirm their safety. However, when dealing with a complex mixture such as would be produced by the mate-

rials that are used in the spacecraft, the definitive evaluation required exposing animals.

Therefore, the fourth step of the program was developed and conducted parallel to the materials-selection program. This aspect of the program provided the basis for the acceptance of the reliability of the analytical chemical results. The methods by which the animal studies were performed and the results that were obtained will be discussed in this report. In addition, the concept of the specialized and custom-designed testing that is necessary for the newer nonflammable materials will be described briefly. Such tests are used to evaluate contact toxicity and the toxicity of the thermal-degradation products of the nonflammable materials.

TOXICITY TESTING WITH ANIMALS

The routine toxicity evaluation with animals involves an examination of the possibility that several materials may offgas the same contaminants in sufficient quantities to constitute a toxic hazard or that the combined effects of the offgassing compounds of one or more materials may result in additive, or even synergistic, toxic effects. The routine testing of spacecraft materials was performed in a 5-psia, 100-percent-oxygen environment. This system consisted of an oven in a closed loop with animal-exposure chambers and the equipment necessary to control the relative humidity and carbon dioxide levels (fig. 141). The materials were tested in

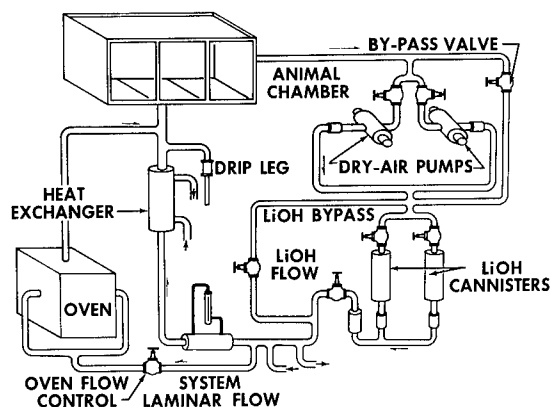


FIGURE 141.—Cabin-materials-screening system.

groups of 10. The materials were selected randomly and were prepared according to recommended procedures. Solid nonmetallic materials were broken up to produce a finely divided mass that had maximum surface area. Liquids were contained in aluminum cups, each with a circular surface 2 in. in diam. Coatings were prepared according to manufacturers' specifications and were applied to clean aluminum backing. The materials to be tested were placed in the oven at $150^{\circ} \pm 5^{\circ}$ F. The effluvium from the materials was circulated over the experimental animals for a period of seven days.

Evaluation by Animal Weight Growth

For the purpose of this evaluation it was necessary to select a sensitive biological system. Death as an end point was undesirable; therefore, rats and mice in the logarithmic phase of growth were chosen as being sufficiently sensitive to a noxious environment to serve as the test system. At the conclusion of the 7-day exposure period, the animals were removed from the exposure chambers and were weighed. Their weights were compared with those of rodents in an identical, unexposed control group. Organ weights were obtained and organ-to-body-weight ratios were calculated. Weight changes and organ-to-body-weight ratios were monitored for an additional period of 28 days to observe any delayed responses that may have occurred.

Although it would have been desirable to test large quantities of materials at one time, the occurrence of a toxic response would have resulted in a difficult identification problem. By limiting each group to 10 materials, it was possible to identify a toxic material relatively easily by dividing the group and re-testing.

Results of Large-Scale, Long-Term Evaluation

Once a level of confidence had been established and materials had passed the initial 7-day exposure test, the materials were combined into groups of 100 for a large-scale, long-term evaluation. The same methods of preparation were used and the same exposure system was used, but the animals were exposed to the offgassing products of the 100 materials for 60 days. Other than the increase in the number of materials that were combined for the study and the duration of

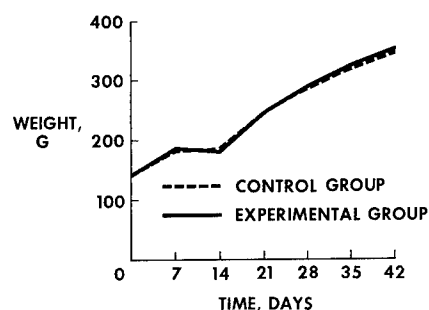


FIGURE 142.—Mean growth rate of male rats.

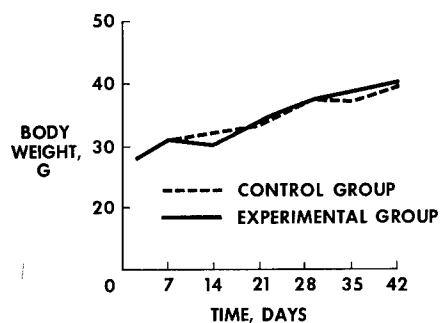


FIGURE 143.—Mean growth rate of male mice.

TABLE LXXV.—*Mean Rat-Organ Weights*

Group	Number of rats	Organ weight, g				
		Heart	Lung	Liver	Spleen	Kidney
Two weeks postexposure						
Control group-----	10	1.0	1.2	9.1	0.7	1.8
Exposed group-----	10	.9	1.3	9.0	.7	1.9
Four weeks postexposure						
Control group-----	10	1.0	1.4	9.9	.8	2.1
Exposed group-----	10	1.1	1.3	10.2	.8	2.2

TABLE LXXVI.—*Mean Organ-to-Body-Weight Ratios*

Group	Number of rats	Organ weight, g				
		Heart	Lung	Liver	Spleen	Kidney
Two weeks postexposure						
Control group-----	10	0.370	0.436	3.254	0.270	0.709
Exposed group-----	10	.353	.449	3.322	.248	.707
Four weeks postexposure						
Control group-----	10	.334	.434	3.049	.236	.656
Exposed group-----	10	.333	.406	3.031	.230	.652

exposure, the procedure remained the same. In this manner, all the materials that were used in the Apollo command module and lunar module were evaluated. Typical results are presented in figures 142 and 143 and in table LXXV and LXXVI. When the materials were tested in this manner, no evidence of offgassing-induced toxicity was noted. The results of the multifaceted approach to spacecraft atmospheric safety provided an extremely high level of confidence.

Special Tests

The introduction of special new materials or the introduction of new uses for established materials requires specialized testing and custom-designed tests. For example, a fire-retardant paper will be handled with the bare hands; in turn, the hands will contact the mouth or perhaps even the eyes. Such a material was proposed, and testing was es-

tablished to provide information on the questions:

1. Would the additives in the paper produce sensitization?
2. Would the additives cause skin irritation after repeated handling?
3. Would the additives cause a toxic response when transferred to the mouth or eyes as a result of handling?

To acquire this information, extracts of the paper were made and skin and ocular tests were performed on animals to determine the extent of primary irritancy. It was found that ocular irritation could occur; however, analysis of the extract proved that the irritating material was innocuous in all other respects, and, if proper precautions were taken, could be used without difficulty. Primary skin-irritancy sensitization was studied in animals before human volunteers were tested; guinea pigs were chosen for the tests. After the initial sensitization period and a

subsequent challenge produced negative results, tests were performed on human volunteers. Neither primary irritancy nor sensitization was noted upon challenge. Therefore, the paper was considered to be toxicologically satisfactory for use on the spacecraft.

Similar tests of flame-resistant garments that are worn next to the skin were not concluded as satisfactorily. Although animal tests with coated woven-glass materials produced satisfactory results, wear tests of garments made from these same materials produced a primary irritation and itching when worn by human volunteers. Because it was not certain whether the material itself or the threads that were used in sewing were the cause of the irritation, the material was returned to the manufacturer for further development.

MATERIAL THERMAL STABILITY

A very significant aspect of the toxicology program is associated with the development of new nonmetallic materials that either prevent the initiation of a flame or, if ignition occurs, prevent flame propagation. The MSC Toxicology Laboratory has been concerned with the thermal stability and the thermal-decomposition products of such candidate materials. Although a given substance may not ignite under test conditions, decomposition at relatively low temperatures results in a loss of desirable physical properties and a release of potentially toxic vapors into the atmosphere. Such behavior is noted in figure 144, which is a thermogram of a noncombustible material. Up to a temperature of approximately 392° F, this material decomposes slowly; however, it decomposes rapidly at 570° F. The decomposition products, which are released abruptly, were found to be highly toxic. It is evident that the use of such a material should be limited to areas that are not subject to accidental overheating. In addition, the material would not be satisfactory as a flame barrier to con-

MATERIALS FOR IMPROVED FIRE SAFETY

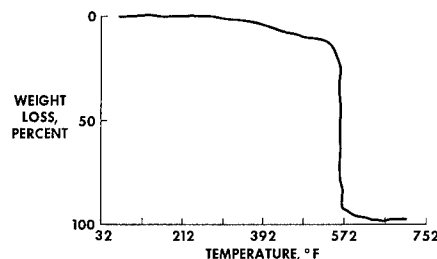


FIGURE 144.—Carboxy nitroso rubber thermogram.

tain an ignition source; although the flame would be contained, the toxic products might be fatal to the crew. Such problems should be considered carefully and trade-offs should be made when materials are being selected.

Materials that have high temperature resistance are preferred to those that have low decomposition temperatures. Slow decomposition rates are preferred to rapid decomposition rates. The relative toxicity of the gases that are produced and the reversibility of the damage must be evaluated and related to the quantity of the material that is decomposed. Experimentally, the 50-percent lethal dose (LD_{50}) is the criterion that is used. The LD_{50} is that concentration in a given value of a substance that is lethal to 50 percent of exposed animals. Thus, a material that has a high LD_{50} (that is, which must be present in large amounts to be lethal) is preferred to a material that has a low LD_{50} . Also, the nature and reversibility of the damage sustained by the survivors become paramount.

CONCLUDING REMARKS

An attempt has been made in this report to convey the significance of some of the work that has been done to establish the toxicological safety both of the old and the new materials that are used in the Apollo Program. When selected and used properly, the materials do not present an atmospheric hazard. However, new materials, such as new drugs or food additives, must be evaluated on the basis of use.

Flammability Control in the Oxygen Environment of the Apollo Guidance and Navigation Equipment*

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In this paper the Apollo guidance and navigation (G&N) equipment test program, the redesign philosophy, and the actual equipment modifications that were used to limit burn rates in an environment of 100 percent oxygen at pressures of 6.2 and 16 psia are described. The G&N systems are major electronic components of both the command module (CM) (fig. 145) and the lunar module (LM) (fig. 146). The G&N system weighs approximately 400 pounds in the CM and approximately 250 lb in the LM. This equipment is furnished by NASA to the spacecraft contractors to incorporate into the manufacture of each spacecraft. Extensive integrated tests of the electronic systems in each spacecraft require that these systems be made available to the spacecraft manufacturers more than a year before launch. Thus, time was a very important factor in each change considered. Schedule requirements dictated that a parallel program of modifications be run because flight-ready G&N equipment had to be furnished to the spacecraft contractors while flammability changes continued to be made to the spacecraft.

The major approach was a serious basic review of the real function of the nonmetallic materials of concern. The result of this review was that the materials could be replaced, eliminated, or covered by nonflammable metallic materials. Although several low-flammability nonmetallic materials were

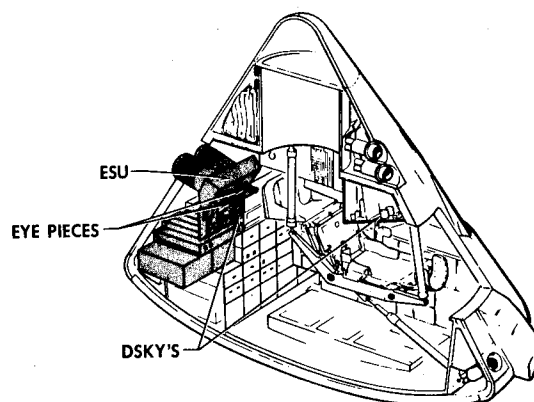


FIGURE 145.—Location of the G&N system in the CM.

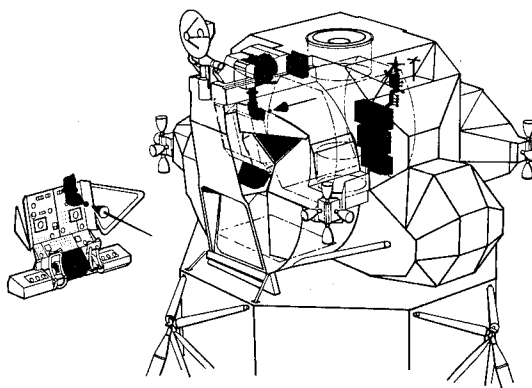


FIGURE 146.—Location of the G&N system in the LM.

investigated, the direct approach of cover, eliminate, or replace generally proved to be quicker and more effective.

The basic design of the G&N system was

*This report was not presented at the conference.

by the Massachusetts Institute of Technology Instrumentation Laboratory; production engineering and manufacturing was by the AC Electronics Division of General Motors (ACED). The flammability test data obtained at the White Sands Test Facility (WSTF) were used to screen existing materials and to identify candidate materials. Application tests on each unit and all required redesigns were by ACED. The final verification tests of all key units were accomplished in the complete mockup tests at the Manned Spacecraft Center (MSC).

APPLICATION TESTS

The tests at ACED were conducted to identify and evaluate the combustion characteristics of nonmetallic materials applications in 100 percent oxygen. Although the program was quite extensive, this presentation is concerned primarily with the test results of the harnesses, connectors, displays, optics shrouds, and eyepiece-storage units before and after flammability modification.

The flammability testing of the G&N equipment was done with a combination of dummy units, simulated units, and actual airborne equipment. The testing was performed in an oxygen chamber that had a volume of approximately 200 ft³, and in accordance with a plan developed from the guidelines and requirements of NASA documents ASPO-RQTD 67-5 (April 10, 1967) and MSC A-D-66-3 (May 13, 1966). Each test was observed and recorded on motion-picture film and test-data sheets. The test-chamber conditions and test-input levels were monitored on chart recorders. In addition, still photographs were taken before and after each test.

During most of the testing, the temperature and pressure increases in the oxygen chamber were negligible. The unit test summary specifies these items only when a significant change results from the testing. Test results and deviations from the test plan are documented in NASA document APM 185-08 (March 22, 1968).

GUIDANCE AND NAVIGATION SYSTEM TEST RESULTS AND CONCLUSIONS

Harness Materials

The G&N wiring harness used to interconnect the various subsystems and to interface with the spacecraft posed a different problem than the spacecraft because of the required function and the associated construction. Unlike the spacecraft harnesses, which are large bundles of Beta-fiber-glass-wrapped Teflon-coated wires in a metal enclosure, the G&N wire harnesses consist of smaller bundles of Teflon-insulated wire and nylon-jacketed, shielded, Teflon-insulated Microdot wire laced with a continuous running lockstitch of nylon lacing tape. The group shields are held in place by wrapping with an adhesive-backed Teflon tape. The harnesses are held in place by correctly positioned silicone-rubber-insulated clamps.

To evaluate the flammability of the G&N harness, wiring samples consisting of six pieces of nylon-jacketed, shielded, Teflon-insulated triplet wire and 21 pieces of single-conductor Teflon-insulated wire were laced with a continuous running lockstitch of either Beta-fiber glass or Tefglas. The samples were placed in the chamber in air. A current overload was applied to two twisted leads of a triplet wire with a time-increasing current until the ignition lead opened. Additional tests also were conducted on modified samples to evaluate the flammability characteristics and/or retardant effectiveness of aluminum-foil tape wrap, Beta-fiber-glass ribbon wrap, a repaired harness containing six spliced and twisted pairs of Teflon-insulated wires, harness clamps, and the exposed PR 1538 potting compound used on G&N harnesses.

The following results were obtained from the flammability testing of the harness materials used in the crew bay:

1. The exposed PR 1538 clear potting material encapsulant burned vigorously, sputtered, and dripped burning material over a wide area.

2. The nylon-jacket material on the Micro-

dot wire burned vigorously at pressures of 16.5 psia and 6.2 psia, independent of whether the ignition source was outside or inside the jacket. It was self-extinguishing in air.

3. Adhesive-backed aluminum-foil tape was an effective fire barrier and retardant when applied to nylon-jacketed wire, Teflon-tape-wrapped group shields, and PR 1538 potting-compound encapsulant.

4. The cable used for the optics heater ignited, burned with a low-intensity flame, and was self-extinguishing in a short time.

5. Application tests were run on G&N harnesses covered with aluminum-foil tape and mounted to a plate simulating the G&N mounting. Harness clamps (silicone-rubber inculated) and locations were identical to those used in the spacecraft. Standard hot-wire ignition coils were located at the three points most likely to permit flame to spread. Although the insulation burned at a very low intensity, only one side of the clamp burned. There was no flame-propagation path between the harness clamps when the clamps were spaced as in the spacecraft.

6. The conductor splices, the Kynar sleeving, and the PR 1538 potting compound burned locally and vigorously but did not propagate flame when properly spaced.

7. No ignition of the nonmetallic materials used on connectors (such as marking inks, DC-4 grease, and lubricants) occurred during the tests because these materials were of such a small quantity or were excluded from easy access to oxygen or both.

8. The potted and taped Deutsch, Microdot, and Cannon connectors and the connectors assembled by using National pins did not ignite when the exposed PR 1538 potting compound was protected with adhesive-backed aluminum-foil tape.

9. Beta-fiber-glass lacing tape ignited only for short periods and self-extinguished quickly.

In view of the test results, two courses of action were indicated: either the G&N harnesses in the CM and the LM interior harnesses would have to be redesigned and re-

built to eliminate the fire hazards or suitable fixes would be required to retard, confine, and prevent the propagation of a fire. The latter approach was taken to meet scheduling requirements and to keep cost at a minimum. With this approach and the results of the testing as a basis, the following conclusions were reached and corrective action was initiated:

1. All PR 1538 potting compounds, nylon-jacketed wires, and Teflon-tape-covered group shields must be protected by wrapping with adhesive-backed aluminum-foil tape (Mystic 7402 or equivalent). The taping technique consisted of wrapping two layers of tape in opposing spirals; each layer was overlapped 50 percent. The covering resulted in four thicknesses of tape at any point.

2. Although the optics-heater cable-material configuration was acceptable, the cable material was replaced with Teflon-jacketed insulated wire when the optics-heater blankets were redesigned.

3. The conductor splices, if adequately spaced, were acceptable for limited use.

4. The harness-connector potting (PR 1538) was protected by adhesive-backed aluminum-foil tape.

5. All exposed lacing tape was changed to Beta-fiber-glass-type tape.

With the replacement materials and protective measures indicated, the CM and LM harnesses are nonflammable in 100 percent oxygen. For use outside the spacecraft (in other than 100 percent oxygen), the nylon-jacketed wire and the Teflon-taped group shields will not support combustion and do not need to be wrapped with aluminum.

Lunar Module Alignment-Optical-Telescope Pressure Seal

The LM alignment optical telescope (AOT) is required to penetrate the LM pressure hull to bring a collimated line of sight to the astronaut for navigation sightings. The accuracy requirement of the AOT allows no significant lateral, longitudinal, or torsional loads to be transmitted to the telescope. This

forced the use of a large, urethane, bellows-type pressure seal between the telescope and the pressure hull to permit mechanical isolation of the unit while maintaining internal oxygen pressure against a space vacuum. The urethane material had been selected after an extensive search for a material with resistance to tearing and leakage. Unfortunately, the urethane had a very low melting temperature and was highly flammable. There was no ignition source outside the cabin in the proximity of the material; however, numerous spacecraft wiring harnesses were in the vicinity of the material inside the cabin. The stress-isolation requirements precluded the replacement of the seal with a steel bellows and the mechanical properties of a series of other flexible nonmetallic materials had proved unsatisfactory; thus, the seal was separated from the ignition source with a thin beryllium-copper bellows (fig. 147) around the seal. To keep from invalidating the pressure test, a split bellows was developed so that disassembly would not be required until the bellows could be incorporated into the assembly. The final proof of this fix required a special vacuum chamber over the seal in the LM full-scale mockup fire test at MSC. This test is discussed in reference 1. The weight of this modification was 5.0 oz.

Eyepieces

Four optical eyepieces are used in the G&N system, three in the CM and one in the LM. To ensure condensation-free viewing in the high-humidity atmospheres possible in the spacecraft, electrical heaters are a part of each eyepiece. This thermal requirement had led to an insulating blanket on each eyepiece. The equipment, as designed, used a polyurethane foam. A particular hazard existed in these units because the heaters represented an ignition source, and the polyurethane foam was known to be a highly flammable material. In the CM eyepieces, the foam also was used as part of the mounting and vibration protection for each eyepiece.

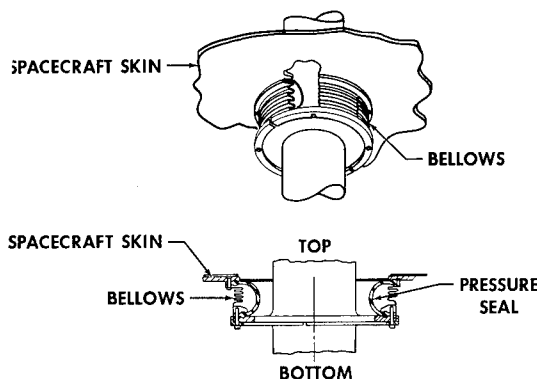


FIGURE 147.—The protective bellows for the AOT seal.

A more detailed review of the thermal requirements for foam insulation indicated that the insulation gained was not an absolute requirement. Thus, the solution for the LM eyepiece was simple; remove the foam and add a metallic protector for the heater blanket. However, the three CM eyepieces did not yield to a solution as quickly. The requirements for storage included the need to remove from storage and mount two eyepieces on the optical unit with only one hand in less than a minute. This requirement to mount and unmount quickly had led to a flexible covering that could be wedged easily into a fitted hole, thus allowing optical glass to survive launch vibration. Several flexible configurations were investigated. A foamed fluorinated-elastomer blanket with a fire-break of Beta-fiber-glass pads separating the blanket from the heater was tried. A significant decrease in the flame rate was provided; however, these eyepieces were potentially loose items in a spacecraft with ignition sources, and any flame rate was considered excessive.

A hard mount to the eyepiece stowage unit (ESU) was considered the most reasonable solution if (1) the vibration environment could be handled and (2) the withdrawal force could be controlled closely. These requirements were accomplished in the ESU design described below. The eyepiece heaters in the CM and the LM were covered with an aluminum shield.

Eyepiece Stowage Unit and Optics Shroud

The ESU is located above the optical unit assembly (OUA) in the CM and is used for the stowage and protection of the eyepieces when they are not in use. The optics shroud is a closeout panel that surrounds the OUA. Both units are passive components of the G&N system and were fabricated originally from epoxy-impregnated fiber glass and molded foam-filled plastic (fig. 148). Preliminary screening tests showed that these materials were highly flammable and unacceptable for crew-bay use. The element of time and cost motivated the first approach, which was the evaluation of various coatings of fireproofing agents such as electroplated nickel over electroless copper, aluminum hot-spray plating painted with 3M-400 gray velvet paint, or a layer of adhesive-backed aluminum-foil tape with paint coating. All of these approaches were considered to be less costly and faster to implement than a total replacement. However, these various methods of coating the epoxy-impregnated fiberglass were found to be unreliable or impractical to implement. The decision was made subsequently to redesign both units and to fabricate the units with aluminum.

The testing of the optics shroud also revealed that the silicone gasket ignited, burned vigorously, and dropped many hot particles. A replacement gasket made of Fluorel burned at a much slower rate and dropped fewer particles. Because the optics shroud had no ignition source and the gasket would have to be ignited by another propaga-

tion source, the Fluorel gasket was used on the metallic unit.

The ESU redesign of aluminum was completed and almost ready for release for production when spacecraft mockup testing at MSC showed that the replacement blankets for the eyepieces were flammable and could drip flaming particles. The decision subsequently was made to construct the heater covers of aluminum. This required another examination of the ESU to ensure that the interface of the stowage holes not only would contain but also would protect the eyepiece under vibration and would not allow wedging that would require excessive withdrawal forces. The redesigned units had no weight impact on the spacecraft. The optics shroud had an increased weight of 1 oz, whereas special care during the engineering design of the ESU resulted in a decrease of 1.2 lb.

Command Module G&N Indicator Control Panel

The G&N indicator control (GNIC) panel, which is located in the lower equipment bay of the CM, contains displays of caution and warning information; computer verb, noun, and star-list information; and controls associated with the optics subsystem (fig. 145). The GNIC panel is made of aluminum honeycomb material upon which are mounted electroluminescent (EL) lamp and incandescent lamp displays, moding switches, and the controllers mentioned previously. Approximately one-third of the panel consists of EL displays that were constructed by covering each EL display with painted acrylic-plastic overlays. In addition, the switch well and the controller wells are lighted with acrylic-supported EL lamps.

An extensive test program on the GNIC panel was conducted. Samples of the GNIC panel and of items such as the EL displays, the sextant hand-controller diaphragm, and the Delrin pushbutton were tested in detail. When applicable, units were modified and tested until suitable redesigns were found that would reduce or eliminate the flammability hazards. The flammability testing on the GNIC proved the following:

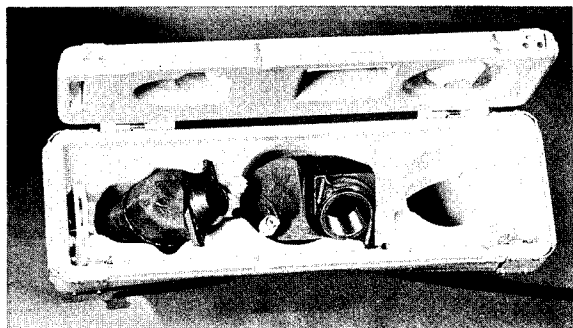


FIGURE 148.—The original ESU.

1. The front-legend-lighting EL lamps with painted acrylic-plastic overlays burned vigorously and ejected burning particles.

2. The metal cover on the back of the GNIC panel was insufficient to meet crew-bay requirements and had to be modified with adhesive-backed aluminum-foil tape to cover the lower external portions of the back cover and the major front access holes to contain a fire successfully.

3. The EL lamps with metal overlays did not ignite.

4. The basic honeycomb panel would not ignite.

5. The silicone-rubber diaphragm of the hand controller burned with a low flame, sputtered, and ejected burning materials.

6. Push buttons made of Delrin burned completely.

7. The master-alarm push button burned and, in turn, ignited the condition annunciator assembly. The fire did not spread inside the assembly or to other panel areas.

From the results, these conclusions were derived, and corrective action was initiated as indicated:

1. The acrylic-plastic-painted overlays of the front-lighting EL lamps were a definite fire hazard and had to be replaced. The unique design of these displays did not lend itself to a so-called quick flammability fix because all displays had to meet specific lighting criteria for readability and intensity; the painting of the overlay was designed to correct the inadequate color lighting of the EL displays. Replacement materials that would enable the lighting criteria to be met and that would protect the panel from fire hazards were not readily available; consequently, the metallic (brute force) approach was taken. This approach was simple and straightforward, but some sacrifice in the type of characters, the size, and the lighting of the lettering was required. The first design attempted was simply an engraved aluminum overlay. This design had the inherent problem of lamp-intensity brilliance (in comparison with other displays) and in correct color luminance. This was overcome subse-

quently by filling the engraved characters with an inked epoxy resin. The finished product consisted of a sandwich construction of Teflon spacer, EL lamp, Aclar sheet (for lamp protection), and aluminium overlay. This sandwich modification prevented ignition of the EL lamps.

2. The EL lamps and acrylic supports in the switch wells did not require modification because the lamps and supports are relatively small and because of a low probability of either external or internal ignition.

3. The screening tests and additional tests on the GNIC panel indicated that the PR 1538 potting compound on the switches (fig. 149) located on the back of the panel offered a serious hazard. Protection in this area was difficult because of the odd shape of the switches and the controller configuration. The tests also indicated that EL lighting slots would allow oxygen feeding of any fire on the back panel even though a cover was applied. Therefore, the corrective action was (1) to tape the EL slots with aluminum tape to restrict the flow of oxygen to an internal fire, (2) to cover the entire back of the panel, and (3) to tape the bottom and side of the cover interface with aluminum tape to prevent dripping and seepage of burning materials.

4. Although the silicone-rubber diaphragm on the hand controller, located on the lower left-hand side of the panel, burned and ejected some hot particles, the diaphragm was considered acceptable. It is highly unlikely that this diaphragm could ignite from a failure within the hand controller itself. The diaphragm is in a recessed well and is relatively small, so that propagation of hot particles from other areas is improbable.

5. The Delrin push buttons burned and hence were replaced by aluminum ones.

The GNIC panel modification is an example of the flammability modification philosophy pointed out earlier. From the start of the GNIC panel testing and previous screening tests, it was apparent that the acrylic-plastic overlays of the EL displays and the PR 1538 potting compound on the back panel

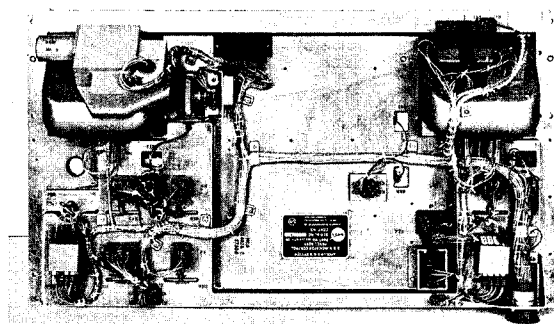


FIGURE 149.—The back of the GNIC panel.

would have to be replaced or protected. The metallic replacement and protection concept was applied again in view of the urgency to metallic protective and containment cover meet spacecraft requirements; hence, the for the back panel and the aluminum metallic engraved overlays for the EL displays evolved.

The computers for both the LM and CM are controlled by the astronauts with 19 push buttons on a display and keyboard (DSKY) located on the main panel and lower equipment bay of the CM (fig. 145) and on one unit in the LM between the astronauts (fig. 146). These push buttons each have back-lighted EL numerics and codes on a face of acrylic. Unit tests indicated that enough fire was generated to each key to propagate flame to the adjacent keys. It was found that a change similar to that used on the GNIC panel could be used. The translucent acrylic covering was replaced with aluminum on which the numerics are etched for visibility of the EL panel (fig. 150). An epoxy-resin fill was used for color correction and light-intensity control.

Each DSKY has a 3- by 4-in. caution-and-warning display matrix of 10 to 14 lights. This display matrix is a sealed potted-acrylic unit. The burn tests of this unit indicated extensive problems. A metal frame with a safety-glass front panel to cover the entire unit was added. This addition effectively separated the display matrix from any ignition source without reducing the function of the unit.

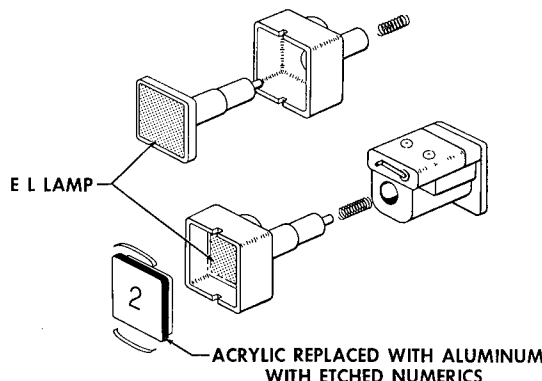


FIGURE 150.—The display and keyboard push button.

The changes made to components of the G&N system in no case significantly compromised functional requirements. In the case of the ESU and eyepieces, function was, in fact, enhanced. The total changes made little weight impact on either spacecraft.

CONCLUDING REMARKS

The emphasis of the guidance and navigation flammability test program on actual application requirements and conventional metallic materials allowed a timely response to program requirements. These changes were made and proven and flight hardware was delivered in less than 12 months from the initiation of the program. The guidance and navigation systems in both the lunar module and the command module were changed from significant fire hazards into virtually burnproof systems in environments of 100 percent oxygen at pressures of 6.2 and 16 psia. The main critical element used was the no-burn redesign discipline. These design approaches are recommended for application in other electrical equipment for which flammability may be a serious consideration.

REFERENCE

1. BRICKER, R. W.; CRABB, J. P.; AND SPIKER, I. K.: Flammability Tests for Apollo Command Module and Lunar Module Mockup. Paper presented at NASA Conference on Materials for Improved Fire Safety (Houston, Tex.), May 1970.

Glossary

SPECIAL TERMS

- Conformal coating—a material uniformly applied over another material for protection
- Cuff cards—cards fixed to the arms of the space suits used on the lunar surface to remind the astronauts of task sequence
- Denier—the weight in grams of 9000 meters of yarn or fiber; a measure of fiber or yarn fineness
- Dielectric—electrically nonconducting
- Durometer—a measure of the hardness of a material
- Edgelock—treatment of the edge of a fabric to prevent fraying
- Fireproof—noncombustible
- Fire resistant—with respect to sheet or structural members, means the capacity to withstand heat at least as well as aluminum alloy in dimensions appropriate for the purpose for which they are used; and with respect to fluid-carrying lines, other flammable fluid system parts, wiring, air ducts, fittings, and power plant controls, means the capacity to perform the intended functions under the heat and other conditions likely to occur at the place concerned
- Fire retardant—slowly combustible
- Fire safety—low probability of serious loss of injury by fire (combustion)
- Flame resistant—means not susceptible to combustion to the point of propagating a flame, beyond safe limits, after the ignition source is removed
- Flammable—with respect to a fluid or gas, means susceptible to igniting readily or to exploding
- Flash resistant—means not susceptible to burning violently when ignited
- Hyperbaric—pressures greater than sea-level atmospheric pressure
- Hypobaric—pressures less than sea-level atmospheric pressure
- Intumescence—the property of certain special plastics to swell upon application of heat
- Lockstitch—prevention of fraying of the edge of fabric by sewing along the edge
- Marquisette—a thin, lightweight fabric of cotton, silk, rayon, nylon, or glass with square, open meshes
- Tricot—a type of knitting that is characterized by a runproof stitch
- Wax pick—a measure of the resistance of the surface of a material to stain
- Modacrylic—a generic name for a synthetic fiber in which the fiber-forming substance is any long-chain synthetic polymer composed of less than 85 percent but at least 35 percent by weight of acrylonitrile units

- Phenol formaldehyde—a thermosetting resin made from phenol and formaldehyde
- Phenolic—of, derived from, or containing phenol
- Polyamide—a polymer in which the structural units are linked by amide or thioamide groupings
- Polybenzimidazole (PBI)—a high-temperature-resistant polymeric fiber containing imide groups
- Polycarbonate—a transparent plastic used for helmet visors. It has exceptionally high impact strength.
- Polyester—a generic name for a manufactured fiber in which the fiber-forming substance is any long chain synthetic polymer composed of at least 85 percent by weight of an ester of a dihydric alcohol and terephthalic acid
- Polyimide—a polymer containing imide groups
- Polymer—a high-molecular-weight organic compound, natural or synthetic, whose structure can be represented by a repeated small unit
- Polyquinoxaline—a high-temperature thermosetting resin derived from quinoline by the substitution of a nitrogen atom for a methyldine group
- Polysulfone—a high-temperature transparent polymer that is characterized by the sulfonyl group doubly united by means of its sulfur, usually with carbon
- Polyurethane—any of various synthetic rubber polymers produced by the polymerization of a hydroxyl (OH) radical and an NCO group from two different compounds
- PVA—polyvinyl acetate
- PVC—polyvinyl chloride
- Room temperature vulcanizing (RTV)—a commercial potting compound

CHEMICAL TERMS

- ABS—acrylonitrile butadiene styrene
- Acrylic—a generic name for a manufactured fiber in which the fiber-forming substance is any long-chain synthetic polymer composed of at least 85 percent by weight of acrylonitrile units
- Brominated polyester—a polyester with bromine added (see Polyester)
- Carboxy nitroso rubber (CNR)—a flame-resistant terpolymer of trifluoronitrosomethane, tetrafluoroethylene, and nitroperfluorobutyric acid with rubberlike properties
- Chloroprene—a colorless liquid, C_4H_5Cl , made from acetylene, which can be polymerized to form a synthetic rubber
- CO—carbon monoxide
- Copolymer—a synthetic substance formed by the addition or condensation polymerization of two or more monomers
- Dimethyl siloxane—a type of silicone resin
- DTA—differential thermal analysis, a method that is used to measure phase changes (endothermic and exothermic) occurring subsequent to increasing the temperature
- Ethylene—a colorless, inflammable, gaseous hydrocarbon of the olefin series

- Fluoropolymer—a polymer containing fluorine
- Fluorosilicone—a silicone resin in which hydrogen atoms have been replaced by fluorine
- Hexafluoropropene—a fluorocarbon monomer
- Melamine formaldehyde—a thermosetting resin made from melamine and formaldehyde, used chiefly in molded products, coatings, adhesives, and textile finishes
- Methyl ethyl ketone (MEK)—an organic solvent
- Methyl isobutyl ketone (MIBK)—an organic solvent
- Silicone—any of a group of synthetic resins, oils, greases, and plastics in which the carbon has been replaced by silicon
- Terpolymer—a product of three different polymerizing substances
- Tetrabromophthalic anhydride—a highly brominated hydrocarbon commonly used as a fire retardant
- Tetrafluoroethylene—a fluoropolymer
- Thermoplastic—a polymer that becomes or remains soft and moldable when subjected to heat
- Thermosetting—becoming permanently hard and unmoldable when once subjected to heat
- Toluene—a colorless liquid hydrocarbon
- Urea formaldehyde—a thermosetting resin made from urea and formaldehyde

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