PLASTIC AND ELASTOMERIC FOAM MATERIALS

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PREFACE

The primary objective of this report is to provide information on the contributions to the technology of plastic and elastomeric foam materials derived from NASA research and development programs. Much of the material for the text was obtained from programs on materials and structures for NASA vehicles and equipment. The discussions include related technology developed in U.S. Air Force and Navy programs. The limitations and trends in utilization of foam materials in space flight systems are emphasized. Wherever possible, the reader is directed to additional material in the open literature.

Emphasis is on the actual or proposed use of foam materials in structures and equipment for vehicles and satellites in NASA's manned and unmanned programs. The applications of these materials in mechanical. thermal, and electrical systems are described in relation to design concepts and requirements as well as to the chemical and processing factors. To the extent that information was available, subject matter is correlated with a specific area of technology. This task was an extensive one in view of the numerous functions and environments for which foam materials have been applied. Advances being made in several current NASA programs on thermal protection have been included for the sake of a more complete presentation of the state-of-the-art.

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Chapter I

FOAM TECHNOLOGY

PERSPECTIVE

Applications of plastic and elastomeric foams in the NASA's space programs are highly diversified. Materials research and materials engineering by NASA on foamed products have exerted a major influence on the design and development of structures and components in many areas of technology. Many of the advances have been the result of effective utilization of an increasing number of base polymers and formulations developed by industry. Progress has been made in formulation, processing techniques, construction of reinforced and composite structures, unique designs, testing methods, measurement of properties and performance reliability.

Foam materials are used in space for many different purposes and under environmental conditions of vacuum, temperature, radiation, gravity, and induced environments. The selection of a foam material with defined mechanical and physical properties is ultimately dependent on compatibility with the environments in which it will exist or function. Because environmental interfaces and constraints influence the behavior and use of these materials, the information in this survey is organized according to the interrelationships which exist between the foam materials, their function and the expected environment.

Most areas of NASA technology for which foam materials have been extensively investigated fall in the following categories:

(1) Structural components—for cavity filling, space shelters and expandable structures, self-sealing and survival equipment.

(2) Ablative materials—composite structures used as thermal protection for reentry systems.

(3) Cryogenic insulation—insulation structures for cryogenic propellants.

(4) Electrical encapsulation—for low voltage and intermediate high voltage circuits.

(5) Human factors—man-vehicle-environment interfaces, involving personnel protection against hazards of the force environments and the toxicology potential of space cabins.

These categories form the basis for the classification and presentation of the technology data obtained during this survey.

CHEMICAL CLASSES

Foamed plastics and elastomers are polymeric materials derived from resins that have been expanded in volume by means of gaseous blowing agents. This results in a cellular structure, achieved by a combination of polymerization reactions and foaming, the latter being due either to the chemical release of blowing agents or the physical addition of inert low boiling point liquids, such as fluorocarbons.

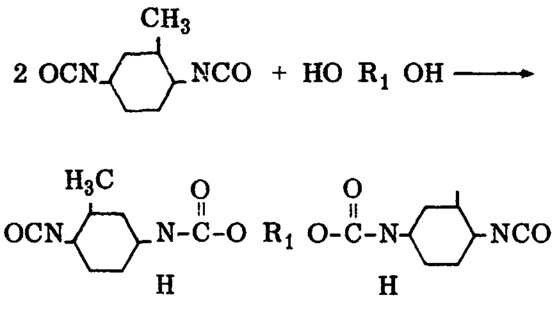
The most commonly used chemical classes of materials for producing foams are the polyurethane, polystyrene, epoxy, silicone, vinyl, phenolic, and polyolefin resins. In the work reported in this survey, the most widely used have been the polyurethanes, followed by the silicones.

The resins employed for producing foams may be either thermoplastic or thermosetting, depending on their polymer structure. In the foaming of the thermoplastic resins (e.g., polystyrene, polyvinyl, and polyolefin), the polymer structure remains unchanged during the foaming process. In the case of thermosetting resins (e.g., polyurethane, epoxy, silicone, and phenolic), foaming occurs along with the polymerization reaction.

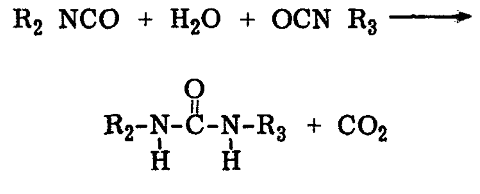
Except in the case of foams blown with fluorocarbons, the polyurethane foams are derived by the same chemical reaction to achieve both polymerization and gas evolution. The principal steps in their preparation are: (a) prepolymer preparation, and (b) foaming and curing. The prepolymer is usually prepared from a high-molecular-weight di- or poly-hydroxy compound and a diisocyanate; e.g., toluene diisocyanate (TDI). The polyhydroxy compound may be a polyether, a polyester or a glycol derivative. Other diisocyanates, such as PAPI (polymethylene polyphenyl isocyanate) or MDI (meta-4,4'-diphenyl methane diisocyanate) may replace the TDI in order to obtain special properties for the polyurethane polymer.

The prepolymer is prepared according to Reaction 1, shown in the following figure. Some [illegible] or triisocyanate may also be included as a cross-linking agent as in the preparation of rigid foams.

The prepolymer, often mixed with further diisocyanate, is then reacted with water in the presence of a suitable catalyst and a foam stabilizer (e.g., a silicone) according to Reaction 2.



(1)



$$R_2\ NCO + H_2O + OCN\ R_3 \longrightarrow$$

$$R_2\text{-}\underset{H}{N}\text{-}\overset{O}{\overset{\|}{C}}\text{-}\underset{H}{N}\text{-}R_3 + CO_2$$

(2)

In Reaction 1 chain extension occurs and in Reaction 2 carbon dioxide is generated which blows the entire reaction mass into a foam, which solidifies in several minutes.

The chemical identification of the polymers, catalysts, or blowing agents in many foam systems reported in this survey has not been possible because of their proprietary nature. This has not significantly diminished their usefulness. However, for evaluating the mechanism of polymer breakdown, either thermally or through oxidation, a knowledge of the chemical species of the polymer is valuable.

Special Classes of Prepolymers

In an investigation conducted to develop closed cell halocarbon plastic foams for use as structural materials at cryogenic temperatures, polyurethanes were synthesized.[1] One material prepared was octafluorobiphenylene diisocyanate. A prepolymer could not readily be formed by reacting the fluorinated diisocyanate with a fluorinated alcohol even after several days at 200°C. Thus an autogeneous foaming-in-place system of this chemical type was ruled out.

Other investigations for cryogenic applications were made to produce foams with closed cell structures at a nominal density of 4 lbs/ft^3, capable of developing maximum physical and thermal properties in large single pour masses of 150 pounds without a post-cure. The formulation giving the highest strength was Freon blown and based on LS-490*/TDI prepolymer (100 parts/320 parts), utilizing Quadrol** as the cross-linking resin.[2] A material with this formula at 4.2 lbs/ft^3 density had a compressive strength of 112 psi. The utility of the system is somewhat limited because of the fast foam time.

PHYSICAL ASPECTS OF FOAMS

Open- and Closed-Cell Foams

The term "cellular materials" has occasionally been applied to closed-cell foams, but it seems preferable to adopt the commonly used term "unicellular" for this type of foam structure. Unicellular or closed cell foams are those which are composed of a cellular structure containing blowing gas within the cell wall membranes of either a flexible or rigid polymer. In open-cell foams, the cells are interconnecting and the gas phase is continuous. This open structure results from the escape of the gas expanding in the foaming process.

Although the definitions of "open" and "closed" cells is clear enough, the classification of foam materials does not always fall neatly into any one category. Foams are commonly designated as open, semi-closed or closed structures. For these

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[1] References are listed at the end of each chapter.

*LS-490 - Sorbitol propylene oxide (Union Carbide Chemicals Co.).

**Quadrol - N,N,N', N'-tetrakis (2-hydroxylpropyl) ethylene diamine (Wyandotte Chemicals).

types, as an approximation, the "closed" foams may have from 0 to 20 percent open cells; and the "semi-closed" foams may have ranges in between this and 100 percent but more often an approximately equal division of open and closed cells. These structural aspects have an important bearing on the wide range of foam properties and thus contribute to the extensive uses of foams.

Syntactic Foams

The syntactic foams form a special case of closed-cell foams. This type of foam system consists of a cured resin as a continuous phase in combination with hollow microspheres which provide the cell structure and function as a density reducing agent. Microspheres are usually made from phenolic resin, glass, or silica, and are often called "microballoons."

Depending on the loading of the microsphere fillers in the formula, the lightweight syntactics have generally been prepared for various uses in the specific gravity range of 0.4 to 0.8. The syntactic foams find important uses in electrical, thermal and ablative applications.

Rigid and Flexible Foams

Foams are also classified on the basis of flexibility or rigidity. Gross changes occur in going from flexible to rigid foams, this property being dependent primarily on the polymers used. Intermediate variations exist, such as the so-called semi-rigid foams. Within each category, variations in properties can be achieved, even for a specific formulation, by varying the density by adjusting the process technique for molding or casting.

Rigid or flexible foams may be specified mechanically.[1] For example, rigid foams generally have low extension in tension (~ less than 10%) and poor recovery after 75 percent deflection in compression. Flexible foams exhibit high elongation in tension (> 100%) and excellent recovery after 75 percent deflection. Most test methods have been developed according to whether the foam is classified as being rigid or flexible. A differentiation between the two types is readily evident from diagrams showing the stress-strain relationships, compressive strength and hysteresis (or resiliency) properties.

Because of the versatility of the polyurethane foams, this class of polymeric materials is particularly useful in illustrating a wide range of structural variations in a foam. The flexible polyurethanes of interest are usually in the range of 1 to 6 lbs/ft^3, when made by a one-shot process. For CO_2-blown systems, densities greater than 4 lbs/ft^3 are difficult to obtain. On the other hand, high density, flexible foams, ranging from about 2 to 10 lbs/ft^3, are achievable by foaming-in-place, using a two-component prepolymer/catalyst system in closed molds. The degree of open-cell structure can diminish as density is increased in this manner.

In the effort to obtain special properties, much interest has been shown in obtaining an open-cell rigid [illegible] example of such a material is the special formula developed by Mob[illegible] a process of rupturing the cell walls by using a special chemical formulation.[2] Such a rigid structural foam was desired during the development of external insulation for cryogenic tankage in order to avoid the outgassing characteristics of a closed-cell rigid foam in a hard vacuum.

At the other extreme, the closed cell flexibles are not very common, especially at the lower densities which are generally desired. Closed-cell, flexible vinyl foams over a range of densities have been prepared by processing under high pressures of the order of 1000 psi.

An unusual current development is a low pressure process for producing a practically 100-percent-closed-cell, flexible vinyl foam in the density range of 7 to 10 lbs/ft^3 (at 1 atmosphere).[3] This advance of the art resulted from an investigation of a closed-cell flexible foam required for integration into a partial pressure suit. The suit is required to fit the human body with sufficient intimacy so as to limit adequately the "swelling of the body" when exposed to a vacuum environment. This foam has successfully retained the gas within the cells after repeated cycling in a vacuum.

Processing Methods

The flexible foams are usually prepared by cutting to the required size from slab or sheet stock made in a one-shot process by the foam producer. Rigid foams are also obtained as board or sheet stock or molded shapes. The rigid foams are processed at the user's facility by casting or molding techniques to prepare molded sections or preforms, or to foam directly to the configuration of a component or assembly. In some instances, flexible foams, usually in the higher density range, are prepared by a molding process. Molding of the foam under controlled pressure and temperature conditions essentially comprises the foam-in-place method of foaming.

Depending on the fabrication and application requirements, the mold may be either a separable mold or integral with the foam. The advantage of the foam-in-place process is that the foam is capable of making a good adhesive bond to the surfaces it contacts, as well as producing intricate shapes. One limitation in casting or molding large shapes by this method is the possible heat distortion due to the large heat release in polymerizing a large resin mass. A study is now in progress under NASA contract (Lewis Research Center)[4] to achieve the foaming-in-place of 4-inch by 5-inch by 10-inch test specimens to evaluate foams for use in embedding high voltage networks to be exposed to vacuum for long periods of time.

Because of the nature of the foaming process, foams usually display anisotropy; that is, a directional dependence of properties. Density, hence properties, vary in a direction parallel to the maximum foam rise. For this reason, the direction of applied stress must be specified in the measurement of properties.

Composite Forms

Foam materials are used to a great extent in composite forms for structural, cryogenic, and ablative applications for which improved or special properties are needed to withstand the mechanical and thermal stresses involved. Material combinations for the composite forms reported in this survey may be classified in the following manner.

A. Filled Systems	Examples
1. Foam/Inorganic Filler	Asbestos in silicone foam (General Electric - ESM1004 heat shield material)
2. Foam/Metal Filler	Aluminum flake in polyurethane foam (Goodyear Aerospace)[5] - opacifying media to internal IR
B. Reinforced Systems	
1. Foam/Fiberglass Yarn	"3-D" Foam (Douglas M&S Division) -cryogenic insulation for Saturn IV-B vehicle
2. Foam/Phenolic-Fiberglass Honeycomb	PAPI foam/HRP honeycomb (North American Aviation) - thermal insulation for Saturn-S-II vehicle
C. Laminate Systems	
1. Foam/Metal Foil or Sheet	1.5, 8.0 or 16.0 mil aluminum-foam combination (G. T. Schjeldahl) - Pegasus detector panel
2. Foam/Fabric or Plastic	Mylar/Foam/Mylar (Goodyear Aerospace) - sealed insulation
3. Flexible Foam/Rigid Foam	Sandwich foam for micrometeorite detector panels (G. T. Schjeldahl) - Pegasus

PROPERTIES OF FOAM MATERIALS

Because of the numerous chemical classes and physical forms, cellular plastics and elastomers have a wide range of properties. Standard test methods for measuring the properties of foam materials have been developed by the Cellular Plastics Division of the Society of the Plastics Industry and various working groups in the American Society for Testing and Material and Society of Automotive Engineers. Test specifications have been prepared for both rigid and flexible cellular plastics to standardize techniques for obtaining physical data.

These test methods have been extensively supplanted by special, and even unique, testing techniques in order to provide meaningful data for aerospace applications. The type and complexity of data often needed to achieve effective designs of equipment and devices for space use depends on the severity of the natural and induced environments in which they are expected to operate. Prime emphasis is placed on simulated environmental testing to match or closely approach the real conditions to which materials will be subjected. Essential goals sought for materials are the permanence of their properties, stability of dimensions, and predictability of useful life.

Thus, special efforts have been applied to the definition of properties and characteristics under the influence of the vacuum, thermal, and radiation environments of space, as well as the induced environments of pressure, temperature, vibration, and shock in launch, re-entry or maneuver trajectories. An additional vital interface of materials is with the zero-gravity, 5 psi oxygen environment which prevails in a manned space system during space flight.

As a result, property data have been acquired on (1) outgassing effects, (2) heat fluxes and heat transfer, and (3) electromagnetic radiation and particle radiation. Permeability properties[6] and the diffusion of gases through the polymeric membranes or cell walls of foams have been measured experimentally to evaluate these effects in connection with corona phenomena. Because of the importance of fire protection in space cabins, especially under zero-g conditions, novel flammability tests and test equipment[7,8] have been devised in the place of the ASTM D1692 test method.

Specific properties of foam materials are presented in this survey in relation to the particular functions and environments governing their use. Additional data on the radiation stability of foams for both vacuum/ultraviolet and vacuum/nuclear-radiation exposures are presented in the following section.

Radiation Damage

In the space environment, foam materials may be exposed to radiation due to solar flares, trapped radiation belts, and cosmic radiation. Radiation effects have been experimentally determined under a variety of conditions, including irradiation in air, in vacuum, and at cryogenic temperatures.[9,10] Table 1 shows the relative radiation resistance of general classes of materials, determined by the dosage required to sustain a 25-percent damage in at least one physical property.

The compressive strength is used as one definitive property for the evaluation of foams subjected to radiation in vacuum at cryogenic temperature. Samples irradiated in air at room temperature show severe degradation at doses as low as 5×10^9 erg/gram(C). The effect of combined environmental testing on two representative types of foam materials is presented in Table 2. One explanation given for the wide difference between the air and vacuum results at this dosage level is that the cross-linking mechanism becomes more pronounced because of the elimination of oxygen. Figures 1 and 2 show the radiation level and cryogenic temperature effect on compression loads for two representative foam materials. The ultraviolet and soft X-ray parts of the solar environment can also cause damage to foam materials. Foam materials that are usable in the space vacuum environment[11] are summarized in Table 3.

Table 1.—Relative Radiation Resistance of Materials

Material	Radiation dosage required for 25 percent damage, ergs per g (C)
Polystyrene	4×10^{11}
Polyurethane	4×10^{11}
Glass fabric reinforced phenolic laminate	$>8 \times 10^{11}$
Glass fabric reinforced silicone laminate	$>8 \times 10^{11}$
Glass fabric reinforced epoxy laminate	$>8 \times 10^{11}$
Phenolic resins	1×10^{9}
Epoxy resins	8×10^{11}
Silicone resins	2×10^{11}
Nitrile phenolic resins	2×10^{10}
Vinyl phenolic	1×10^{11}
Epoxy nylon	1×10^{11}
Kel-F	6×10^{8}
Teflon	5×10^{6}
Viton A	3×10^{9}
Nitrile rubber	7×10^{8}
Neoprene rubber	6×10^{8}
Kel-F elastomer	5×10^{9}

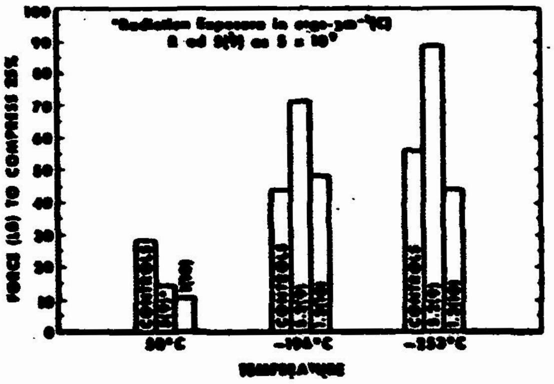

Figure 1.—Radiation-cryogenic temperature data for a polystyrene foam (styrofoam 22).

Table 2.—Combined Environmental Testing of Foamed Insulation

Material	Test	Pressure, torr	Temperature, deg C	Radiation, ergs per g (C)	Compressive strength at 25 percent deflection, psi
Stafoam AA 402 (polyurethane)	Air	760	27	-	40.2
	Air and radiation	760	27	8×10^9	14.0
	Vacuum and radiation	3×10^{-7}	40	9×10^9	33.4
Styrofoam 22	Air	760	27	-	29.5
	Air	760	27	1×10^{10}	10.5
	Vacuum and radiation	2×10^{-6}	44	1×10^{10}	30.5

Table 3.—Foams for Space Station Use

Materials	Limiting dose for mechanical properties,* rad	Continuous service temperature range, °C	Ultraviolet radiation stability	Vacuum stability
Foams (closed cell, rigid thermoset types):			Not applicable if protected by sandwich skin	Good (poor for open cell and some flexible types)
Polyurethane (alkydisocyanate)	10^9	-423 to 300		
Polyether	10^9	-423 to 300		
Phenolic	10^9	-423 to 450		
Epoxy.	10^9	-423 to 250		
Silicone	10^9	-423 to 500		

*Maximum dosage permissible to assure constant tensile strength; 1 rad = 100 ergs per g of material.

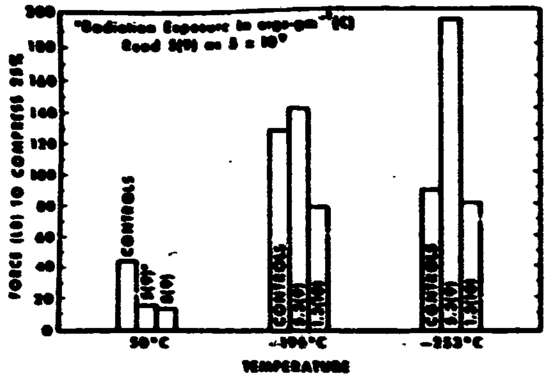

Figure 2.—Radiation-cryogenic temperature data for a polyurethane thermal insulation (stafoam AA402).

REFERENCES

1. Binder, Rene J., Handbook of Foamed Plastics, p. 54, Lake Publishing Corp., Libertyville, Ill. (1965).
2. Shriver, C. B., Investigation of Fabrication and Processing Parameters Associated with Use of Polyurethane Foams in Sealed Cryogenic Insulation, Goodyear Aerospace Corporation, Final Report GER-12249, NASA Contract NAS 3-5646. 1965.
3. Heitz, R. M., and Jones, G. W., Research on Closed Cell Sponge as a Pressure Technique for Protective Assemblies, Northrop Space Laboratories, Final Report, July 1966, Contract AF 33(615)-2953.
4. Foam In Place Materials, RFP-202799, NASA Lewis Research Center, Oct. 1965, Thompson-Ramo-Wooldridge, Contract NAS 3-8905.
5. Private communication, Goodyear Aerospace Corp.
6. Cuddihy, E. F., and Moacanin, J., Polymer Permeation Constants from Diffusion Data on Polymeric Foams, JPL Space Programs Summary No. 37-36, Vol. IV, pp. 153-154.
7. Schreihaus, F. A., and Drysol, D. E., Flammability Characteristics of Some Organic Spacecraft Materials in Zero Gravity, Report No. SID 65-640, May 1965, North American Aviation, Inc., S&ID.
8. Flammability Testing, Non-Metallic Materials for Manned Spacecraft, Process Specification MA 0115-008, Feb. 20, 1964, North American Aviation, Inc., S&ID.
9. Lucas, William R., Effect of Vacuum and Nuclear Radiation on Engineering Materials, NASA Marshall Space Flight Center, ASTM Special Tech. Publ. No. 363, pp. 106-120 (1964).
10. McKannam, E. C., and Gause, R. L., Effects of Nuclear Radiation and Cryogenic Temperature on Non-Metallic Engineering Materials, NASA Marshall Space Flight Center, Journal of Spacecraft, Vol. 2, No. 4, pp. 558-564, July-Aug. 1965.
11. Rittenhouse, John B., and Singletary, John B., Materials for Space Stations, Lockheed Missiles & Space Co., Metal Progress, Feb. 1966, p. 61.

Chapter II

APPLICATIONS OF FOAMS

The usage of plastic and rubbery foams in commerce has been climbing at a phenomenal rate. Foams now appear in widely divergent places and in applications ranging from lightweight packaging and aquatic equipment to foamed-in-place structures in the construction and transportation industries. Although light weight is the key attribute of foams, their usefulness stems from their unique combination of properties and the capability of being tailored to a specific end use. Thus, plastic foam displays a number of good points such as:

Low thermal conductivity, which makes it useful in thermos bottles and cryogenic dewars and in protecting man and his equipment from extreme heat and cold.

Low electrical conductivity, an intrinsic property that leads to the use of foams as encapsulating and embedment materials in electronic equipment.

Good energy absorption properties, which make plastic foams desirable for insulating man and machines from mechanical shock, vibration, and intense sound.

Because plastic foams are low density materials with a relatively favorable strength-to-weight ratio, and insulate against heat, electricity, and attenuate mechanical forces, they are valuable in insulated structures.

In addition, foams possess some unique and intriguing extrinsic properties, such as:

Expandability, a property that makes foams useful in self-erecting structures, in void filling, and in the expulsion of fluids in difficult locations; viz., the raising of sunken ships.

Self-sealability, which is a desirable attribute where fluid leakage must be avoided.

Surface adhesion, meaning that foams can be applied easily to nonuniform surfaces and complex shapes.

Rigidification after distribution, which refers to the fact that plastic foams can be applied (perhaps unexpanded) and hardened or expanded when necessary.
These extrinsic properties combined with the preceding intrinsic qualities place plastic foams among the most versatile materials in industry. Indeed, plastic foams have so many uses that it is reasonable and logical to describe here only those specifically derived from aerospace research and development.

In the following chapters, nine specific aerospace developments in plastic foam technology are highlighted. These are:

Aerospace Foam Development	Aerospace Application
Reinforced thermal insulation	Saturn cryogenic tank insulation
Open-cell rigid foam	Reduction of preinstallation outgassing in sealed thermal insulation
High-strength, low-density foam	Thermal insulation
Predistributed, rigidizable foam	Solar concentrators
Vapor-barrier materials	For foams used as cryogenic insulation
Expandable structures	Solar concentrators, lunar shelters, antennas
Self-sealing composites	Micrometeoroid protection in spacecraft walls
Self-erecting mechanisms	Spacecraft antennas
Helmet-forming techniques	Astronaut helmets

The aerospace applications listed above may seem rather narrow and specialized, but it is possible to find many potential terrestrial uses for these developments. In the following sections, each development is presented in terms of commercial utility. Details of each foam composition, its preparation, and its aerospace application may be found in the body of this report.

REINFORCED THERMAL INSULATION

A novel composition insulation, used in the walls of the liquid hydrogen tanks of the Saturn S-IV stage, consists of polyurethane foam three-dimensionally reinforced by fiberglass threads introduced during the foaming operation. The resulting material is strong, and light weight, with low thermal conductivity.

In the Saturn S-IV stage, the reinforced foam is installed as machined tiles adhesively bonded to the walls of the 8-foot diameter tanks. The resulting thermal insulation layer has a density of 3 lb/ft^3. The Freon-blown, closed-cell polyether polyurethane foam tiles combat thermal stresses and differences in thermal expansion between the insulation and the tank wall. The foam's vastly improved compressive and tensile strengths and good thermal expansion properties allow it to be used in direct contact with liquid hydrogen, protected only by a fiberglass liner.

Possible Commercial Applications

Insulation for ships and trucks carrying liquified methane and natural gas.

Insulation for storage vessels, transport trucks, and even automobiles that may use liquid hydrogen as fuel in the future. (Note: liquid hydrogen is a *clean* fuel.)

Thermal insulation of industrial furnaces, retorts, refrigerator cars, etc.

Structural material in housing, for example in geodesic domes.

OPEN-CELL RIGID FOAM

A special open-cell rigid foam was developed in the space program for use as sealed insulation around cryogenic tanks. The use of open-cell foams reduced pre-installation outgassing and insulation outgassing under vacuum. The polyurethane foam was blown with Freon-11, resulting in 90 percent open cells and an overall density of 2.3 lb/ft^3. A small amount of aluminum flake was added to the foam recipe to open the cells. The molded foam was cut into slices 0.020-in. thick and sandwiched with layers of Mylar to form a composite with low deflection.

Possible Commercial Applications

A lightweight filter for low-temperature fluids.

Stiffening members for structures or devices that must remain permeable to gases, water vapor or other liquids.

Lightweight, large-area (whole rooms) first stage or primary filters for air conditioning and pollution control.

Reinforcing member for flexible foams now used as low density, high-void content ballistic shock attenuator in fuel systems.

HIGH-STRENGTH, LOW-DENSITY FOAM

Another cryogenic insulator is based on sorbitol propylene oxide/TDI prepolymer, using Quadrol as the cross-linking resin. This material has a compressive strength of 112 psi at a density of 4.2 lb/ft^3. This appears to be the highest compressive strength yet obtained for unreinforced polyurethane low-temperature insulation capable of being poured in masses as large as 150 lbs.

The potential commercial applications of this foam are similar to those for the fiberglass-reinforced thermal insulation discussed earlier in this chapter.

PREDISTRIBUTED RIGIDIZABLE FOAM

An azide-base polyurethane foam was developed for rigidizing unfurlable space structures, such as solar concentrators. The unexpanded foam can be applied as a paste to plastic films, such as Mylar and H-film, and stored as a compact, lightweight package, that is completely inert below about 180°F. The foam can be activated and rigidized after deployment by the application of heat which triggers an exothermic reaction.

The predistributed material consists of a prepolymerized polyolresin, a blocked isocyanate, and a special diazide that produces a nitrogen blowing agent when triggered by heat. Thus, a small electrical heater embedded in the predistributed paste can initiate the foaming reaction upon command. The reaction is then carried to completion without the addition of any external energy.

Possible Commercial Applications

Expandable shelters, shields, and camouflage during emergencies and military operations.

Lightweight, expandable, disposable shelters and structures for camping and field use.

Expandable solar concentrators for remote and impoverished areas.

VAPOR-BARRIER MATERIALS

Improved vapor-barrier materials have been developed to seal foam insulations used around storage tanks containing cryogenic fluids. Hermetic sealing is essential to prevent cryopumped gases from increasing the thermal conductivity of the foam insulations.

One particular material employs a Mylar/aluminum/aluminum/Mylar (MAAM) laminated film with Adiprene L100/MOCA as a seam adhesive. The helium permeability of this film is approximately 1×10^{-10} cc/sec-in^2. The vapor-barrier laminate is adhesively bonded to foam insulation panels in space applications.

Possible Commercial Applications

Vapor barriers in transport and storage systems for liquified natural gas, liquid hydrogen fuel, and various refrigerants.

EXPANDABLE STRUCTURES

Space structures can be expanded and rigidized in several ways: (1) with the predistributed rigidizable foam described earlier; (2) expansion by inflating a shape by means of gas pressure with subsequent rigidization through blown foam cavities; and (3) by blowing foam directly into structural cavities.

Rigidization by foaming (the second and third categories above) necessitates techniques for inducing the polymerization and foaming reactions in a programmed, predictable manner. In addition, the unexpanded foam must be storable at ambient or near ambient temperatures and capable of being triggered by heat, radiation, or some other stimulus. Expandable solar concentrators two to five feet in diameter have been built.

The potential commercial applications are essentially the same as those listed for predistributed, rigidizable foams. In assessing possible uses of expandable structures, it is worthwhile noting that linear expansion ratios of 40:1 are possible, corresponding to a volume expansion ratio of 64 000:1.

SELF-SEALING COMPOSITES

The protection of spacecraft against the effects of meteoroid puncture has always been a key problem of space vehicle design. If the spacecraft walls are built from composite materials containing foam ingredients in liquid form, the self sealing of punctures becomes an engineering reality. The passage of a high velocity projectile through a wall built with an internal layer of resin mixed with microencapsulated catalyst will release the catalyst and generate a foam that will harden and seal the puncture. In the laboratory, silicone resin foams have effectively sealed structural panels punctured by 1/8-in. steel spheres.

Commercial applications of such self-sealing techniques might include protective structures surrounding hazardous fluids, such as chlorine and radioactive wastes, and vital supplies of compressed gas.

SELF-ERECTING MECHANISMS

Erectable space antennas employing compressible cured plastic foam have been constructed in prototype form. Flexible polyether urethane foam, with a density between 1 and 2 lb/ft^3, can provide packaging ratios of perhaps 15.1 in volume, without the puncture and leak hazards inherent in pressure-actuated devices. Compression "set" is about 3 percent, but the initial design can compensate for this failure to return to the precise dimensions of the original shape.

Possible Commercial Applications

Compressed life rafts, shelters, and other emergency equipment.

Compressible mattresses, rafts, camping equipment, and other recreational equipment that must be transported at minimum volume.

HELMET-FORMING TECHNIQUES

The advantages of polyurethane foam for astronaut helmet liners are: (1) low density (about 10 lb/ft^3); (2) minimum bulk or thickness of cross section; (3) good energy absorption characteristics; (4) good thermal insulation; and (5) it is amenable to processing by foam-in-place methods. The special fabrication techniques developed during the Mercury, Gemini, and Apollo programs involve two key steps: (1) preparation of a silicone cast of the helmet liner, and (2) transposition of the cast to a mold in which a polyurethane foam liner is formed in the required head shape.

The helmet liner is intended to effectively attenuate shocks and vibration forces incident on the helmet exterior so as to prevent head injury.

Possible Commercial Applications

Fabrication of crash helmets.

Fabrication of protective padding around complex surfaces in automobile interiors.

Application of acoustic attenuating materials to complex shapes; viz., airport noise attenuation helmets.

Although not dealt with in this survey, numerous programs have been put into effect by both the USAF and NASA to determine toxic effects of various materials in space cabin atmospheres. Maximum threshold levels for toxic compounds, expressed as MAC values (maximum allowable concentration in ppm), have been adopted as the preferred standard by the American Governmental Industrial Hygienists in preference to TLV (threshold limiting value) units. Basically different standards, criteria, and test procedures apply for the determination of toxicological and flammability characteristics. Toxic outgassing effects of plastic or elastomeric foams are associated with their thermal and chemical stability under the environmental conditions.

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Chapter III

STRUCTURAL APPLICATIONS OF FOAMS

PERSPECTIVE

Numbers of applications exist for foam materials as structural, load-bearing elements in space-oriented engineering and development work. In the use of foams for insulation and thermal protection systems, structural support in electrical encapsulation and impact protection in space-suit helmets and restraint systems, their structural behavior is connected with prime functions, either thermal or electrical or for life support, which govern the situation. These technology areas, relating to specific application functions, are discussed in the following chapters. The material in this chapter is based on structural applications.

Examples of potential space applications include components of lunar or space shelters; expandable space structures,* such as in the rigidization of solar reflectors, communication satellites, and self-erecting antennas; structural elements of a composite structure to enhance meteor-bumper performance; and self-sealing composites for repair of micrometeorite damage. Other applications of lightweight foam materials are flexible foam-filled buoyant structures for survival at sea and as a rigid-foam cavity filler in the S-1C fuel tank bulkhead.

For deployment and rigidization process of interest for expandable structures, the polyurethane foams have been used in preference to silicone, phenolic and epoxy foam materials, due to a wide range of properties and processing characteristics.

Aerospace expandable structures cover many areas of research and technology. Projects in these areas have been discussed and reported in considerable detail at the First and Second Aerospace Expandable Sturctures Conferences in 1963 and 1965.[1,10] An Expandable Structures Design Handbook has been prepared under Air Force sponsorship.[2]

The advantages of the expandable structure package for space application, are minimum volume, minimum drag during the boost phase, and minimum weight for maximum range. Many construction concepts have been based on fabrication from woven flexible materials; e.g., Goodyear's "Airmat," inflatable plastic films, laminate materials of Mylar of H-film combined with lightweight foams and metallic

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*The term "expandable structure" refers to a construction of flexible materials or of a flexible configuration which can be packaged into a small volume, and which can be programmed to expand into its useful shape by inflation or inflation-rigidization techniques.

structures with variable geometry features. In many cases high packaging ratios of the order to 30 to 1 or higher are sought as a design goal for the expandable structure unit. For space antennas expansion ratios of 12 to 1 are of interest.

The NASA work on foams relevant to expandable space structures, self-erecting space antennas, and solar energy collectors has been largely performed or sponsored by Langley Research Center. Investigations on structures with foam applications by Marshall Space Flight Center have included lunar landing vehicles and shelters, and a fuel exclusion riser in the Saturn-1C flight vehicle.[4,5,6,7]

Because development efforts on foams for structural purposes have varied according to existing or contemplated needs for equipment and components in different systems, the NASA investigations in these areas will be discussed in relation to individual applications.

POLYURETHANE FOAM FUEL-EXCLUSION RISER

The lower fuel tank bulkhead of the 33-ft. diameter, 54-ft. long, Saturn-V S-1C booster serves a double purpose in that it directs the fuel to the engine outlets and occupies a volume that would be a natural sump containing more than 100 cubic feet of fuel. The objects of the fuel-exclusion riser development program conducted by Marshall SFC[4,5,6,7] was to select a suitable rigid polyurethane foam to fill this space and to develop a manufacturing procedure for its production and installation in the aft bulkhead of the S-1C fuel container. The foam was to be adhesively bonded to the bulkhead and covered with a nylon fabric. The Manufacturing Engineering Division (M-ME-M) of Marshall SFC succeeded in producing and installing polyurethane foam segments to fill voids in the sump area and to meet the design requirements for the assembled foam structure.

The fuel-exclusion riser structure investigation was originally conceived along three different lines: (1) foam entirely in one piece, (2) foam in segments bonded to the bulkhead, and (3) foam-in-place in segments. Various commercial foams were screened for use, but were found to be inadequate for large pours, either due to inherent high exotherm, poor viscosity characteristics for controlling the mixing and pour, or failure to provide the required properties.

Design requirements for the foam were: (a) 3 to 4 lbs/ft^3 density, (b) 75 psi minimum compressive yield strength at 6 percent deflection, (c) 5 percent maximum creep under long-time static loading, and (d) compatibility with kerosene fuel. The foam had to have high elasticity to allow for flexing under the static load. The material had to be cast satisfactorily in large sections in single pours.

The requirements for Creep under static loads constituted a serious material limitation for low-density rigid foams. Early in 1963, a 4.0-lb/ft^3 nominal-density foam (Flexible Products Company) was found to creep up to 67 percent in a 24-hour period; but a 6.0-lb/ft^3 density foam had only 2.55 percent creep after 120 hours at room temperature.

Previous work on structural applications of rigid foams in filling large spaces or cavities by "foam-in-place" techniques had indicated a variety of problems such as pull-away caused by after-shrinkage, under- or over-fill, blow holes resulting from cell collapse, large density gradients, shrinkage cracks, undercure, and other defects.

A NASA-supported investigation[3] screened twenty-two foam formulations for suitability to produce very large foam castings with the specified compressive and creep strengths. The foam was intended either to be cast as large blocks for machining out detailed parts or for foaming-in-place on complex surface configurations.

Foam Material

A low-density rigid polyurethane foam, designated R-4803-5 was developed by General Plastics Mfg. Co. that met the design requirements.[3] Another rigid polyurethane (R-4603) formulation was developed which could be cast into a plastic exclusion riser closed mold. The selected composition (R-4803-5). was successfully cast into sixteen blocks measuring 30" x 68" x 78", which were X-rayed to determine the internal quality of the foam. A formulation and reliable application technique was developed for repairing damaged regions such as large holes or defects with fresh foam so as to meet the strength requirements and dimensional tolerances.

The foam formulation R-4803-5 that gave the required density and that could be closed molded was as follows:

R-4803-5, Polyether-Polyurethane Type, Two Part Formula

Part A (110 parts by weight)	
Polyether resin (510 Hydroxyl No.)	80
Toluene Diisocyanate (80-20 TDI)	298
Benzoylchloride	0.2
Silicone Glycol Copolymer, DC 201	3.9

Part B (100 parts by weight)	
Polyether resin (500 Hydroxyl No.)	75
Fluorocarbon 11	14
Silicone Glycol Copolymer, DC 201	1.0
Triethylene diamine	0.1
Dipropylene Glycol	0.2

The R-4803-5 formula produced a closed-cell, Freon-blown foam with a density in the range of 3.4 to 4.0 lbs/ft^3. The measured maximum creep was in the range of 2.75 to 4.65 percent versus an allowable of 5 percent maximum. A 3.4-lb/ft^3 sample gave a minimum compressive strength of 75 psi at 6 percent deflection.

Production and Installation of Fuel Exclusion Riser

The fabrication requirements were to: achieve accurate placement of foam segments in the bulkhead, prefit them for uniform spacing, secure them by adhesive bonding. The segments were precast in-place by vacuum bagging the contoured metal surface in the tank, tack-coating with epoxy resin, lining the surface with 181-fiberglass fabric, and foaming an entire segment to shape in one operation. Later, the fiberglass fabric was peeled away to yield an excellent surface on the foam for subsequent adhesive bonding to the tank surface Each segment was trimmed on all mating planes.

The installation of the fuel-exclusion riser in the S-1C tank bulkhead is described in a Manufacturing Process Data Specification[7] issued by the Manufacturing Engineering Laboratory of Marshall SFC. Installation of polyurethane foam segments was made in three stages (Figures 3, 4 and 5).

Several similar elastomeric adhesive formulations were used for which the primer was PR 420 (Products Research).

Adhesive Formulation

Material	1	2	3
Adiprene L-100 (duPont)	100	100	100
Micro-Balloons	20	40	--
Moca	9	9	9

Formulation 2 was applied around the inboard, LOX, tunnel-to-bulkhead fitting. Formula No. 2 was applied as a 0.062-in. thick (minimum) coat to all of the foam interfaces and to the bulkhead area. The centerpiece, LOX tunnel-enclosure segments, and two adjacent gore segments were bonded with Formula No. 1. Vacuum bagging under a 27-inch vacuum and curing for 16 hours at room temperature completed the bonding.

After installation of all the segments, a nylon fabric cover was applied in sections to fit the various segments.

DEVELOPMENT OF FLEXIBLE-FOAM FILLED STRUCTURES

A marine-oriented application of foaming-in-place and void-filling to form a lightweight buoyant structure was developed by Whirlpool Corporation for the forming of life rafts.[15, 16]

The foam components were required to be stable from 40°F to 120°F over a wide range of relative humidity, to have a low viscosity and to be storable for one year in the package. The foam formulation was:

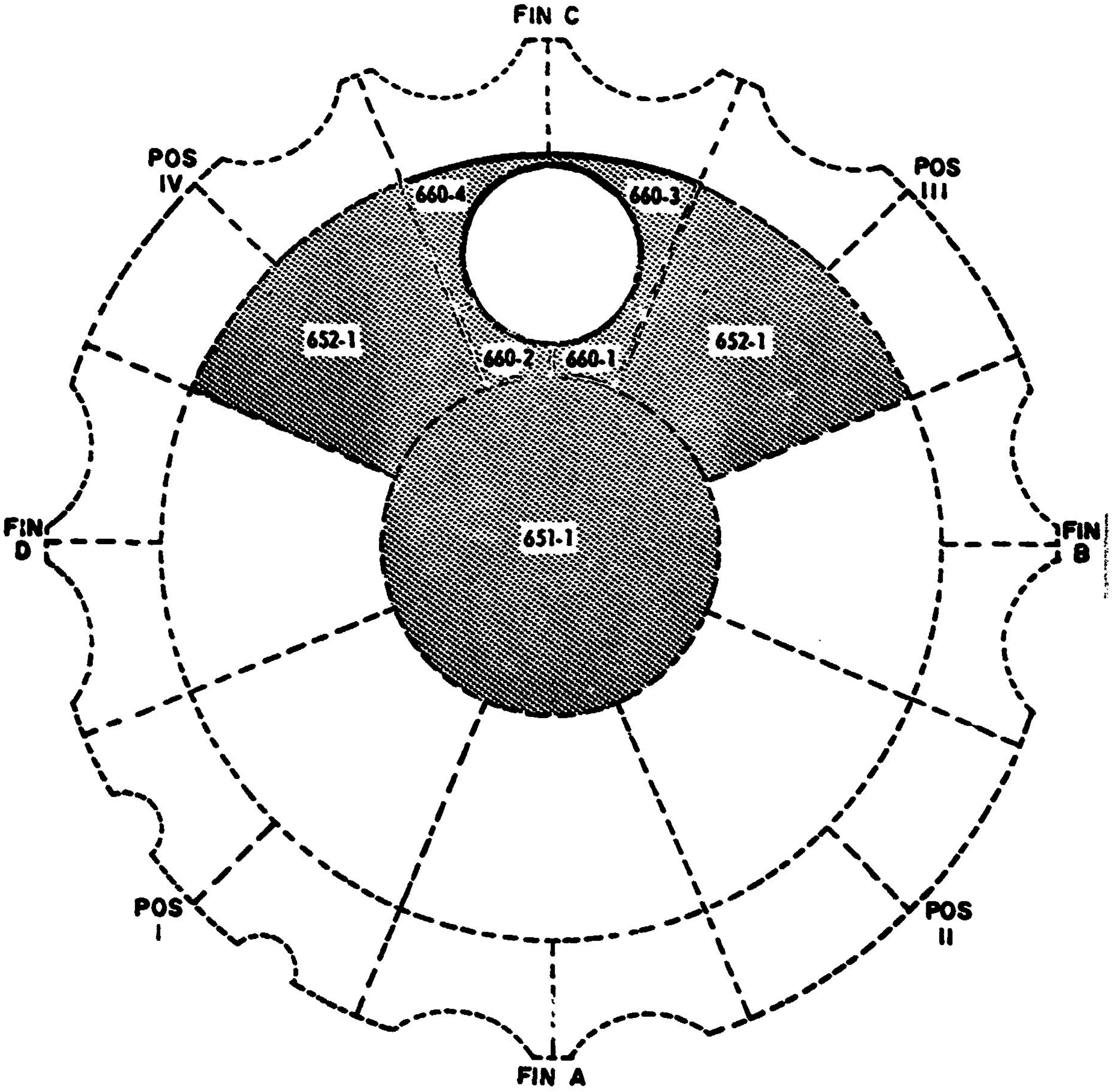


Figure 3. —Installation of polyurethane foam segments of the fuel exclusion riser in the aft bulkhead.

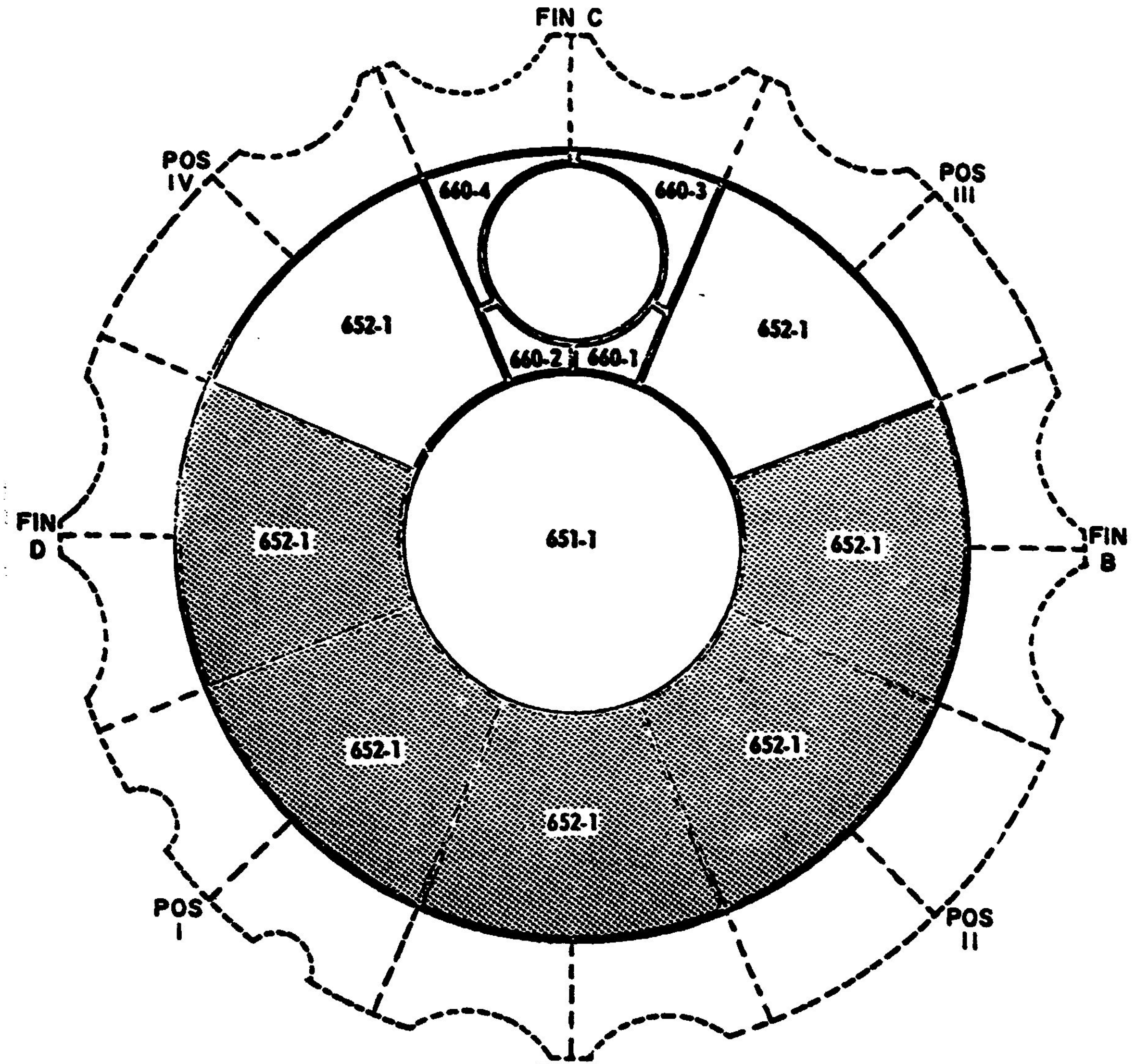


Figure 4. —Installation of polyurethane foam segments of the fuel exclusion riser in the aft bulkhead.

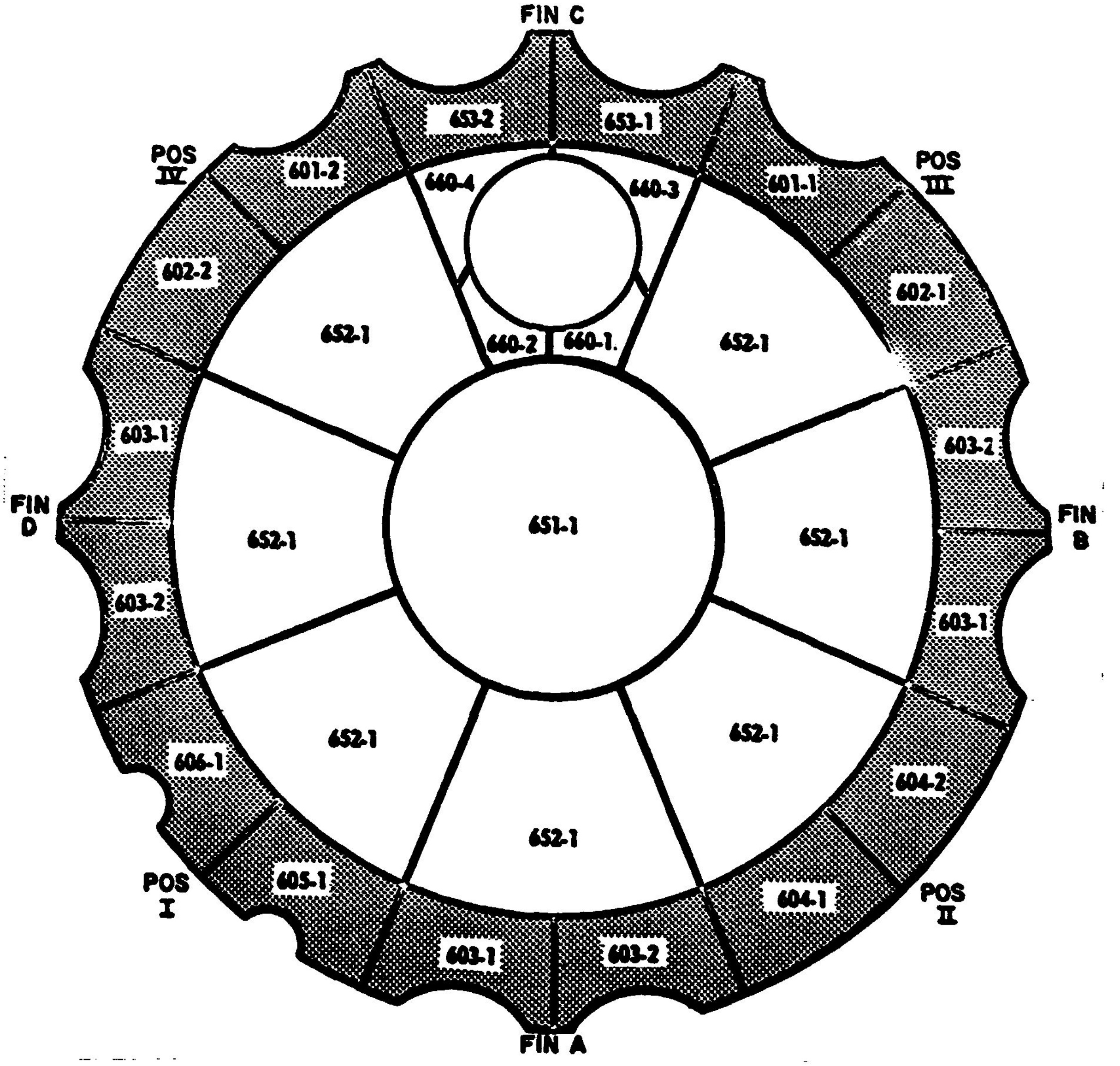


Figure 5. —Installation of polyurethane foam segments of the fuel exclusion riser in the aft bulkhead.

	Parts by weight	Manufacturer
Part A (Resin Mixture)		
G-2571 Polyether Resin	100.00	Atlas Chemical Co.
G. E. - 1074 Silicone Surfactant	3.00	General Electric - Silicone Division
Triethylene Diamine (Dabco)	.01	Houdry Process & Chemical Co.
Dimethyl Ethanol Amine	3.00	Union Carbide Chemical Co.
R-11 Monofluorotrichloromethane	50.00	DuPont Chemical Co.
	156.01	
Part B		
Mondur MR Isocyanate	107.00	Mobay Chemical Co.

The foam was metered in the ratio of 1.46 parts A to 1 part B, and hardened to a dimensionally stable, rigid foam. The formulation filled 9 feet of the life-raft tube and hardened to a foam suitable for the life-raft application.

A static head for mixing this formulation was tested at various machine rates up to 0.472 lb/second. A mixing blade made of a series of perforated aluminum discs stacked on top of each other was inserted in the static head. Two pressure tanks introduced the materials under pressure to the static mixer. The final design incorporated an inner CO_2-gas chamber with an outer concentric tube spaced with narrow tapes of the raft material. The raft was designed so that the inflated partial portion and the foam-in-place would each support a load of 200 pounds.

The raft was formed with 8 pounds of foam giving a total weight of 11.12 pounds. The foamed raft was very strong and did not show any measurable deflections under the load of a test subject while standing. The foam formulation was considered to be a breakthrough, in that it produced a foam that would travel a great length in a thin sandwich construction and provide the required strength.

LUNAR STAY-TIME EXTENSION MODULE STUDY (STEM)

This study was conducted by Goodyear Aerospace Corporation under the direction of NASA Langley Research Center,[9] to design a 400- cu. ft., cylindrical, lunar shelter module, defined within Apollo Extension System (AES) constraints. In this concept, the 7-foot diameter and 13-foot long module has a composite wall structure. A two-inch thick layer of approximately 1.2 lbs/ft^3 density flexible polyurethane foam (Nopco Chemical UU-15) would be used as part of an integral micrometeorite barrier and to protect the structure against the loss of life-sustaining oxygen.

The shelter wall would carry a structural load and was essentially designed as a space radiator to keep the integral shelter temperature at 75°F even under 250°F lunar temperature conditions. An insulation blanket would be drawn over the shelter to help achieve temperature control over the range of +250°F to -300°F.

The life-support system would utilize a 5-psi oxygen atmosphere as in the Apollo capsule. An oxygen pressure barrier contains a bladder foam layer of 0.070 inch thick PVC foam (Rubatex R-313-V of Great American Industries).

Power requirements of 300 watts minimum would be supplied by a dual system of hydrogen-oxygen fuel cells. Power cells are foamed after assembly to serve as a dampener for acoustical noise and vibration, and to minimize free gas volumes for safety.

A special feature is assembly by filament winding. Axial copper filaments are placed through the 2-inch dimension (Fig. 6) to increase the thermal conductivity of the foam in order to improve heat transfer characteristics through the wall. The thermal conductivity (k) may be varied from 0.156 to 5.00 Btu-inch/sq. ft.-hr° F, by varying the area density of the copper filaments. A h value of 1.46 was measured for approximately twenty-six copper filaments (5-mil diameter) per square inch.

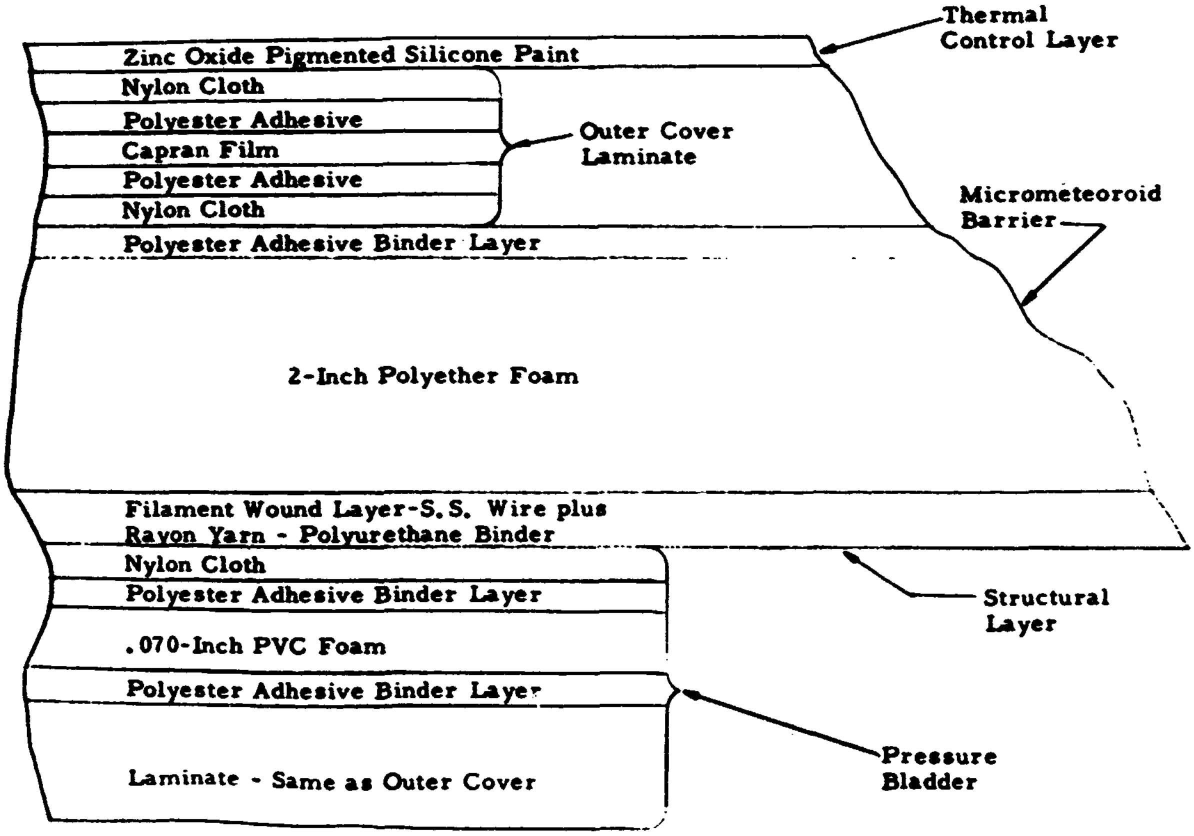


Figure 6.—Schematic-composite wall structure.

FOAMS FOR RIGIDIZED SOLAR-ENERGY CONCENTRATORS

Foams for the rigidization of solar energy concentrators in space require highly precise techniques for polymerization and foaming reactions in space environment. The rigidized solar collector represents one of several concepts for lightweight solar-energy collectors. Rigidization has also been achieved by structural techniques which do not involve foams, as in the case of an inflatable pressurized collector in which an inflatable shape of Mylar is attached to the collector. Other methods have been reported in a review on solar-collector development.[11] Experimental development work on rigid solar collectors has mainly been directed by the Langley Research Center.

Principal considerations for foam materials as structural components of a rigidized collector are weight per unit projected area, prelaunch storage volume, deployment method, structural integrity and stiffness, space environment effects, and scalability to larger-diameter paraboloids.

Prototype paraboloid solar concentrators have been produced from two to five feet in diameter. One method consists of expanding foam into hollow areas on the rear surface of an inflated parabolic structure. The foam system stored in the unexpanded structure before deployment must possess suitable storage life under controlled ground conditions and also react under the stimulus of some form of heating under space vacuum conditions.

Major studies on the processing capabilities of foam materials for this purpose have been performed; one by Hughes Aircraft[12] on an inflatable, rigidizable solar collector, and another by Goodyear Aerospace Corporation[14] on a predistributed, azide-base, polyurethane foam for rigidization.

Predistributed, Azide-Base Polyurethane Foam[14]

The azide-base polyurethane foam system developed by Goodyear Aerospace Corporation can be foamed in a vacuum at about 10^{-5} torr, in a heat-initiated process. The formulation developed for a precoat material can be applied as a paste on a membrane structure (examples are stressed Mylar film or H-film); it can also be foam-activated and rigidized by the application of heat and can produce a foam product to meet the design goals of rigidizing a space solar concentrator. The material is a single package containing these chemical reactants: a prepolymerized polyolresin, a blocked isocyanate, and a di-azide, which is convertible to a diisocyanate and nitrogen blowing agent when heat triggered. The system is stable when stored at temperatures below the 150°F to 200°F range (usually below 180°F).

This method for "foaming-in-place" contrasts with other approaches to delay foaming such as (a) rapid chilling and low-temperature storage of reactants after mixing,[8] (b) the use of marginally stable derivatives of isocyanates (chemically blocked isocyanates), (c) solid reactants with low melting points above room temperature, and (d) systems that are heat-activated on exposure to ultraviolet or infrared radiation.

Standard Formulation of Precoat

The precoat formulation adopted as a standard was designated formulation No. 382-40 and had the following composition:

Component	Weight (%)
Prepolymer 382-37 (or equivalent) solids	55.4
Azide Structure X	16.5
Bisphenol adduct of 4,4'-diphenyl methane diisocyanate (duPont's Hylene MP)	26.0
Surfactant (Union Carbide's L-5310)	1.6
Tin Catalyst (Union Carbide's D-22)	0.5
	100.0

Prepolymer 382-37 is a hydroxyl-terminated prepolymer, prepared from HP-370 polyol resin (hydroxyl No. 370) and MDI (4,4' diphenylmethane diisocyanate) at a reactants ratio (-NCO/-OH) of 0.30. The reaction time/temperature was 2 hours/ 120°C. The polymer melt temperature, when compounded into a precoat and foamed in vacuum is 280-320°F. The prepolymer 382-37 gave a clear, homogeneous solution at 80 percent solids in acetone solution, making it superior for use in a precoat.

The polyol resin had a suitable viscosity at the critical foaming stage and an M_c (molecular weight/cross-link) value of 500 to obtain a high softening temperature. HP-370 is classified as a heterocyclic initiator (α-methyl-glucoside).

Azide Structure X is 4,4'-diphenylmethane diacyl azide (Mol. Wt. = 250, amine equivalent = 125), melting point 181-184°F (dec.) and a half-life at 193°F of 30 minutes (preliminary result). The vacuum loss of undiluted compound at 75°F and 10^{-5} torr was 0.3 percent in 17.5 hours. This diazide was preferred because of the high purity obtainable and the high polymer melt temperature it provided to the foam product. The azide on decomposition into isocyanate supplies nitrogen as blowing gas.

Bisphenol adduct of 4,4'-diphenyl methane diisocyanate is a blocked diisocyanate. The sum of azide and blocked isocyanate supplies a -NCO/-OH ratio of 1:1. The blocked isocyanate allows a reduction of isocyanate from azide to about one-third of the total supplied.

Reduction of the azide concentration provides greater storage stability and improved foaming process control (undiluted azides are impact sensitive).

The amount of azide is adjusted to give an adiabatic temperature rise from 175°F-190°F into the range at which the blocked isocyanate is rapidly "unblocked" with absorption of heat.

Process

In the delayed foaming reaction a di-azide (or polyazide) may be employed as the inert ingredient in a mixture of reactants which can form a polyurethane polymer. Rearrangement of the acid azides at slightly elevated temperatures above 150°F, can initiate the polymerization to a polyurethane along with foaming due to the released nitrogen.

To avoid an isothermal process, the foaming was made adiabatic and involved heating the precoat to a temperature of approximately 180°F. The azide decomposition is self-propagating, although slow compared to explosions. The final foam temperature is controlled at a level between 300 and 400°F, by azide concentration. The inert, storage-stable, blocked isocyanate derivative requires a minimum temperature of around 300°F for activation.

Application of Precoat

Strength, hardness, and heat-distortion temperature (Fig. 7) are improved by the addition of 2.0 percent by weight of chopped silica fiber (microquartz, 0 to 3-micron diameter). For application 30 to 40 parts of acetone per 100 parts of formula homogenize the material. Acetone is then evaporated to a 20 percent level to obtain a spreadable paste.

The storage stability of deacetonized precoat spread on Mylar film is 44 days at room temperature and 139 days at 40°F. Vacuum in the 10^{-4} to 10^{-5} torr range for 30 hours at room temperature, did not impair the foaming behavior.

Physical Properties of Predistributed Foam

A testing program measured: 1) tensile stress-strain, 2) compression stress-strain, 3) shear, 4) thermal coefficient of expansion, 5) creep, 6) bond strength (under UV exposure), 7) dimensional stability, 8) thermal conductivity, and 9) reflectance.

GAC predistributed foam is brittle from -200°F to 78°F and becomes somewhat ductile at 240°F. On the average, tensile and compression properties at 4.5 lb/ft^3 density are 25 percent of those for the corresponding mechanically mixed foams. Mechanical-property test data for a number of foam specimens (from precoat weighing 3.8 gm/in^2) are given in Tables 4, 5 and 6. Linear thermal expansion and thermal conductivity data are shown in Figures 8 and 9. Weights of distributed precoat solids were 3.8 gm/in^2 in the expansion tests and 0.8 gm/in^2 in the conductivity tests.

The predistributed foam material has useful structural strength and stiffness in vacuum at temperatures approaching 240°F, for densities greater than 3 lbs/ft^3. Tensile ultimate stress values as high as 20 psi and tensile modulus values up to 1385 psi were obtained for 4 lbs/ft^3 densities.

Fabrication

Two-foot models were fabricated as gored paraboloids. H-film (duPont) was used as the mirror film. Contour measurements of one model gave less than 0.1 inch deviation from a perfect paraboloid over almost all of the surface area.

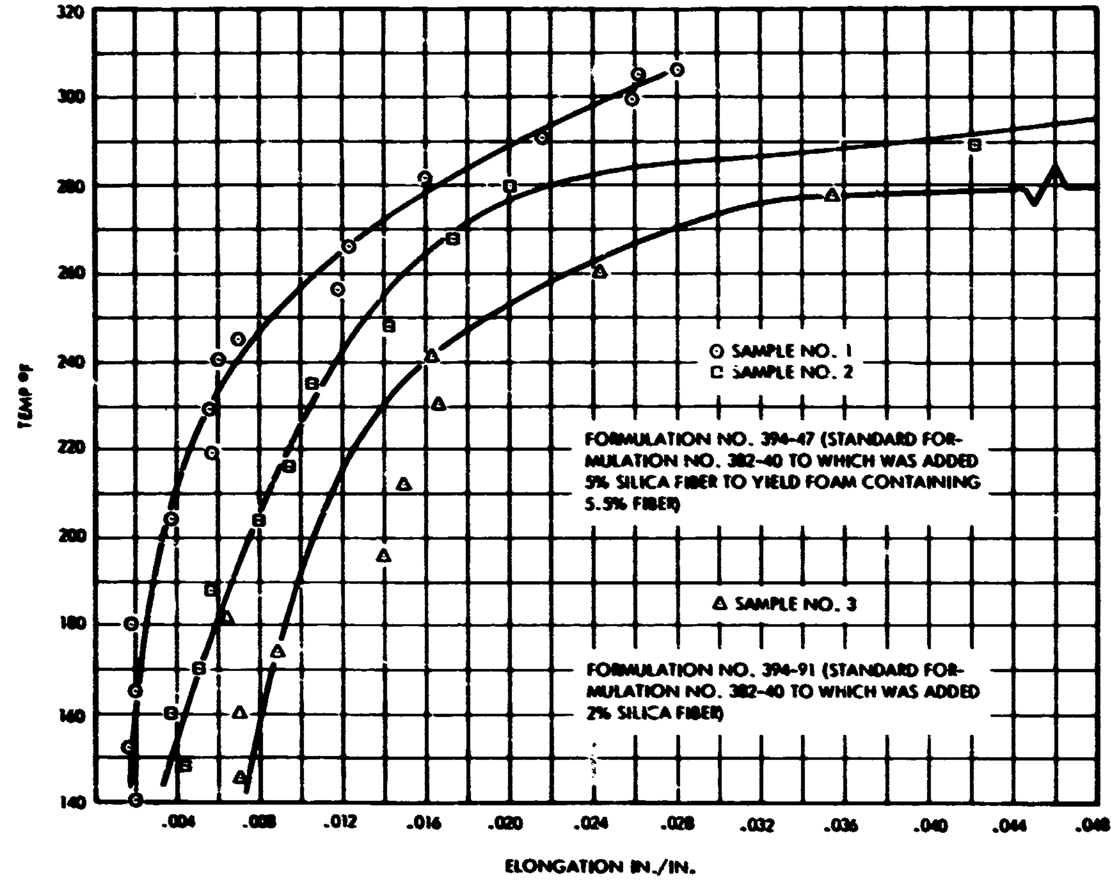


Figure 7.—Heat distortion tests—with microquartz added

Epoxy Syntactic Foams for Rigidized Inflatable Solar Collectors[12, 13]

In this investigation an epoxy syntactic foam was a reinforcement material for a five-foot diameter inflatable solar-energy collector. The reflective surface was a 2-mil, aluminized Mylar film paraboloid. The epoxy syntactic foam was activated by infrared radiation. This foam system supplanted a polyester resin-fiberglass laminate (UV-activated) which failed to produce high quality optics. Polyester syntactic foam systems to be cured by activation with UV light were unsatisfactory because of failure to cure throughout their thickness.

A suitable small volume package which could automatically eject and expand to shape was demonstrated. The target weight of 0.4-lb/ft^2 and reflectivities of 80 percent were achieved for the model collector.

Epoxy Syntactic Foam Formulation

The formulation developed was:

Table 4.—Tension Test Data for GAC Predistributed Foam

Specimen No.	Temp (°F)	Total wt		Density		Strain rate		Pressure (mm of hg)	Specimen size (in.)	F_{tu} (psi)	F_{ty} (psi)	E_t (psi)	e_{tu} (in./in.)
		G	Lb	PCI	PCF	In./Min	In./In./Min						
394-122 No. 2	78	4.8577	0.01071	0.00268	4.6310	1.0	0.25	- - -	1 x 1 x 4	19.5	19.5	1025	0.0200
394-124B No. 3	78	3.4113	0.00752	0.00188	3.2486	0.40	0.10	9.8×10^{-5}	1 x 1 x 4	8.0	6.5	360	0.0270
394-126 No. 2	78	3.3813	0.00745	0.00186	3.2141	0.40	0.10	9.8×10^{-5}	1 x 1 x 4	3.5	2.7	316	0.0196
394-121 No. 2	78	4.0109	0.00884	0.00221	3.8189	0.40	0.10	8.2×10^{-5}	1 x 1 x 4	11.95	11.95	585	0.0217
394-124B No. 2	78	3.8227	0.00843	0.00211	3.6461	0.20	0.05	9.2×10^{-5}	1 x 1 x 4	13.3	11.9	530	0.0296
394-122 No. 1	78	4.5752	0.01009	0.00252	4.3546	0.20	0.05	8.8×10^{-5}	1 x 1 x 4	19.1	19.1	853	0.0238
394-126 No. 1	78	3.4358	0.00757	0.00189	3.2659	0.20	0.05	8.3×1^{-5}	1 x 1 x 4	5.55	5.55	318	0.0190
394-124B No. 4	78	3.4826	0.00768	0.00192	3.3178	2	0.5	9.0×10^{-5}	1 x 1 x 4	7.9	7.6	405	0.0225
394-122 No. 3	78	4.5590	0.01005	0.00251	4.3373	2	0.5	8.8×10^{-5}	1 x 1 x 4	19.1	19.1	886	0.0230
394-126 No. 3	78	3.4990	0.00771	0.00193	3.3350	2	0.5	8.8×10^{-5}	1 x 1 x 4	7.5	7.5	405	0.0205
394-122 No. 4	-195	4.3901	0.00968	0.00242	4.1818	0.4	0.10	8.0×10^{-5}	1 x 1 x 4	20.6	20.6	1385	0.0155
394-124D No. 2	-200	3.8698	0.00853	0.00213	3.6806	0.4	0.10	8.0×10^{-5}	1 x 1 x 4	12.9	12.9	929	0.0155
394-126C No. 2	-205	3.7444	0.00825	0.00206	3.5597	0.4	0.10	6.0×10^{-5}	1 x 1 x 4	12.35	12.35	903	0.0144
394-124C No. 3	241	3.8925	0.00858	0.00215	3.7152	0.25	0.0625	2.8×10^{-4}	1 x 1 x 4	3.50	3.35	126	0.0386
394-124D No. 2	239	3.8475	0.00848	0.00212	3.6634	0.40	0.10	1.7×10^{-4}	1 x 1 x 4	4.0	3.90	152	0.0297
394-121	240	3.6784	0.00811	0.00203	3.5078	0.40	0.10	1.3×10^{-4}	1 x 1 x 4	4.95	4.10	150	0.0434
394-122 1X	250	2.8595	0.006304	0.00252	4.3546	0.25	0.10	3.0×10^{-4}	1 x 1 x 22.5	11.8	8.0	372	0.0450
394-122 3X	240	2.8494	0.006282	0.00251	4.3373	0.25	0.10	2.4×10^{-4}	1 x 1 x 22.5	13.85	9.5	470	0.0403

Table 5.—Compression Test Data for GAC Predistributed Foam

Specimen No.	Temp (°F)	Total weight		Density		Strain rate		Pressure (mm of Hg)	Specimen size (in.)	F_{cu} (psi)	F_{cy} (psi)	E_c (psi)
		G	Lb	PCI	PCF	(In. /Min)	(In. /In. /Min)					
394-92A No. 1	75	2.3109	0.00509	0.002545	4.4017	0.2	0.1	9.0×10^{-5}	1 x 1 x 2	35.0	16.0	883
394-92B*	75	1.2223	0.00269	0.001345	2.3282	0.2	0.1	4.0×10^{-5}	1 x 1 x 2	9.1	3.0	25
394-1266 No. 1	75	1.7969	0.00396	0.001980	3.4227	0.2	0.1	6.2×10^{-5}	1 x 1 x 2	12.5	7.3	475
394-92B	240	1.6562	0.00365	0.001825	3.1547	0.2	0.1	9.0×10^{-5}	1 x 1 x 2	5.4	4.3	92
394-92A	240	1.9796	0.00436	0.002190	3.7707	0.2	0.1	6.3×10^{-5}	1 x 1 x 2	5.3	3.4	163
394-92B	240	1.3115	0.00289	0.001445	2.4981	0.2	0.1	5.5×10^{-5}	1 x 1 x 2	2.3	0.9	42
394-124 No. 1	-200	2.0832	0.00459	0.002295	3.9680	0.2	0.1	8.6×10^{-5}	1 x 1 x 2	21.6	18.3	800
394-126 No. 2	-200	1.8443	0.00407	0.002035	3.5129	0.2	0.1	9.0×10^{-5}	1 x 1 x 2	21.0	15.0	575
394-124C No. 1	-200	1.8543	0.00409	0.002045	3.5320	0.2	0.1	8.8×10^{-5}	1 x 1 x 2	19.4	11.6	454

*Poor specimen—too spongy and offered little resistance to loading.

Table 6.—Shear Test Data for GAC Predistributed Foam

Specimen No.		Temp (°F)	Pressure (mm of Hg)	Cross-head speed (in./min)	Chart speed (in./min)	Weight				Density based on failed specimen		P_{su} (lb)	P_{sy} (lb)	* $F_{su} = \frac{P_{su}}{8}$ (psi)	** $F_{sy} = \frac{P_{sy}}{8}$ (in.)	δ_{sy} (in.)	$\frac{P_{sy}}{\delta_{sy}}$ (lb/in.)	*G:0.057408 (P_{sy}/δ_{sy}) (psi)
						Grams			Failed† specimen (lb)									
A	B†					A	B†	Avg*		(pci)†	(pcf)†							
394-124D No. 1	394-132 No. 2	75	9.4×10^{-5}	0.20	2.0	1.2965	1.9700	1.6198	0.004343	0.002895	5.003	287	287	35.9	35.9	0.035	8200	471
394-132 No. 9	394-132 No. 5	75	9.2×10^{-5}	0.20	20.0	1.4764	1.4444	1.4604	0.003185	0.002123	3.668	174	135	21.8	16.9	0.0195	6920	397
394-132 No. 11	394-132 No. 4	75	9.9×10^{-5}	0.20	20.0	1.4439	1.4307	1.4373	0.003155	0.002103	3.634	195	150	24.4	18.8	0.0203	7389	424
394-132 No. 7	394-132 No. 1	185	9.2×10^{-5}	0.20	20.0	1.5283	1.6148	1.5716	0.003560	0.002373	4.101	185	135	23.1	16.9	0.0187	7219	414
394-124A No. 1	394-124A No. 2	185	9.4×10^{-5}	0.20	20.0	1.0950	1.0106	1.0528	0.002228	0.001485	2.567	105	70	13.1	8.8	0.0162	4321	248
394-132 No. 12	394-132 No. 13	185	9.0×10^{-5}	0.20	20.0	1.4055	1.4018	1.4037	0.003090	0.002060	3.561	180	130	22.5	16.3	0.0198	6566	377
394-132 No. 6	394-122 No. 2	240	9.[illegible] $\times 10^{-5}$	0.20	20.0	1.3628	1.2970	1.3299	0.002859	0.001906	3.294	145	110	18.5	13.8	0.0204	5392	310
394-132 No. 8	394-122 No. 1	240	9.9×10^{-5}	0.20	20.0	1.2434	1.2003	1.2219	0.002646	0.001764	3.048	133	93	16.6	11.6	0.0176	5284	303
394-132 No. 3	394-132 No. 10	240	8.8×10^{-5}	0.20	20.0	2.1095	1.2571	1.6833	0.002772	0.001848	3.193	133	97	16.6	12.1	0.0167	5808	333

*Average weight of the two (columns A and B) 2 x 2 x 3/8-inch specimens.

**Average stresses.

†Based upon specimen that actually failed.

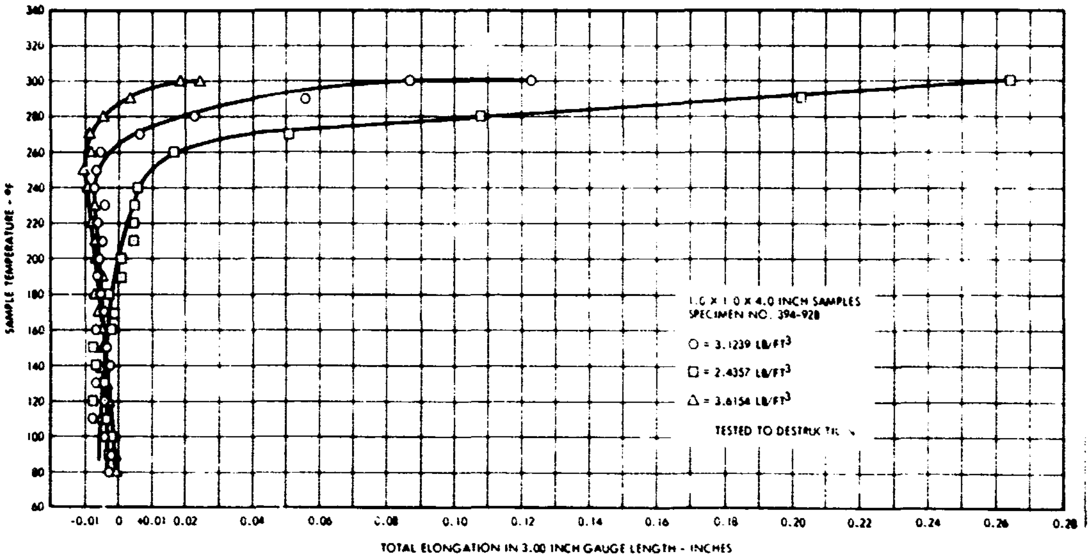


Figure 8. —Linear thermal expansion of precoat foam.

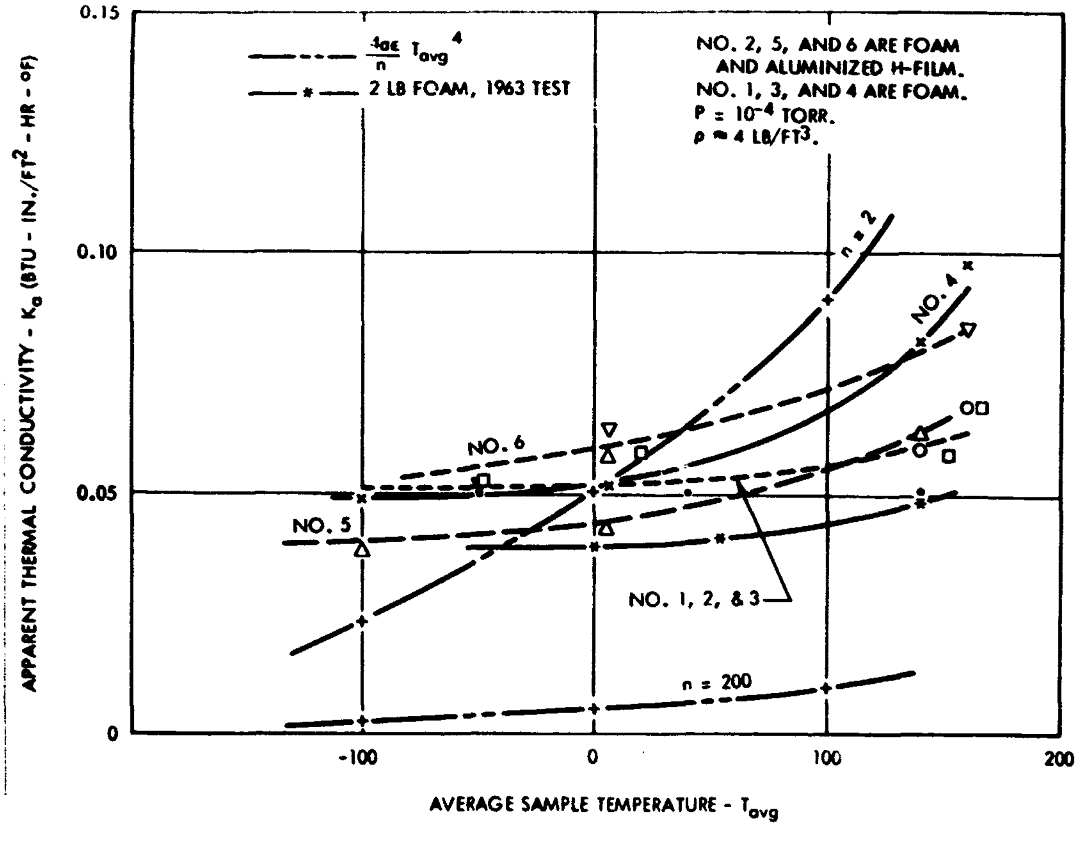


Figure 9. —Thermal conductivity versus temperature.

Component	Parts by Weight
Epoxy Resin	100
Phenolic microballoons	27.5
Pyrogenic Silica	4.5
Borate catalyst	10.0
Diethylaminopropylamine	0.55

The borate catalyst is 2- (β-dimethylamino ethoxy) -4 methyl 1, 3, 2-dioxaborinane. It can be mixed with the resin with no reaction at room temperature.

The epoxy foam resin formula cures in 4 to 6 hours at 225°F. Storage tests of the uncured material indicated that it would be flexible for a minimum of three weeks at room temperature.

Application Techniques

Several spreading techniques were tested. The preferred method consisted of making a 4- to 6-inch diameter ball of foam and the flattening this to a 24-inch diameter disc between heated (120-140°F) platens of a hydraulic press, using 0.1 inch thick spacers. The discs were butt-joined to each other and the spaces between the discs were filled in with additional foamant. The "foamant" material was then softened and the edges pressed together to form a large, homogeneous sheet.

Although the system cured satisfactorily at normal pressures, paraboloids made under vacuum did not retain the required optics, apparently due to volatiles in the resin. A back pressure technique maintained the reinforcement at pressure while the outer surfaces of the assembly were simultaneously subjected to vacuum (Fig. 10).

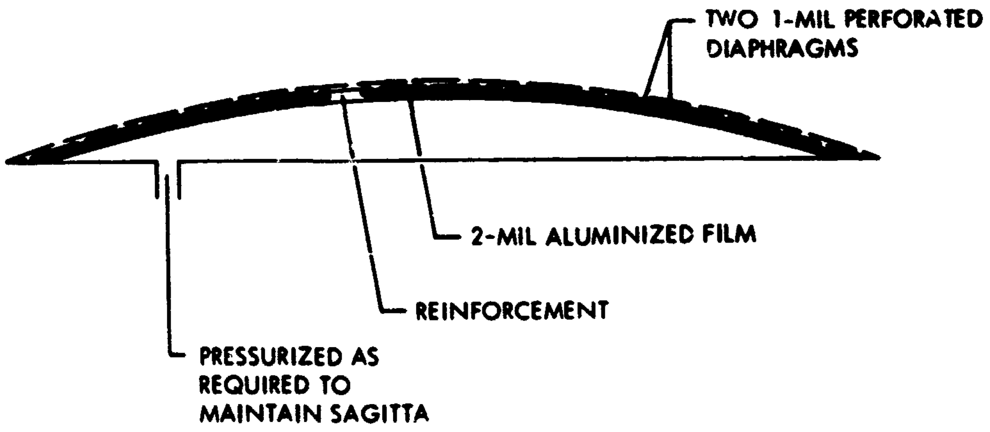


Figure 10. —Mechanical "back pressure" configuration.

Properties of Epoxy Syntactic Foam

Samples of the epoxy syntactic foam were cut out of paraboloids which had been inflated and rigidized in an altitude chamber (simulated to 150,000 feet altitude). Results are shown in Tables 7 and 8.

Vacuum-radiation tests were performed in a 10^{-6} mm Hg. vacuum for 240 hours heating the sample surface to 180°F by infrared plus exposure to one solar equivalent of ultraviolet radiation. The weight loss for this period was approximately 4.5 percent.

SELF-ERECTING FLEXIBLE FOAM STRUCTURES FOR SPACE ANTENNAS

The concept of self-erecting space-vehicle antennas, using flexible foam material in the structure as the erecting mechanism, has been investigated at NASA Langley Research Center[17, 18] and shown to be feasible. The system objective was to store the erectable antenna during the launch phase to reduce surface drag and subsequently expand it into the relatively large size needed for a high-gain directional antenna for space communications in the 960 to 2300 MC range. Erection was based on compression deformation of a flexible foam without exceeding its elastic limit and subsequent release from this shape to return to its original size by the relief of internal stresses.

The self-erection technique was demonstrated with an erectable Yagi disk array of antenna elements. These elements were chosen because their broad-band properties allow large physical tolerances on the flexible structure.

Construction Technique

Antenna elements consist of dipole-ground plane units made of epoxy printed circuit laminate, and director assemblies of brass or aluminum-foil discs separated by polyether flexible urethane foam spacers. Figure 11 shows a Yagi disk antenna without the foam spacers. The precut and shaped foam acts as the supporting structure for the disks and as the erecting mechanism for the whole director assemblv. Pyramidal and cylindrical erectable elements were investigated. Illustrations of the pyramidal element in the erected and packaged conditions are shown in Figures 12, 13 and 14. The director assemblies are packaged into the units by compressing the foam along the assembly axes.

Flexible Foam Materials

The foams used in these elements have low dielectric constants, are lightweight, and can be compressed to ratios of 8 to 1 and 12 to 1 for foams with densities of 1.7 and 1.0 lbs/ft^3, respectively. These foams were open-cell, polyether type, with an effective grain in their cell structure which allowed them to compress properly only in a direction perpendicular to the grain.

Table 7.—Mechanical Properties of Epoxy Foam

Test Type	Temp °F	Epoxy Foam	
		Strength, psi x 10^3	Modulus, psi x 10^5
Tensile	72	.410, .990, .380 Av = .593	4.940, 0.458, 4.680 Av = 3.359
Tensile	240	.310, .300, .235 Av = .282	1.730, 1.480, 1.080 Av = 1.430
Flexural (4-1/2" span)	72	.915, .601, .647 Av = .721	Not run
Flexural (4" span)	240	.500, .561, .492 Av = .518	Not run
Compressive Edgewise	72	.610, .690, .575 Av = .625	Not run
	240	.150, .150, .120 Av = .140	.938, .994, .756 Av = .896

Table 8.—Thermal Coefficients of Expansion of Epoxy Foam

Test	Coefficient of Expansion, in/in/°F x 10^{-5}
Temp °F	Epoxy Foam
-320	1.85
-118	2.63
+32	3.25
+150	2.07 (130°F)
+185	2.71
+240	Could not be run

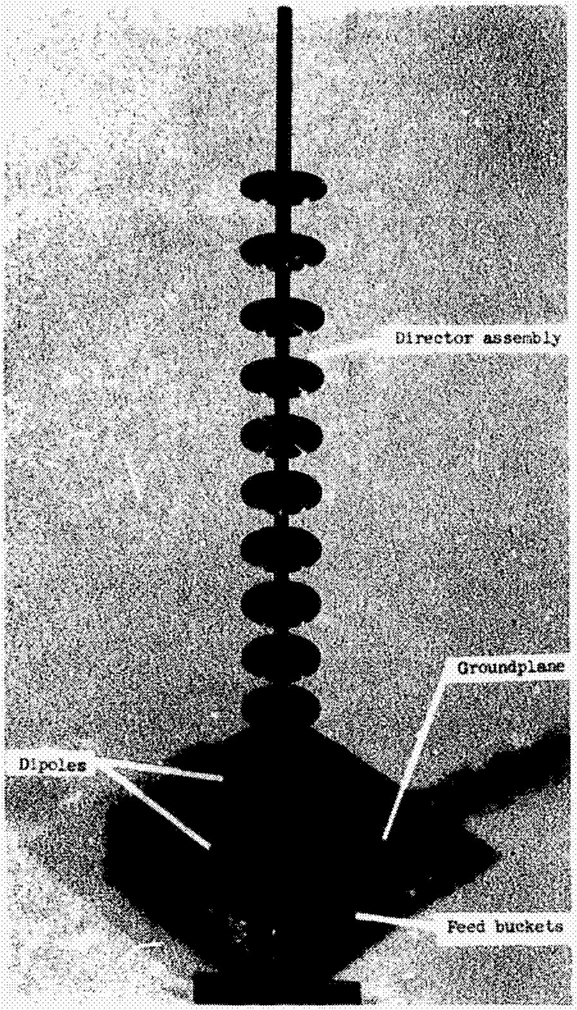


Figure 11. —Yagi disk antenna (standard element).

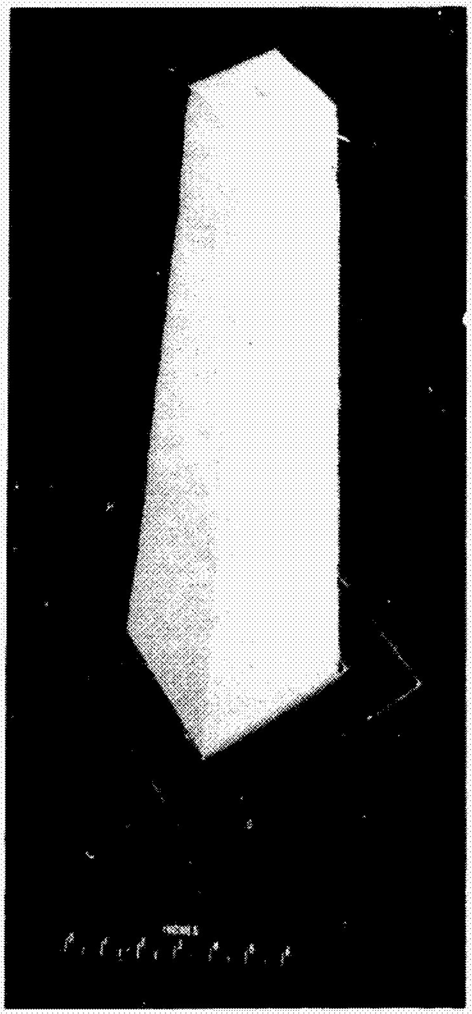


Figure 12.—1.7 pyramidal element (erected).

Mechanical Tests

Recovery, stress-strain, vibration damping and temperature differential tests showed the erectable elements to be acceptable. Foam samples 3 inches in diameter and 2 inches thick, were compressed to a 12-to-1 ratio for 20 hours, and recovery was tested at 760 mm Hg. and at 1×10^{-5} torr pressure. Recovery expressed in percent of original thickness (Fig. 15), was almost immediately within 10 percent of the original thickness. After 6 hours of recovery the elements retained permanent compression sets of 3 percent.

Loading and unloading curves for 1.0 and 1.7 lbs/ft^3 density foams (Fig. 16) show the behavior typical of low density flexible foams. The compression resilience $\left(\frac{\text{area of unloading curve}}{\text{area of loading curve}} \times 100\right)$ of the denser foam was 52 percent before and after

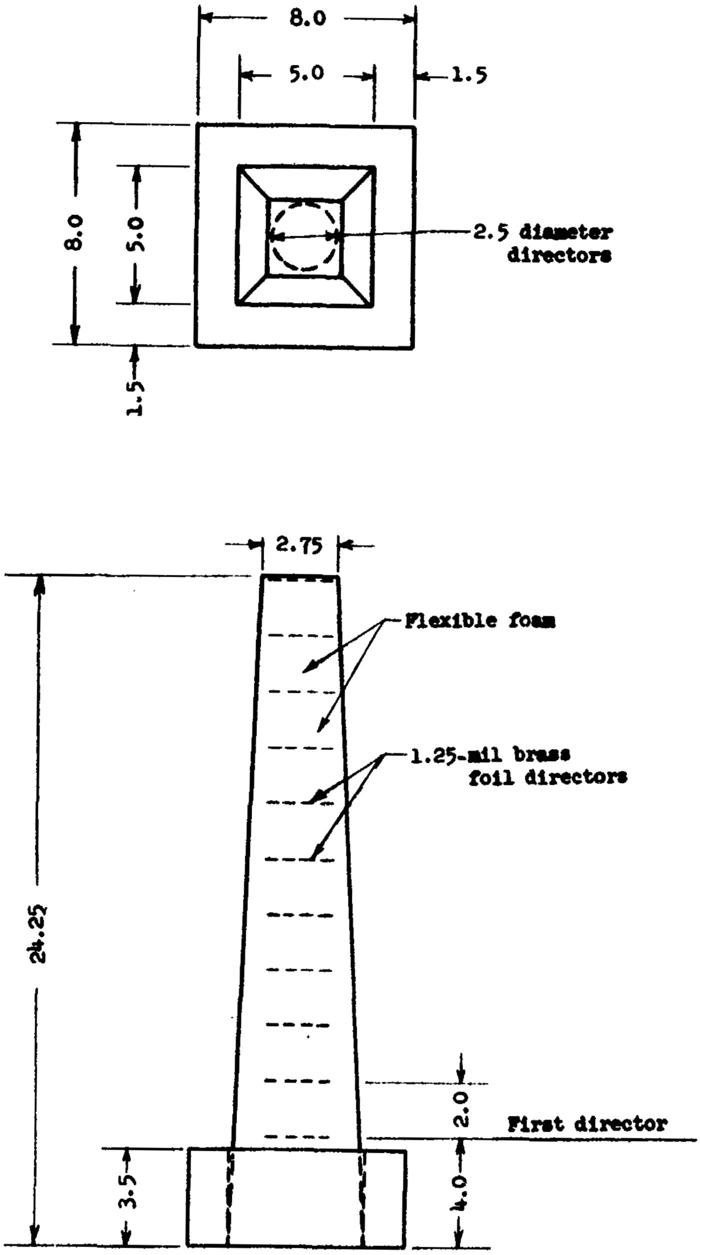


Figure 13. —1.7 pyramidal element.

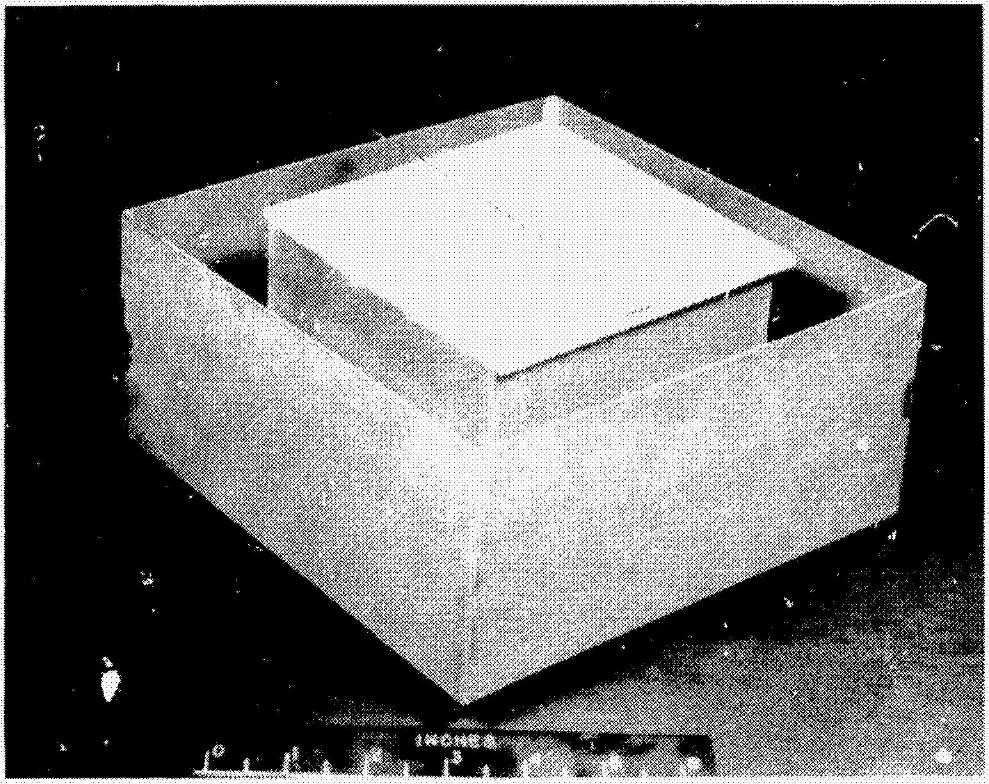


Figure 14. —1.7 pyramidal element (packaged).

environmental exposure. The simulated space environment applied to a 1.0 lb/ft^3 density foam was 1.0×10^{-5} torr vacuum, BH-6 mercury-arc UV emission in the range of 3650 to 3663 Angstrom units, and 140°F temperature for 50 hours.

In damping tests on samples freely vibrating in vacuum:

(1) A 1.0-lb/ft^3 cylindrical element vibrated at a frequency of 1.3 cps and damped to half-amplitude in 3.2 seconds.

(2) A 1.7-lb/ft^3 pyramidal element vibrated at a frequency of 3.4 cps and damped to half-amplitude in 0.9 seconds.

Temperature differential effects on a 1.7-density pyramidal element are shown in Figure 17.

MISCELLANEOUS STRUCTURAL APPLICATION CONCEPTS

Expandable Airlock Utilizing the Elastic Recovery Concept[19]

An expandable airlock design concept for use in the space environment utilizes the stored potential energy of a compressed foam for deployment. For external airlock application the composite wall would consist of a laminate of a 2-inch-thick protective layer of resilient foam material sandwiched between structural fabric layers. The foam also offers micrometeoroid protection and insulation for thermal control.

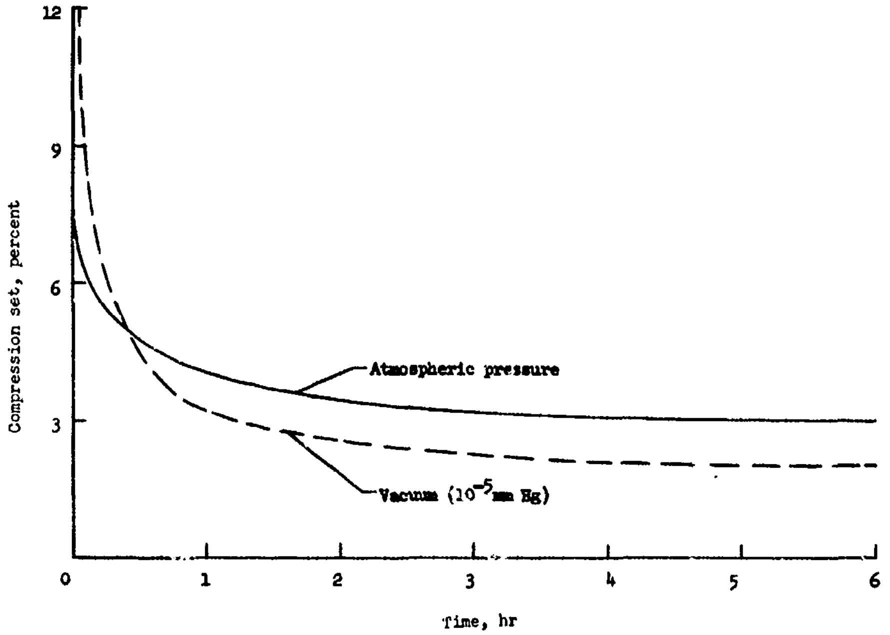


Figure 15.—Recovery properties of the flexible foams.

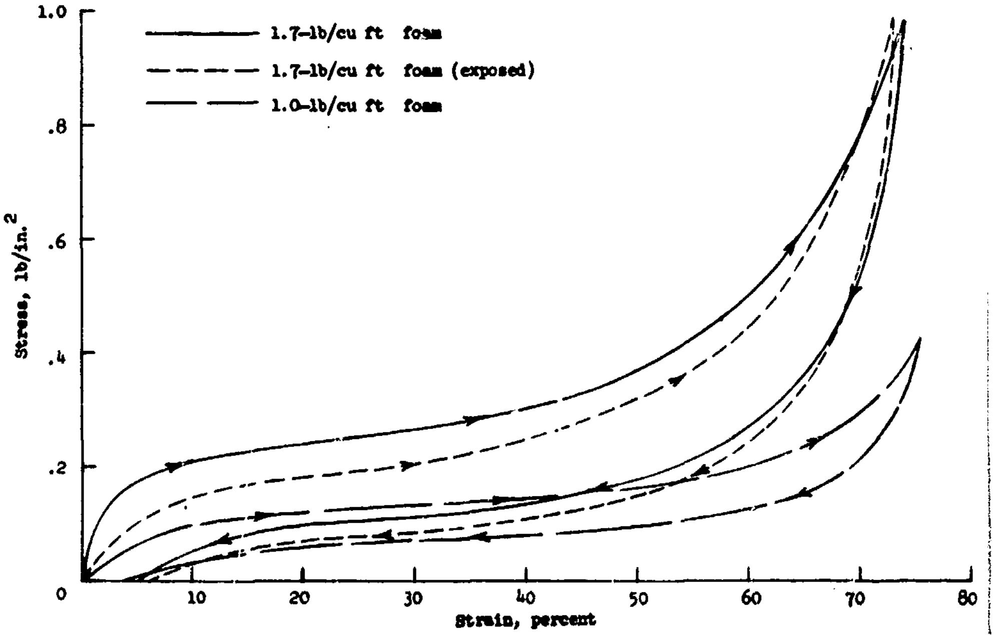


Figure 16.—Stress-strain properties of the 1.7-pound-per-cubic foot flexible foam before and after the environmental exposure and the unexposed 1.0-pound-per-cubic-foot flexible foam.

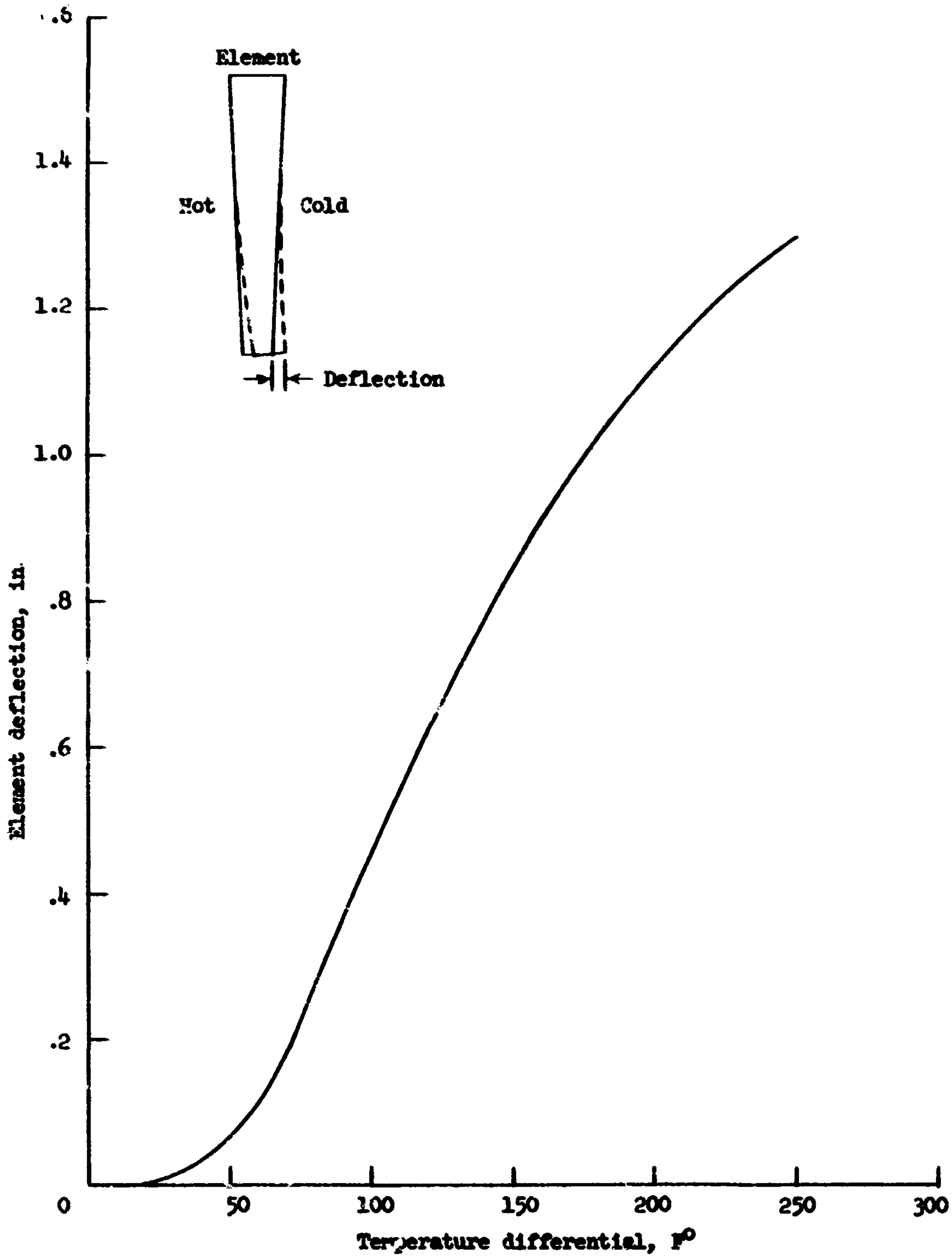


Figure 17.—Effect of temperature differential on the 1.7 pyramidal element at a pressure of 2×10^{-5} millimeters of mercury.

Expandable Space Structures - Evaluation of the Elastic Recovery Concept[20, 24]

This investigation determined the type of elastic recovery composite for possible application to manned space stations or shelters, storage tanks, antennas and secondary structures.

One expandable structure consisted of 1.9 inches of foam bonded to regenerated cellulose cloth on one side with polyvinylidene chloride latex resin adhesive, and to polyvinylidene chloride film on the other side. This film was selected because of its physical properties and low permeability to gases.

In another structure foam was made into a laminate of 1-ply fabric inner skin, one inch of 1.35 lbs/ft^3 flexible foam and an aluminized Mylar outer skin. The shear strength was 1.8 psi and the "k" (in vacuo) was 0.13 $Btu\text{-}inch/ft^2\text{-}hour\text{-}^\circ F$.

A flexible plastic foam was loaded with barium titanate to obtain a large antenna aperture with a spherical surface. Major conclusions reached were:

(1) The flexible foam core is more effective as an elastic recovery composite than compressible honeycomb.

(2) The elastic recovery composite will erect under vacuum or cryogenic temperature and after being stored for long periods.

For meteoroid protection the foam core absorbs fragments produced when an outer skin breaks up the particle.

Wall concepts for expandable space structures are illustrated in Figure 18.

Resistance of Composite Space Structures to Hypervelocity Impact

Ames Research Center[21] investigated the effects of hypervelocity (20 000 to 23 000 feet per second) impact of 1/8 inch diameter glass projectiles fired from a light-gas gun into a variety of composite structures. The study indicated the effectiveness of low-density filler materials for protection of a space structure against meteorite impact.

The foam core composite structures tested were composed of aluminum sandwiches of 2024-T3 aluminum alloy separated by layers of polyurethane foam, polystyrene foam, and rigid cellulose foam, or they were low density ablative heat-shield materials. The fillers performed with approximately equal effectiveness on the basis of weight per unit volume, independent of composition.

For the multiple-wall target samples, the walls were made of sheets of 2024-T3 aluminum alloy of two thicknesses and generally spaced at one inch with the filler material in the core. The targets were at zero external load level when impact occurred. Various configurations were employed for targets which comprised either two 0.050 inch thick sheets of aluminum or three sheets of 0.031 inch thickness so that the total weights of the respective targets were kept constant. Sheet spacing was also kept at one inch.

The polyurethane filler, a 2-lb/ft^3-density, open-celled flexible foam, and the 2-pound-density, rigid, polystyrene foam provided about equal protection to the rear sheet in the two-sheet model, as measured by damage effects on the rear face of the composite. Inclusion of metal honeycomb behind the bumper sheet increased impact damage, which was still further increased when a foam plastic

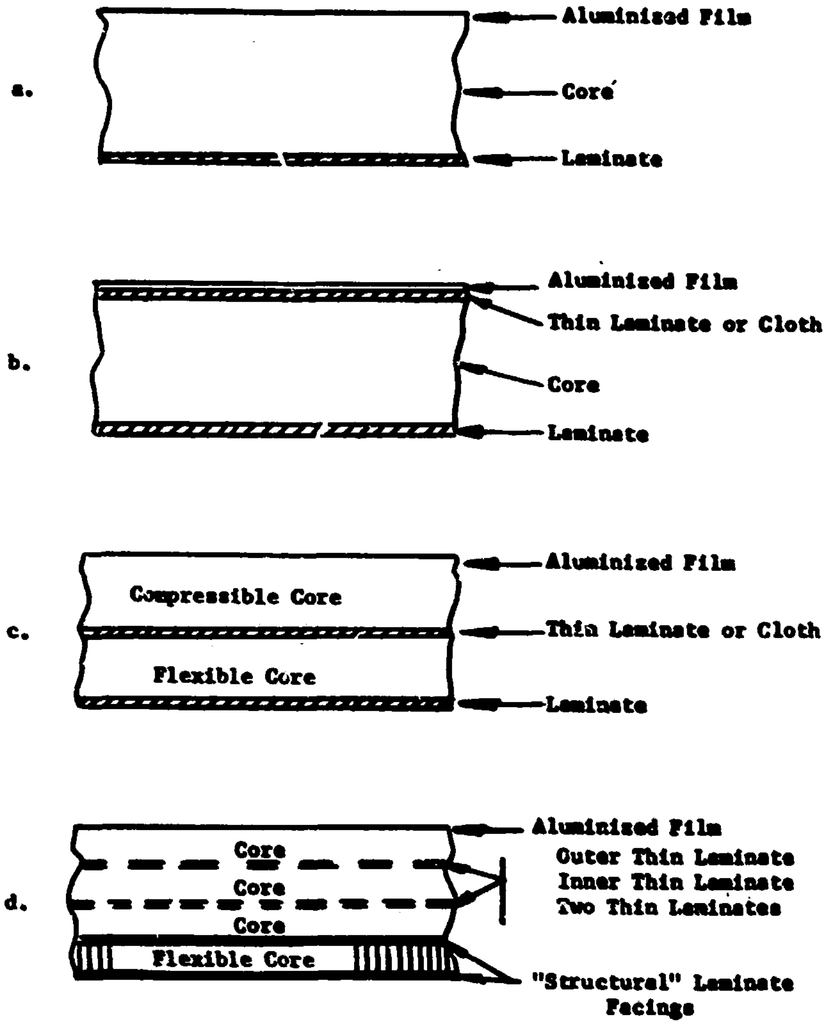


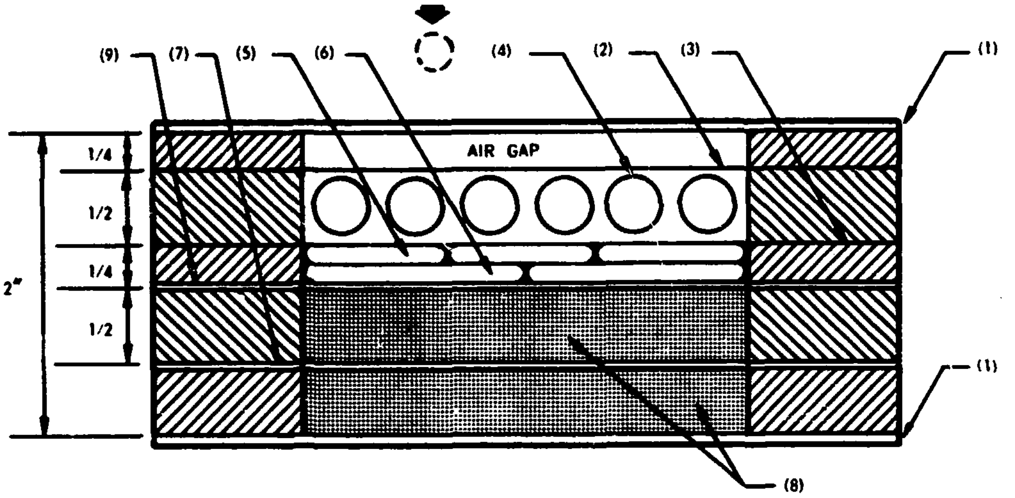
Figure 18.—Wall concepts for expandable space structures.

filler was combined with the structure. Addition of a bumper shield effectively improved the penetration resistance at equivalent weight.

Combined Concept for Control of the Meteoroid Hazard

Two approaches for protection against hypervelocity impact damage are the bumper shield and the single-thickness, armor-plate structure.[22] The armor-plate approach lacks good design criteria for a reliable, lightweight structure.

Northrop Space Laboratories[23] investigated a combined system with a self-sealing feature under the direction of OART, Space Vehicle Division of NASA, and the Protective Structures Section of NASA Langley Research Center. The system combined penetration resistance and self-sealing capability.



MATERIAL CODE

NO.	
1.	0.020″ ALUMINUM (2024 – T3)
2.	3 MIL MYLAR
3.	9 MIL MYLAR
4.	3/8″ DIA. RUBBER SPHERES (EC1878)
5.	3/16″ THICK RIGID FOAM RESIN (XR-6-3700) ENCAPSULATED IN HEAT SEALABLE PLASTIC FILM
6.	1/16″ THICK CATALYST (T-9), ENCAPSULATED IN HEAT SEALABLE PLASTIC FILM
7.	3 PLY FIBERGLASS-EPOXY LAMINATE
8.	FLEXIBLE POLYURETHANE FOAM (ρ = 1.5 #/FT^3)
9.	1/64″ NITRILE SHEET

Figure 19.—Integral system - combined mechanical - chemical sealing concept (rigid foam resin/rubber balls).

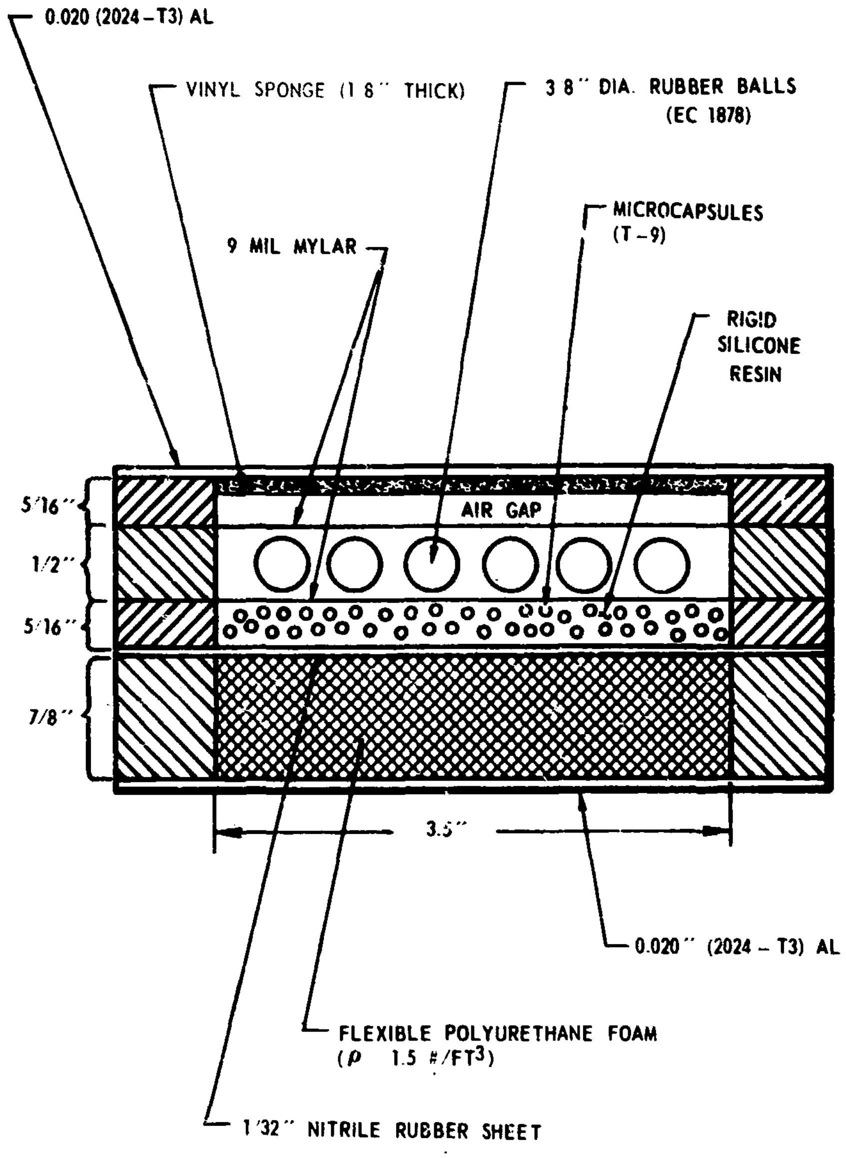


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Figure 20.—Integral system - microencapsulation/ rubber balls concept.

Materials of construction for two test panels are shown in Figures 19 and 20. In the first case the uncured foam resin and catalyst are separated by confinement in sealed plastic films and in the second case the resin is contained between Mylar membranes with the microencapsulated catalyst distributed uniformly in the resin.

Self-sealing for these systems is based on release of catalyst following puncture in a hypervelocity impact test. The rigid silicone foam resin expands upon interacting with the catalyst and then cures to form a solid sealing plug, replacing the material along the pellet entry path.

The microencapsulated catalyst T-9 (stannous octoate) was prepared by means of a shell formulation of Algin-Gel-Polyvinylalcohol at Southwest Research Institute. The catalyst-resin mixture could be made into a paste which is easy to apply, and a dry mix could be prepared. The microcapsule paste provides the correct ratio throughout its volume when impacted. The foaming reaction and the depletion of catalyst are localized, thereby maintaining protection on subsequent impacts.

Leakage rates were determined after impacting a 1/8-inch diameter steel sphere on test panels. Projectile velocities in the range of 20,000 to 24,000 fps were used under room, elevated, and reduced temperature conditions at the McGill University light-gas gun facility.

Without the self-sealing concept, leakage rates for a 1/8 inch diameter hole, at a pressure differential of 1 atmosphere, were greater than 260 pounds per day. Self-sealing test panels (Figures 19 and 20), were found to have a zero leakage rate within 5 to 10 seconds after impact by flowmeter measurements.

REFERENCES

1. Aerospace Expandable Structures Conference, sponsored by AF Aero Propulsion Laboratory and AF Flight Dynamics Laboratory, Oct. 23-25, 1963, Dayton, Ohio - AD 432006.
2. Expandable Structures Design Handbook, ASD-TDR-63-4275, Part II, Contract AF 33(657)-8776, Lockheed Aircraft Corp. (1965).
3. Eckman, K. J.; and Brazier, T. S.: Development of Low Density Rigid Polyurethane Foam for Use of S-1C Flight Vehicles, NASA CR-62110, 1964, NASA Contract NASA 8-11688.
4. Yates, I. C.: Status Report M-ME-F-18, Fuel Exclusion Riser. NASA MSFC M-ME-F-185, June 11, 1963.
5. Beyerle, F. D.: Polyurethane Foam Fuel Exclusion Riser - Launch Vehicle Program, S-1C, NASA MSFC; EP 2221, M-ME-M, Dec. 18, 1963.
6. Reference 5, Addendum 1, MSFC; EP 2221, M-ME-M, Feb. 12, 1964.
7. Fuel Exclusion Riser Installation for S-1C Stage. NASA MSFC: MPD No. 23001A, Feb. 5, 1965.
8. Moore, H. R.: Urethane Foams for Aerospace Application. Report No. NADC-EL-N6208, U. S. Naval Air Development Center, March 2, 1962.
9. Lunar Stay Time Extension Module (STEM), Final Report GER-12246, Aug. 21, [illegible] Goodyear Aerospace Corp. NASA Contract NAS1-4277.

10. Second Aerospace Expandable Structures Conference, May 1965, Minneapolis, Minn.

11. Heath, Jr., Atwood R.; and Maxwell, Preston T.: Solar Collector Development. Astronautics and Aerospace Engineering, pp. 58-61, May, 1963.

12. Schwartz, S; and Bagby, J.: Rigidized Inflatable Solar Energy Collectors. NASA CR-254, NASA Contract NAS 1-3244, Hughes Aircraft Co., 1965.

13. Schwartz, S.: Rigidized Inflatable Solar Energy Collectors. Report, Feb.-May, 1964, NASA Contract NAS 1-3244, Hughes Aircraft.

14. Jouriles, N.; and Welling, C. E.: Development of a Predistributed Azide Base Polyurethane Foam for Rigidization of Solar Concentrators in Space. NASA CR-235, NASA Contract NAS 1-3301, Goodyear Aerospace Corp. 1965.

15. Berford, A. E.: Development of Flexible Foam Filled Structures. Whirlpool Corp., NASA CR-59832, NASA Contract NAS 9-2031, 1963.

16. Development of Flexible Foamed Filled Structures. Final Report, Whirlpool Corp., NASA CR-65013, NASA Contract 9-2031.

17. Vaughan, Jr., Victor L.; and Hoffman, Edward T.: Self-Erecting Flexible Foam Structures for Space Antennas. NASA TND-1610, 1963.

18. Croswell, W. F.; Gilreath, M. C.; and Vaughan, Jr., V. L.: Self-Erecting Space Antennas, IRE Transactions on Space Electronics and Telemetry, pp. 139-142, June 1962.

19. Williams, Jerry G.: Development of an Expandable Airlock Utilizing the Elastic Recovery Principle. NASA paper, presented at the Second Aerospace Expandable Structures Conference, Minneapolis, Minn., May 25-27, 1965.

20. Brink, N. O.; Anderson, B. C.; Thompson, C. E.; and Wolcott, C. E.: Development and Evaluation of the Elastic Recovery Concept for Expandable Space Structures. NASA CR-121, NASA Contract NASw-661, Whittaker Corp. 1964.

21. Summers, James L.; and Nysmith, Robert C.: The Resistance of a Variety of Composite Space Structures to Hypervelocity Impact. NASA paper, presented at the AIAA Conference, 1966.

22. D'Anna. Philip J.: A Combined System Concept for Control of the Meteoroid Hazard to Space Vehicles. Journal of Spacecraft, vol. 2, no. 1, Jan.-Feb. 1965, pp. 33-37.

23. D'Anna, Philip J.; and Heitz, Roger M.: Evaluation of Self-Sealing Structures for Space Vehicle Application. Northrop Space Laboratories, Report NSL 64-176, April 1, 1962 through June 30, 1965, NASA Contract NASr-102.

24. Brink, N. O.: Research on an Expandable Airlock Utilizing the Elastic Recovery Principle. Final Report, Feb. 1965, NASA Contract NAS 7-283, Narmco Res. & Dev. Div., Whittaker Corp.

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Chapter IV

SYNTACTIC FOAMS IN THERMAL PROTECTION SYSTEMS

PERSPECTIVE

Hypersonic flight during the re-entry imposes severe requirements for thermal protection. The large translational kinetic energy of the flight vehicle must be dissipated as heat, often requiring an ablative heat shield. Ablation provides for the orderly removal of surface material in the hyperthermal environment. This erosion results from interaction between the surface and the aerodynamic heat and shear, coupled with a combination of thermal, chemical, and mechanical effects in the ablation material. Syntactic foam materials have been applied as ablators for vehicle protection on a variety of missions.

Ablation Process

Thermal protection materials, other than metallic heat sinks, achieve their purpose by two mechanisms: (1) sacrificial loss of the surface region material by an ablation process, and (2) insulation of the vehicle interior by the remaining layer.

Initially, the material absorbs incident heat as an insulator. Then, the surface temperature rises sharply and thermal decomposition begins. Gaseous products from the pyrolysis of the ablative material are injected into the boundary layer and effectively block a major fraction of the convective heat input.

Surface charring occurs for many ablators, except those based on physical-state changes, such as melting and sublimation. The largely carbonaceous char has high emissivity in the infrared region and is re-radiating considerable heat if its surface reaches a sufficiently high temperature. The char at the surface is continually removed by a combination of oxidation reactions, shear forces imposed by the flowing gases, and spallation. Char will also continue to be regenerated at its back surface as the heat pulse penetrates inward.

Ablative thermal protection systems are inherently self-regulating and, therefore, respond effectively to a wide range of re-entry conditions.

Selection of Materials

The choice of thermal protection is dictated by the severity of the re-entry environment. A particular re-entry condition is an interrelated function of vehicle velocity, shape, and re-entry trajectory. Thus, different types of ablative protection materials have been designed. Re-entry or flight profile parameters which can influence the thermal and mechanical stresses on ablative materials and structures are shown for various manned missions in Table 9.

Table 9. —Reentry Profile Parameters for Thermal and Mechanical Stress

Mission	Gemini	Apollo	X-15-2	Manned lifting reentry body
Heat Flux Rate (Btu/ft^2-sec)	50-200	~250	30-50[a]	50-150
Total Integrated Heat Flux (Btu/ft^2)	--	~100,000	~10,000[a]	50,000-100,000[c]
L/D Ratio[b]	0.3	0.5	3	1-3
Reentry Time (Range) (seconds)	300	--	--	1800-2400
(Average Time)	--	--	750 (Mach 6) 1000 (Mach 8)	2000
Shear Forces 1) Aerodynamic (lbs/ft^2)	~2	~2	<10 (mainly 3-5)	--
2) Thermal Stress (lbs/ft^2)	10^3[d]	10^3[d]	10^5[d]	--

a. At Mach 6.

b. L/D ratio is the maximum lift/drag value for each vehicle at some angle of attack in which the vehicle operates.

c. Total integrated heating is an order of magnitude higher than for vehicles in ballistic re-entry) stagnation load if 90,000-100,000 Btu/ft^2.

d. Number denotes an order of magnitude.

Low density thermal protection materials serve in missions where the time of transit through the atmosphere is an order of magnitude larger than that for ballistic missile re-entry.

The syntactic foams have been more widely used as ablators than chemically blown foams. Syntactic foams have a cured resin as the continuous phase in combination with microballoons or microspheres. The microspheres are preformed, hollow particles, made either from a phenolic resin or silica. Foam density is dependent on the resin/microsphere ratio and the fabrication conditions. Syntactic foams used for thermal

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protection may have one or more resins combined with one or more density-reducing agents, and often contain other fillers.

Research and development is focused on three classes of syntactic foam, namely those derived from silicone, phenolic-nylon, and epoxy resins. Examples of each class, and data on their compositions and physical, mechanical, and ablative properties are provided in the following sections. For proprietary considerations. it has not always been possible to identify the resin, catalyst, or the ingredient proportions in the formula. A summary of ablator systems is presented in Table 10.

Mechanical Forms and Configuration

The principal forms of ablator foams as a heat shield are (1) composites of foam inserted into honeycomb cells, (2) refurbishable spray coatings, (3) surface castings, and (4) molded modules.

Composites

Composites are usually individual heat shield sections mounted by vacuum bonding and mechanical attachment to a primary heat shield substrate. A heat-resistant, phenolic-fiberglass honeycomb matrix is filled with ablative material in 3/8 or 3/16 inch cells. The final complex is machined to the required dimensions. One-half inch of excess material can result in a 300-pound weight penalty.

Refurbishable Coatings

Refurbishable spray coatings for re-entry vehicles are a fairly recent outgrowth. A major impetus for their development stemmed from the goal, at Edwards Research Center, of increasing the speed of the X-15-2 hypersonic vehicle from Mach 6.5 to Mach 8. A material was required for application to the large and complex surfaces of the vehicle by spraying while inside a hangar, under a variety of ambient temperature conditions. Spent sections of the coating had to be removed after each test flight and replaced with new material. The material is a rubbery silicone that will char but retain its shape during atmospheric flight.

Molded Shapes

Molded sections are prepared where the design requires extra thickness.

Material Properties

Physical, mechanical, thermal and ablative properties of five syntactic foams and one gas blown silicone foam (Table 10) are presented in the following sections. Thermophysical property data has been compiled for six charring ablators.[1]

Emphasis in composite ablator materials has been placed on low density to produce minimum thermal conductivity. Silica or phenolic microballoons reduce mechanical strength. In several formulations reinforcement fillers such as asbestos, glass or quartz fibers have been used effectively.

Table 10. —Designations of Ablative Foam Resin Systems for Heat Shields

Spacecraft, vehicle or probe	Ablative resin material	Type of resin system
Gemini	DC 325	RTV castable silicone
Apollo	AVCO 5026-39	Epoxy-novolac
X-15-2	Martin MA-25S	RTV sprayable elastomeric silicone (special catalyst)
Lifting Body	Langley-Nylon-Phenolic	Zytel 101 nylon-phenolic
M2 HL 10	Langley - "Purple Blend"	RTV 602 or Sylgard 182 silicone
SV5	Langley-Nylon-Phenolic Langley-"Purple Blend"	Zytel 101 nylon-phenolic RTV 602 or Sylgard 182 silicone
Planetary Probes	ESM 1004 (blown)	Phenylmethyl silicone
Scout	Phenolic nylon	Phenolic nylon

Functional properties will include density, char strength, composite mechanical strength, char porosity, emissivity, thermal conductivity, and ablation efficiency for a particular environment.

Stability to the vacuum-thermal effects in space prior to re-entry is mandatory to retain full performance. A jettisonable boost protective cover over the Apollo heat shield is an example protection against the effects of ascent heating and rocket motor exhaust, where a temperature of 1200°F may be reached.

DOW CORNING 325 SILICONE-BASED ABLATOR

Dow Corning 325 (DC325)[2] has been used as an ablator in at least two important space programs.

Composition: Silicone - Dow Corning (proprietary).
DC325 resin - 92.7 parts (wt.)
DC325 catalyst - 7.3 parts (wt.)
Cure: 7 days at room temperature, or 4 hours at 180° F, or 15 minutes at 350° F.
Form: Molded or phenolic-glass honeycomb (3/16" cell) reinforced.
Density: 54 pounds per cu. ft. for unreinforced material.
55 to 57.5 pounds per cu. ft. when reinforced with honeycomb.
Mechanical Properties: The mechanical properties reported are for unreinforced material at ambient temperature.

1. Hardness, Shore A: 68
2. Tensile Strength: 315 psi
3. Elongation: 60%
4. Modulus of elasticity in compression: 2200 psi

Thermophysical Properties:

1. Thermal Conductivity: Figure 21
2. Specific Heat: Table 11
3. Linear thermal expansion coefficient: Figure 22

Table 11 contains mean specific heat data obtained at mean temperatures ranging from -124° F to +274° F.[3]

Table 11.—Mean Specific Heat vs. Temperature DC-325

Mean temperature °F	Mean specific heat Btu/lb/°F
-124	0.28
112	0.31
148	0.33
212	0.36
274	0.37

Ablation Performance

The ablation effectiveness of Dow Corning 325 has been measured under a variety of conditions including propane torch, hypersonic arc tunnel and plasma arc tests.[2,4,7] Ablation data obtained by plasma arc exposure are presented. Ablator effectiveness (E) in the data presented is a function of the time required for the backface temperature of an ablative sample to rise to 300°F. The ablation effectiveness, or efficiency, is defined by [illegible] (2).

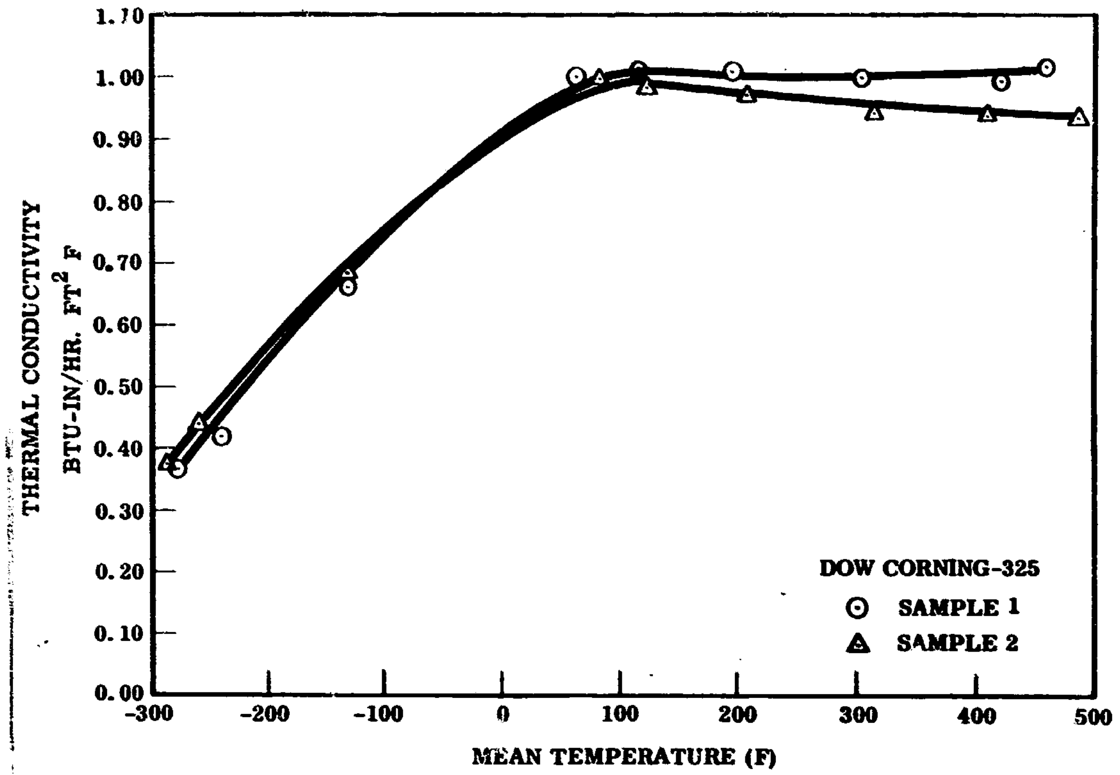

Figure 21.—Apparent thermal conductivity-versus-temperature (Dow Corning -325).

$$E = \frac{\dot{q}t}{\omega} \tag{1}$$

$$\overline{E} = \frac{\dot{q}t}{\rho t_p} \tag{2}$$

$\dot{q}$ = cold wall heat flux, Btu/ft^2-sec.
t = time required for the backface to reach 300° F, in seconds
ω = specimen weight per unit area, lbs/ft^2
ρ = specimen density, lbs/ft^3
t_p = thickness of material ablated, feet.

Ablation performance of DC 325 varies with the density, cold wall heat flux, stream enthalpy, stream chemistry, and aerodynamic shear stress. Values for DC 325 are shown in Tables 12 and 13 and Figures 23 and 24. Definitions of the symbols used throughout are provided in Table 14.

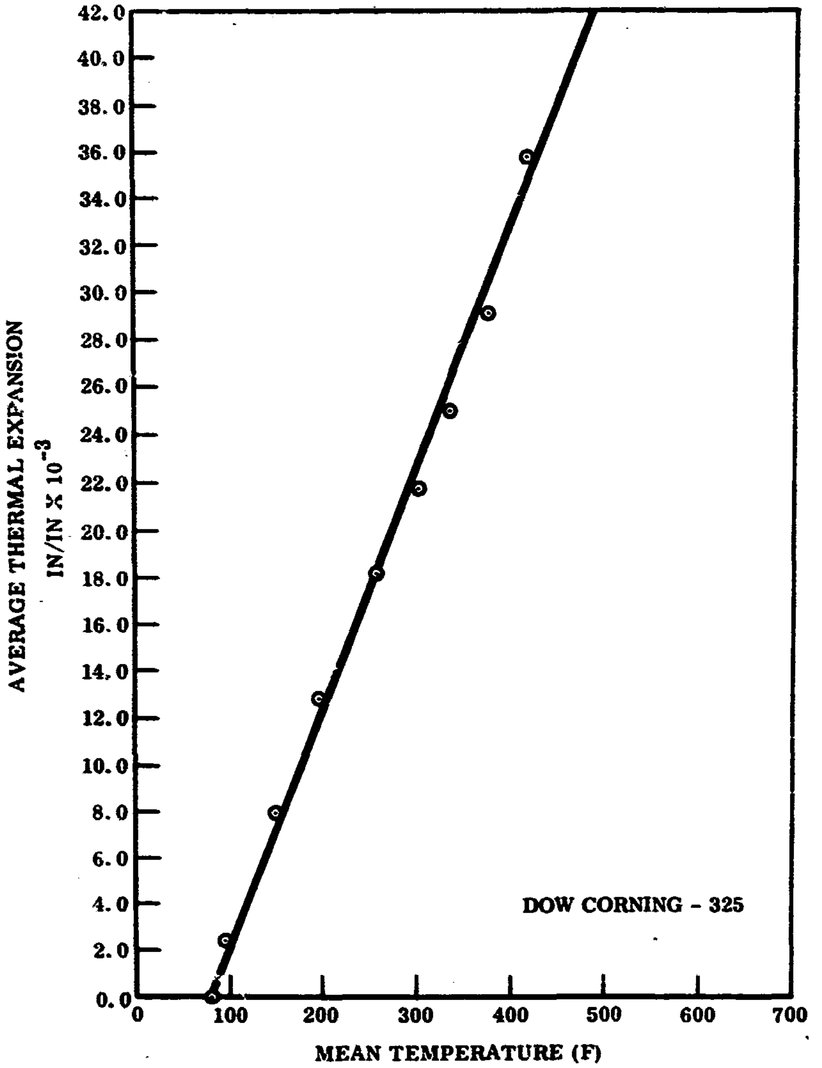

Figure 22. —Average thermal expansion-versus-temperature.

Table 12[4]. —Ablation Performance of Reinforced DC 325[a,b]

ω	O_2	$\hat{q}$	H	τ	$\dot{W}/A$	E
2.98	3.5%	111	3300	0.5	0.35	11,720
3.00	3.7%	120	3200	1.5	0.15	14,950

[a] ρ = 57.5 lbs/ft^3

[b] See table 14 for definitions of symbols

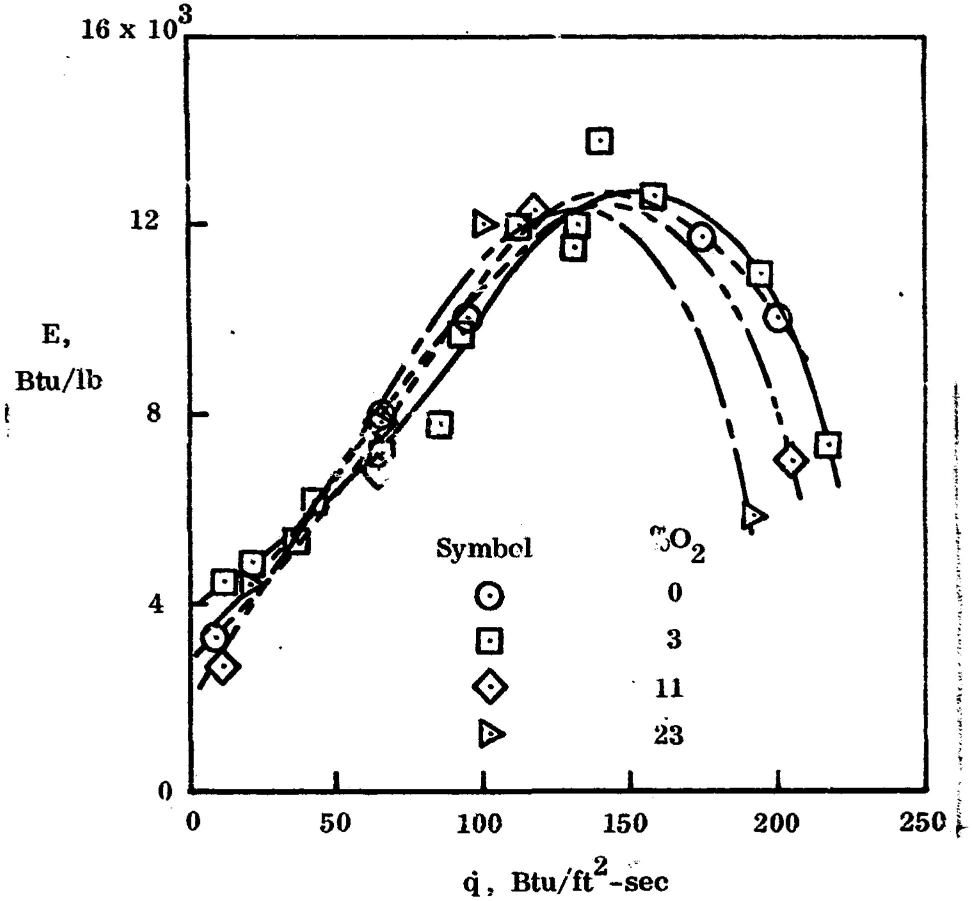

Figure 23.—Effectiveness of reinforced DC-325 silicone resin as a function of heating rate and stream chemistry.

After arc-jet exposure, the surface of DC 325 specimens is covered with a tenacious, siliceous layer. The thickness of this layer depends on the surface temperature attained and the imposed aerodynamic shear stress.

DC 325 ablative effectiveness increases with increasing cold wall heat flux up to about 150 Btu/ft^2-sec, essentially independent of the oxygen content of the plasma stream. DC 325 is sensitive to combined effects of surface temperature and aerodynamic shear.

NASA "PURPLE BLEND" SILICONE-BASED ABLATOR

NASA "Purple Blend' is a second-generation silicone-based ablative material with a lower density and improved ablative performance compared to DC 325. Its characteristic purple color is due to the presence of phenolic microspheres.

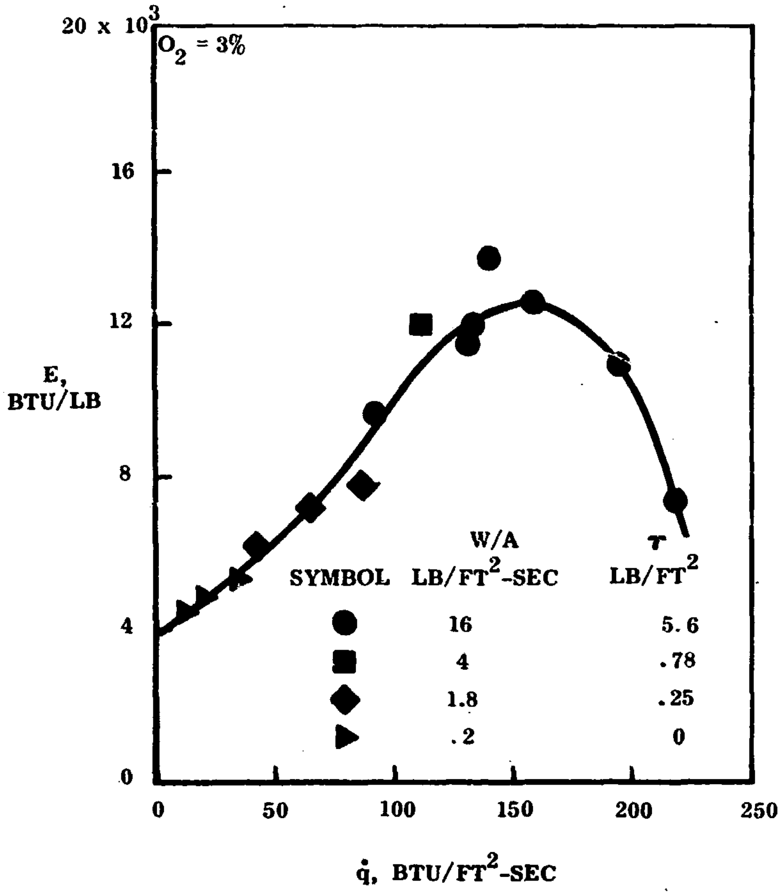

Figure 24.—Effectiveness of reinforced DC-325 silicone resin as a function of heating rate, stream mass flow and aerodynamic shear stress.

"Purple Blend" is a term for a series of low density silicone-based ablators originated within NASA. Three examples are given below:

Composition Reports:	Parts by Weight
1. Silgard 182 Resin (Dow Corning)	67.5
Silgard 182 Catalyst (Dow Corning)	7.5
Silica Microspheres	15.0
Phenolic Microspheres	10.0
2. RTV 602[4] (General Electric Silicones Div.)	75.0
Silica Microspheres	15.0
Phenolic Microspheres	10.0
3. RTV 602[4] (General Electric Silicones Div.)	70.0
Silica Microspheres	10.0
Phenolic Microspheres	16.0
Microquartz Fibers	4.0

Table 13.—Summary of Results for Reinforced DC 325 Silicone Resin$^{(2)c}$
(ρ = 55 lb/ft^3; w = 3 lb/ft^2; specimen thickness = 0.66 in.)

Specimen	Stream diam. in.	$\dot{W}/A$, $\frac{\text{lb}}{\text{ft}^2\text{-sec}}$	O_2 percent	$\dot{q}$ Btu/ft^2-sec	H Btu/lb	τ lb/ft^2	t_{300}, sec	E_{300}, Btu/lb	Wt. loss, percent	Thickness, in. Total	Virgin	Char
1	2	16	23	193	3400	6.40	91	5860	94	0.28	(a)	(a)
2	2	16	11	118	2200	4.93	312	12280	21	.60	0.07	0.53
3	2	16	11	206	3600	6.54	102	7000	99	(a)	(a)	(a)
4	2	16	3	93	2050	3.94	311	9640	26	.73	.06	.67
5	2	16	3	132	2250	5.57	260	11450	29	.48	.04	.44
6	2	16	3	133	2250	5.57	270	11980	29	.55	.03	.52
7	2	16	3	140	2275	5.87	295	13770	13	.46	.06	.40
8	2	16	3	160	2700	6.13	236	12590	66	.28	.04	.24
9	2	16	3	195	3400	6.45	169	10940	(a)	(a)	(a)	(a)
10	2	16	3	217	3750	6.75	102	7370	(a)	.33	(a)	(a)
11	2	16	0	95	2050	4.03	315	9975	44	.60	.05	.55
12	2	16	0	175	2950	6.35	201	11715	98	.40	(a)	(a)
13	2	16	0	200	3500	6.47	150	10000	83	.48	.15	.33
14	4	4	23	101	3250	.83	356	12000	(a)	(a)	(a)	(a)
15	4	4	3	112	3400	.90	321	12000	(a)	(a)	(a)	(a)
16	6	1.8	23	66	2350	.27	356	7840	13	.66	.14	.52
17	6	1.8	11	66	2350	.27	358	7840	14	.69	.15	.54
18	6	1.8	11	66	2350	.27	310	6810	18	.68	.21	.47
19	6	1.8	3	43	1900	.20	429	6150	9	.77	.23	.54
20	6	1.8	3	66	2675	.26	426	7170	14	.75	.14	.61
21	6	1.8	3	84	3150	.30	278	7780	15	.78	.14	.64
22	6	1.8	0	66	2550	.26	364	8000	12	.70	.18	.52
23	12	.2	23	20	(b)	0	658	4380	9	.73	.21	.52
24	12	.2	11	12	(b)	0	666	2641	10	.78	.33	.45
25	12	.2	3	13	(b)	0	1005	4450	9	.83	.28	.55
26	12	.2	3	22	(b)	0	652	4820	23	.80	.08	.72
27	12	.2	3	36	(b)	0	443	5320	17	.83	.14	.69
28	12	.2	0	9	(b)	0	1072	3250	7	.82	.39	.43

[a] Specimen damaged before postexposure data taken.
[b] No spectrographic data available for 12-inch test stream.
[c] See Table 14 for definitions of symbols.

Table 14.—Symbols and Definitions of Units

A = area, ft^2

E = effectiveness of ablation material, $\frac{\dot{q}t}{w}$, Btu/lb.

$\overline{E}$ = ablative effectiveness based on weight of material degraded, $\frac{\dot{q}t}{\rho\ell_p}$, Btu/lb.

H = enthalpy, Btu/lb.

k_t = thermal conductivity, Btu-inch/ft^2-sec-$^{\circ}$R

ℓp = thickness material pyrolyzed, ft.

m = molded

$\dot{m}(O_2)$ = oxygen mass transfer through boundary layer, lb/ft^2-sec.

P = stagnation pressure, atmosphere

$\dot{q}$ = cold wall heat transfer rate, Btu/ft^2-sec.

$\dot{s}$ = char surface recession rate, ft/sec.

t = time, sec.

$\dot{W}$ = mass flow, pounds/sec.

w = specimen weight per unit area, lb/ft^2

ρ = density, lb/ft^3

τ = aerodynamic shear stress, lb/ft^2

Processing and Fabrication

The compositions are prepared by mixing the phenolic and silica microspheres until a uniform color is obtained then adding the catalyzed resin. Because both phenolic and silica microspheres are fragile, blending must take a minimum of agitation.

"Purple Blend" is always used as a filled phenolic-glass honeycomb reinforcement. The "Purple Blend" mixture is pressed into the honeycomb under a vacuum,[3] or it is inserted into the individual cells by a modified caulking gun. Curing requires 2 hours at 250°F,[3] although RTV 602 resin can cure at ambient temperature. Density varies from 36 to 40 pounds per cubic foot.

Mechanical Properties

Table 15 presents "Purple Blend" tensile strength data parallel and perpendicular to the ribbon direction of the honeycomb reinforcement.

Table 15.—Honeycomb-Reinforced "Purple Blend" Tensile Strength[3]

Test direction to ribbon	Temperature, °F	Soak time, minutes	Tensile strength, psi average
Parallel	-300	15	190
Perpendicular	-300	15	64
Parallel	RT		310
Perpendicular	RT		140
Parallel	500	30	106
Perpendicular	500	30	18

The tensile shear (double lap shear) strength of split honeycomb reinforced "Purple Blend" is shown is Table 16 for the temperature range -280° F to +300° F.

Table 16[4] Honeycomb Reinforced "Purple Blend": Tensile Shear*

Temperature, °F	Ultimate stress, psi (average)
RT	32.3
+300	20.9
- 35	36.5
-130	478
-280	1305

*Bonded to aluminum with RTV-560; two-square-inch total cross-section.

In split honeycomb, each of the six-cell walls is cut and separated. This practice was followed to allow the elastomeric properties of the ablative material to dominate the behavior under test as opposed to measuring primarily the properties of the honeycomb reinforcement. Table 17 contains flatwise compression data for unmodified honeycomb reinforced material tested parallel to the ribbon direction over the temperature range from -300 to 500° F.

The fully cured material has a Shore A hardness of 60.

Thermophysical Properties

Data on thermal conductivity, mean specific heat, and thermal expansion are presented in Figures 25 and 26, and in Table 18.

Table 17.—Honeycomb Reinforced "Purple Blend": Flatwise Compression Data

Test direction to ribbon	Temperature, °F	Soak time, minutes	Flatwise compression (average)
Parallel	-300	15	10,830
Parallel	RT		1,700
Parallel	+300	30	1,230
Parallel	500	40	760

Table 18.—Mean Specific Heat vs. Temperature: "Purple Blend"[3]

Mean temperature, °F	Mean specific heat, Btu/lb/°F
115	0.32
152	0.33
220	0.37
274	0.42
-126	0.28

Ablation Properties

The data on the ablative effectiveness of reinforced "Purple Blend" are limited in comparison with DC 325. Ablation data (Table 19) demonstrate the improved performance of "Purple Blend" compared to Dow Corning 325 in the limited range where testing has been reported.

NASA PHENOLIC-NYLON ABLATOR

Low density and fully dense phenolic-nylon charring ablators have been developed at NASA's Langley Research Center. These range from 75 lbs. per cu. ft. for a 1:1 mixture of powdered nylon and phenolic resin to 18 lbs per cu. ft. for syntactic foams filled with phenolic microballoons. The major portion of the work at Langley was focused on syntactic foams with densities of 25 to 40 lbs. per cu. ft., to determine the influence of the constituents on ablative properties.

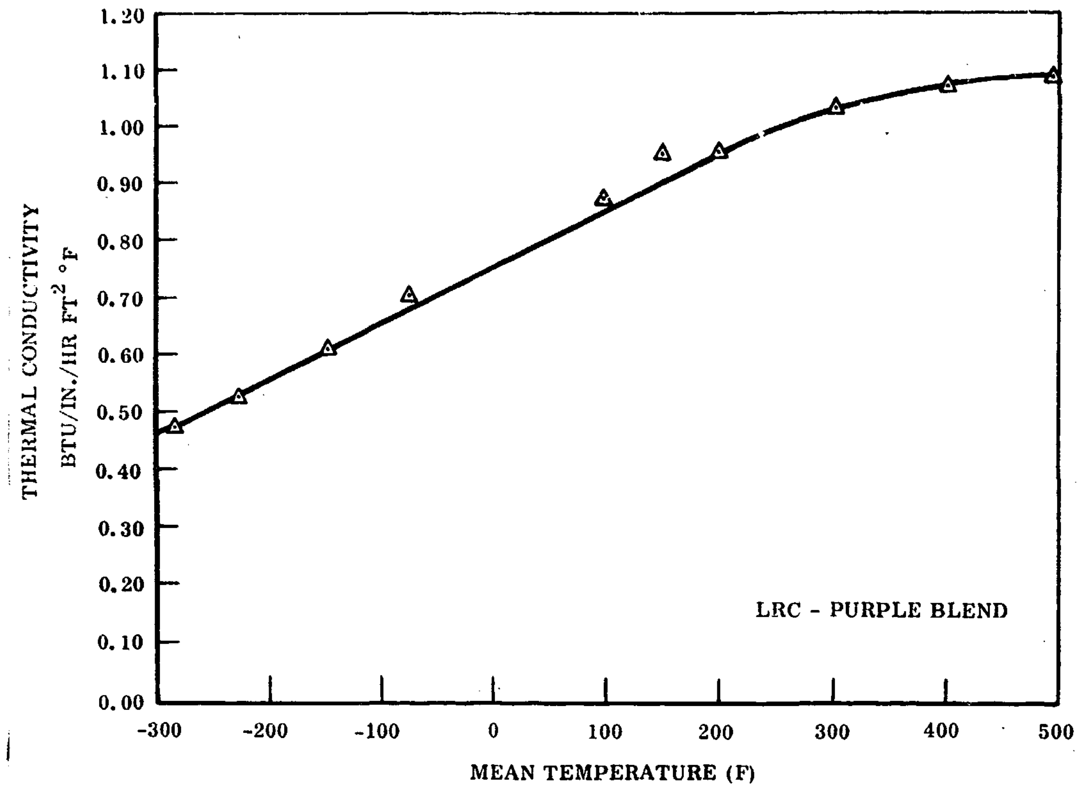

Figure 25.—Apparent thermal conductivity-versus-temperature (LRC - Purple Blend).

Table 19.—Ablation Performance Reinforced "Purple Blend" Formulations

Formulation	w	t_{300}	q	H	τ	$\ddot{\omega}/a$	E
NASA 182*	2.96	363	113	3300	0.5	0.35	13,800
NASA 602**	3.02	374	109.5	3300	0.5	0.35	13,350
NASA 182	2.96	403	128.5	3200	1.5	0.15	17,500
NASA 602	3.00	454	124	3200	1.5	0.15	18,780
NASA 602***	3.00	555	120	3200	1.5	0.15	22,200

* Material density 39.4 lb/ft^3

** Material density 36.4 lb/ft^3

*** Material density, 38.7 lb.ft^3, split honeycomb for columnar reinforcement.

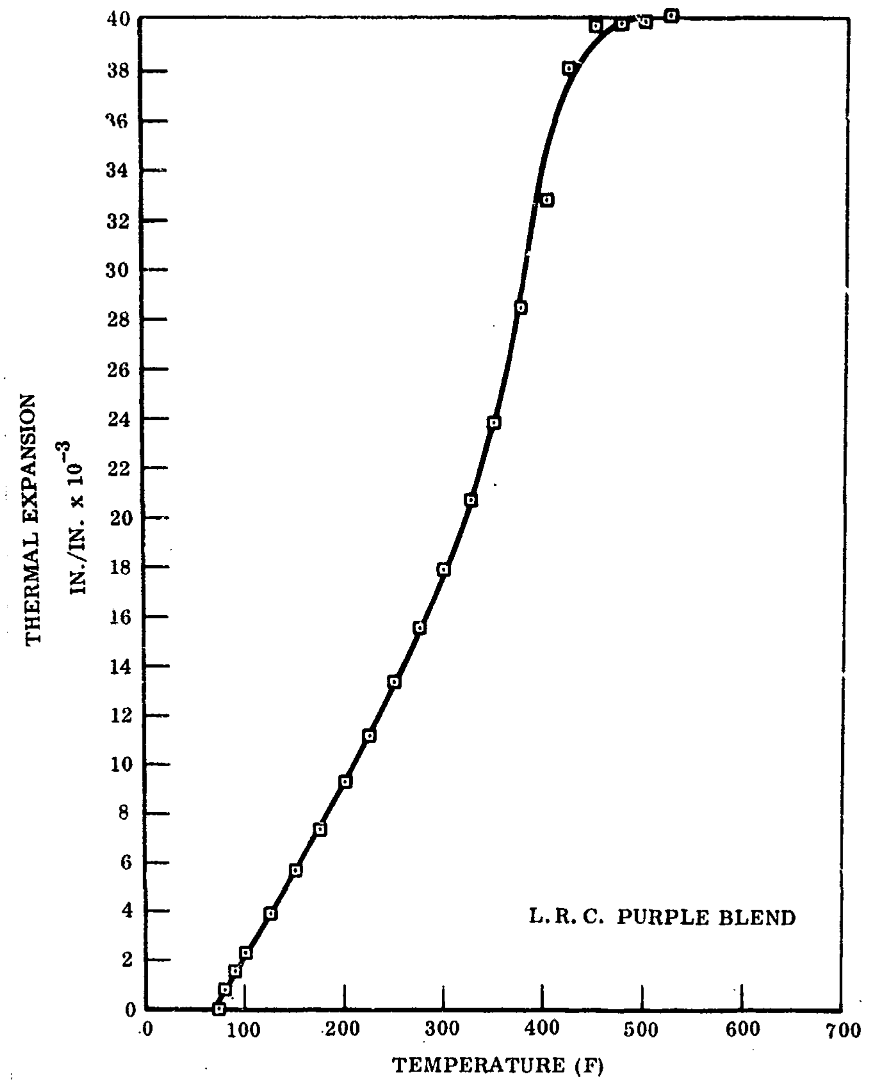

Figure 26.—Average thermal expansion-versus-temperature.

Phenolic-nylon compositions studied are listed below.

Formulation No. 1[5, 6]	Parts by weight
Union Carbide phenolic resin BRP-5549	25.0
DuPont Zytel 103 nylon resin	50.0
Union Carbide phenolic microspheres BJO-0930	25.0
Formulation No. 2[7]	
Phenolic-novolac resin	23.0
Nylon resin	47.0
Phenolic microspheres	25.0
Silica microspheres	5.0

Formulation No. 3[5]

Phenolic-novolac resin	25.0
Nylon resin	40.0
Phenolic microspheres	35.0

Hughes Aircraft Company investigated techniques to optimize phenolic-nylon syntactic foams, under a contract sponsored by Ames Research Center. The final formulation was:

Formulation No. 4[8]

HFN phenolic-novolac resin	37.0
Nylon resin	40.0
Phenolic microspheres	23.0

Processing - Langley Method

The Langley utilized a V-type blender for mixing 80-mesh nylon powder, 240-mesh phenolic resin, and 15.6 lbs. per cu. ft. phenolic microspheres. The nylon and phenolic resins were each vacuum dried at 200° F prior to use. After blending, the powder was compressed at 2000 psi under vacuum. The pressure was then reduced to 100 psi and the temperature to 325° F, and maintained there for 20 hours. The molded part was post-cured in argon for 67 hours at a maximum temperature of 300° F.

Density can be varied by changing the proportion of phenolic microspheres or by varying the molding pressure. When a series of densities in the range of 18-43 lbs. per cu. ft. was prepared from a single formula (e.g. Composition 3), the variation in density required crushing the phenolic microspheres during the molding cycle.[5] Crushing makes the product porous due to the opening of the spherical surfaces. The porous structure created is quite different from the internal structure of syntactic foams and this influences its ablative and physical properties.

Processing - HAC Method

Hughes Aircraft Co. (HAC), determined that the 33.5 lbs. per cu. ft. nylon-phenolic prepared by the Langley process had a heterogeneous microstructure. Large nylon particles, voids and gaps were present and almost all of the microspheres were fractured. Both nylon and microspheres appeared to be poorly wetted by the phenolic resin.[8]

The Hughes process differs from the Langley process in several important ways. First, the Hughes formulation was designed to produce a 35-lb. per ft^3 material, without crushing microspheres, by adjusting the quantities of ingredients. Second, preselection of ingredients screened out clusters of phenolic microspheres and the larger nylon particles. Third, the Hughes material was shaped into preforms and heated dielectrically to 200° F in 35-seconds, then introduced into a hot mold with little pressure. The cure cycle was 90 minutes. After cure, the molding was ejected hot.

The molding was post-cured in an argon atmosphere for twelve hours while heating to 350° F, then for six hours at 350°F, it was then cooled to 100° F over six hours.

Moldings showed a uniform microstructure, and low porosity.

Mechanical and Thermal Properties

Data on the mechanical properties of phenolic-nylon ablative material are scarce. The tensile strength versus temperature of an unspecified composition is shown in Figure 27. It has been reported that the tensile strength and compressive strength at room temperature of Composition 3 (35 lbs. per cu. ft.) are 372 psi and 2600 psi, respectively.[8]

Data for thermal conductivity versus density in the density range 18 to 43 lbs. per cu. ft. are given in Figure 28.

Ablation Properties

The ablation performance of phenolic-nylon was determined under two sets of test conditions:

	Constant	Variants
1.	Material composition and 36 lbs./cu. ft. density	Stream oxygen content, heating rate and aerodynamic shear stress
2.	Heating rate, stream composition, stream enthalpy and aerodynamic shear stress	Material composition and density.

Results of ablation testing of Formulation No. 2 (36 lbs. per cu. ft.) are presented in Table 20 and Figures 29, 30, and 31.

The ablative effectiveness of Formulation 2 diminishes rapidly with increased oxygen concentration in the gas stream and increases with increasing stream enthalpy. Increased heating rate in a low oxygen content stream increases surface temperature in the heat radiation.

Little or no erosion of the ablator surface occurred in a pure nitrogen test stream. With oxygen present, spalling occurred and the surface was pitted and rougher. Oxidation of the char layer adds heat, reducing ablator effectiveness.

Susceptibility to shear stresses is shown in Figure 30. The ablation performance as a function of stream oxygen content, aerodynamic shear stress, and mass flow at two enthalpy levels and constant heating rate is given in Figure 31.

Data on the effects of composition and density variation on ablative performance[5] have been obtained for three test conditions (Table 21). Condition I is directly comparable to earlier figures and tables. Condition II data were obtained in a 6-inch subsonic high temperature arc tunnel and compare the surface recession of ablators with nylon contents of 40, 50 and 60 weight percent, (Figure 34). Condition III tests allowed some direct heating to the back side of the specimens preventing direct measurement of E-values which are based on total material degraded within a predetermined exposure period.

Table 20.—Summary of Results for Low-Density Phenolic-Nylon(2)

(ρ = 36 lb/ft^3; w = 3 lb/ft^2; specimen thickness = 1.0 inch)[d]

Specimen	Stream diam. in.	$\dot{W}/A$, $\frac{lb}{ft^2\text{-sec}}$	O_2 percent	$\dot{q}$, Btu/ft^2-sec	H, Btu/lb	τ, lb/ft^2	$\dot{m}(O_2)$, lb/ft^2-sec	t_{300}, sec	E_{300}, Btu/lb	Wt. loss, percent	Thickness, in.		
											Total	Virgin	Char
1	2	16	23	140	2200	5.91	0.0155	141	6560	(a)	(a)	(a)	(a)
2	2	16	23	206	3650	6.60	.0135	101	6950	92	0.15	0.12	0.03
3	2	16	11	107	2100	4.54	.0060	202	7200	(a)	.19	(a)	(a)
4	2	16	11	200	3500	6.43	.0065	140	9320	(a)	.19	.09	.10
5	2	16	3	100	2025	4.12	.0016	234	7800	95	.15	.12	.03
6	2	16	3	128	2150	5.38	.0019	234	9984	94	.34	.29	.05
7	2	16	3	170	2950	6.20	.0018	241	13660	(a)	.20	.07	.13
8	2	16	3	201	3500	6.46	.0018	200	13400	94	.20	(a)	(a)
9	2	16	3	205	3625	6.52	.0018	229	15645	98	.29	.12	.17
10	2	16	3	207	3650	6.60	.0018	193	13300	95	.20	.02	.18
11	2	16	3	242	4000	7.20	.0019	207	16700	96	.09	.02	.07
12	2	16	0	82	2000	3.41	0	376	10280	79	.87	.02	.85
13	2	16	0	198	3550	6.35	0	292	19280	68	.75	.05	.70
14	4	4	23	78	2100	.76	.0091	282	7340	(a)	.25	.04	.21
15	4	4	23	120	3550	.95	.0081	222	8870	(a)	.20	(a)	(a)
16	4	4	11	49	1800	.52	.0032	388	5850	85	.50	.29	.21
17	4	4	11	50	1800	.52	.0033	382	6350	88	.43	.24	.19
18	4	4	11	102	3250	.84	.0036	280	9580	89	.37	.09	.28
19	4	4	3	50	1675	.55	.0010	471	7840	76	.78	.30	.48
20	4	4	3	78	2400	.72	.0010	427	11100	84	.68	.18	.50
21	4	4	3	103	3050	.87	.0011	364	12500	77	.78	.22	.56
22	4	4	3	130	3575	1.02	.0011	314	13600	71	.83	.21	.62
23	4	4	0	49	1800	.52	0	594	9700	64	.97	.14	.83
24	4	4	0	108	3300	.88	0	449	16180	65	.97	.02	.95
25	6	1.8	23	66	2350	.27	.0068	363	7990	(a)	.48	.17	.31
26	6	1.8	23	104	3750	.38	.0066	281	9730	96	.32	(a)	(a)
27	6	1.8	11	42	1750	.20	.0028	569	7970	83	.42	(a)	(a)
28	6	1.8	11	66	2250	.27	.0034	445	9790	74	.72	.24	.48
29	6	1.8	11	68	2350	.27	.0034	406	9200	72	.77	.36	.41
30	6	1.8	3	43	1750	.20	.0008	573	8210	78	.77	.28	.49
31	6	1.8	3	66	2250	.27	.0009	497	10920	61	.85	.43	.42
32	6	1.8	3	80	3050	.30	.0008	453	12100	77	.87	(a)	(a)
33	6	1.8	0	39	1825	.18	0	797	10350	66	.90	.03	.87
34	6	1.8	0	43	2250	.20	0	786	11250	74	.80	(a)	(a)
35	6	1.8	0	97	3650	.34	0	461	15000	73	.80	(a)	(a)
36	12	.2	23	20	(b)	0	(b)	934	6224	78	.72	.59	.13
37	12	.2	0	10	(b)	0	0	1260	(c)	47	.94	.60	.34

[a] Specimen damaged before postexposure data taken.

[b] No spectrographic data available for 12-inch test stream.

[c] Test ended after 1260 seconds (T = 241 F (134 K)).

[d] Formulation 2.

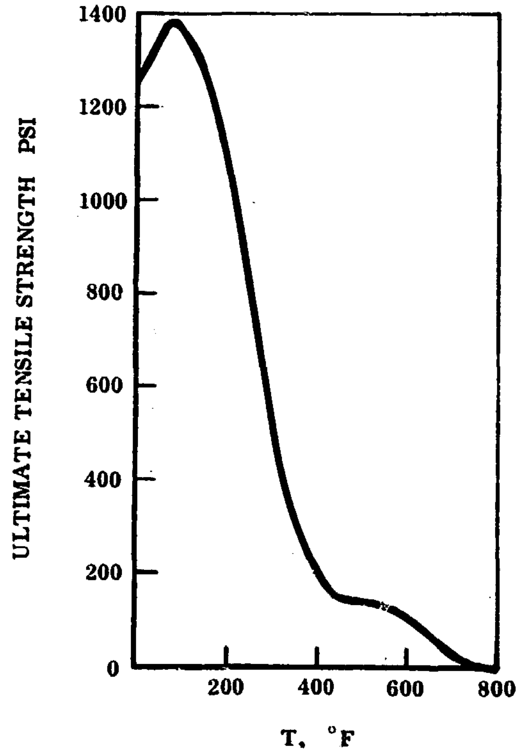

Figure 27.—Ultimate tensile strength of phenolic nylon.(6)

Figures 32, 33 and 35, while not directly comparable, show the combined effect of composition and density. Densities were controlled in molding by applied pressure, causing a proportional fracture and collapse of the phenolic microspheres. This increases the interconnected porosity in more dense samples which increases their thermal conductivity. Therefore, maximum ablative efficiency occurs at an intermediate density. A lower effectiveness at densities of 20 pounds per cubic foot or below results from nonuniform char properties and increased spalling.

ELASTOMERIC SHIELD MATERIAL

Elastomeric Shield Materials (ESM) have been under development at the Aeromechanics and Materials Laboratory Operation, Re-entry Systems Dept. of the General Electric Co.^{9} This type of ablative material is a fiber-filled, foamed silicone elastomer with a density range of 23 to 66 lbs. per cu. ft. The fiber is randomly oriented. The ESM compositions are blown or chemically expanded foams rather than syntactic foams. ESMs of the 1000 series are char forming, based phenyl methyl silicones and additives to increase char stability.

Table 21. —Summary of Materials and Test Results(5)

Composition, percent by weight			Type of material, m . . . molded	Block density, $\frac{lb}{ft^3}$	E, $\frac{Btu}{lb}$ (Condition I)	$\bar{E}$, $\frac{Btu}{lb}$ (Condition III)	$\rho \dot{s}$ char' $\frac{lb}{ft^2\text{-sec}}$ (Condition II)
Phenolic	Nylon	Microballoons					
25	50	25	m	21	12,420	----	---
25	50	25	m	24	14,445	14,050	0.070
25	50	25	m	31	14,900	14,450	.030
25	50	25	m	35	14,270	----	.011
25	50	25	m	43	11,750	10,450	.011
15	50	35	m	19	13,320	15,500	0.126
15	50	35	m	25	15,425	16,200	.050
15	50	35	m	30	14,150	15,450	.019
15	50	35	m	36	14,225	18,400*	.034
15	50	35	m	42	12,590	12,750	.016
25	40	35	m	18	13,100	17,000	0.042
25	40	35	m	23	13,850	16,200	.021
25	40	35	m	30	13,815	16,100	.004
25	40	35	m	37	13,850	13,750	0
25	40	35	m	43	11,460	----	---
35	30	35	m	24	14,600	13,100	---
35	30	35	m	30	----	15,200	---
35	50	15	m	36	13,250	16,000*	---
25	60	15	m	36	13,665	16,700*	---
15	60	25	m	36	13,015	17,000*	---
35	40	25	m	37	12,780	17,100*	---
35	40	25	m	30	----	14,700	---

*Indicates $\bar{E}$ based on time of 60 seconds.

Test condition	$\dot{q}$, $\frac{Btu}{ft^2\text{-sec}}$	H, $\frac{Btu}{lb}$	p, atm	Stream composition	Termination of tests
I	110	2,300	1.0	97 percent N_2 3 percent O_2	Tests stopped when back surface temperature increased 300°R
II	350	2,300	1.8	97 percent N_2 3 percent O_2	All tests stopped at 10 sec
III	500	12,500	1.0	Air	Tests were stopped at 30 or 60 sec

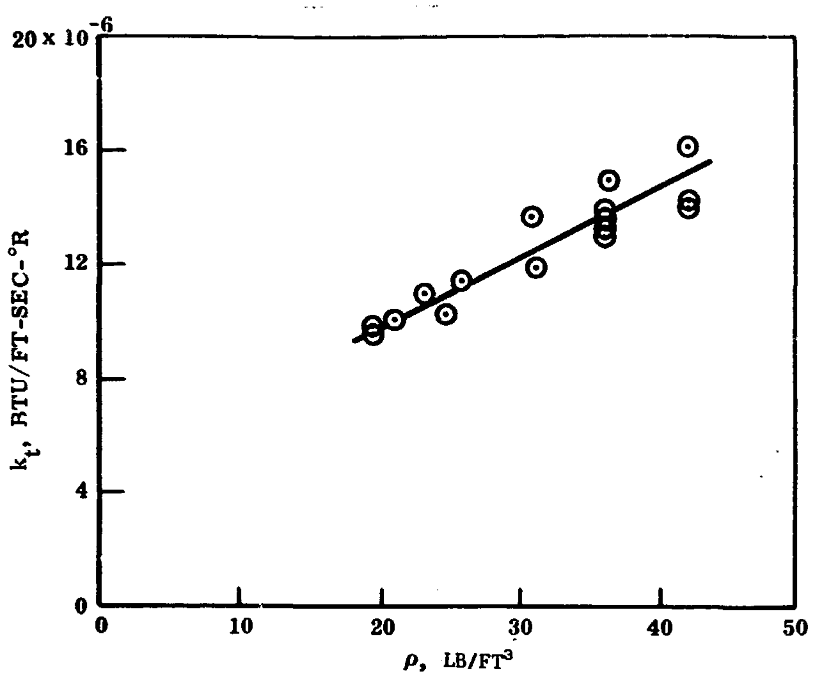

Figure 28.—Effect of density on thermal conductivity of uncharred material.(6)

Environment Compatibility

Development of the ESM family anticipated a mission temperature cycle of ±300° F prior to re-entry. Phenolic-glass honeycomb in the composite upgrades resistance to re-entry shear forces. A phenyl-substituted silicone in place of methyl silicone polymers retains the elastic properties of the matrix filler at much lower temperatures.

Composition

Typical ESM compositions are:

1. ESM 1001 P	Parts by weight
RTV 560	94.9
Asbestos Fiber	4.3
Glass Fiber	0.8

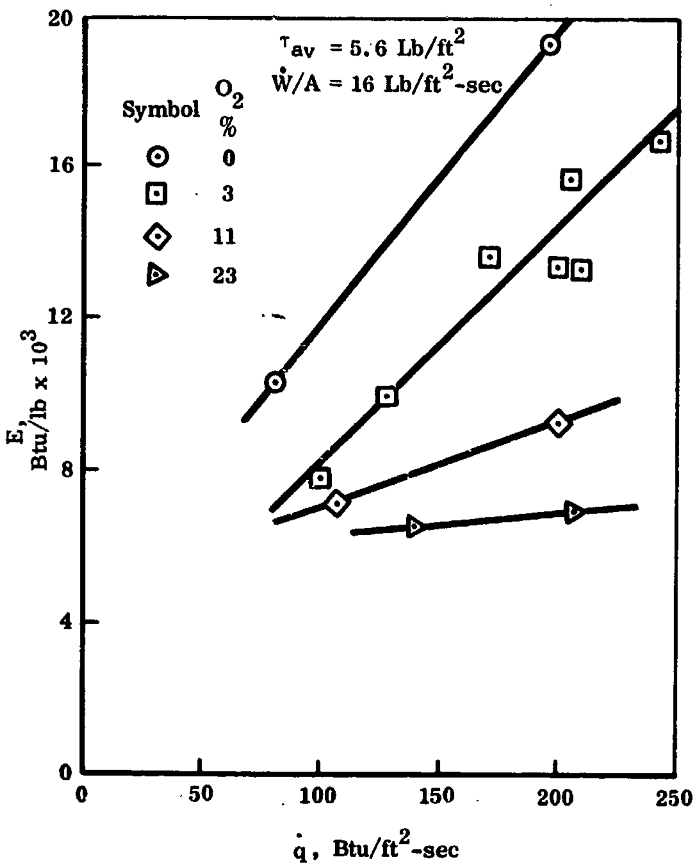

Figure 29.—Effectiveness of 36 lb/ft^3 phenolic-nylon as a function of heating rate and stream chemistry. Formulation 2.

2. ESM 1004 B P	Parts by weight
RTV 560	90.5
Aluminum Silicate Fiber	6.0
Asbestos Fiber	3.0
Glass Fiber	0.5

Density

Range, 23-66 pounds per cubic foot
ESM 1001 P, 37.7 pounds per cubic foot
ESM 1004 BP, 39.0 pounds per cubic foot.

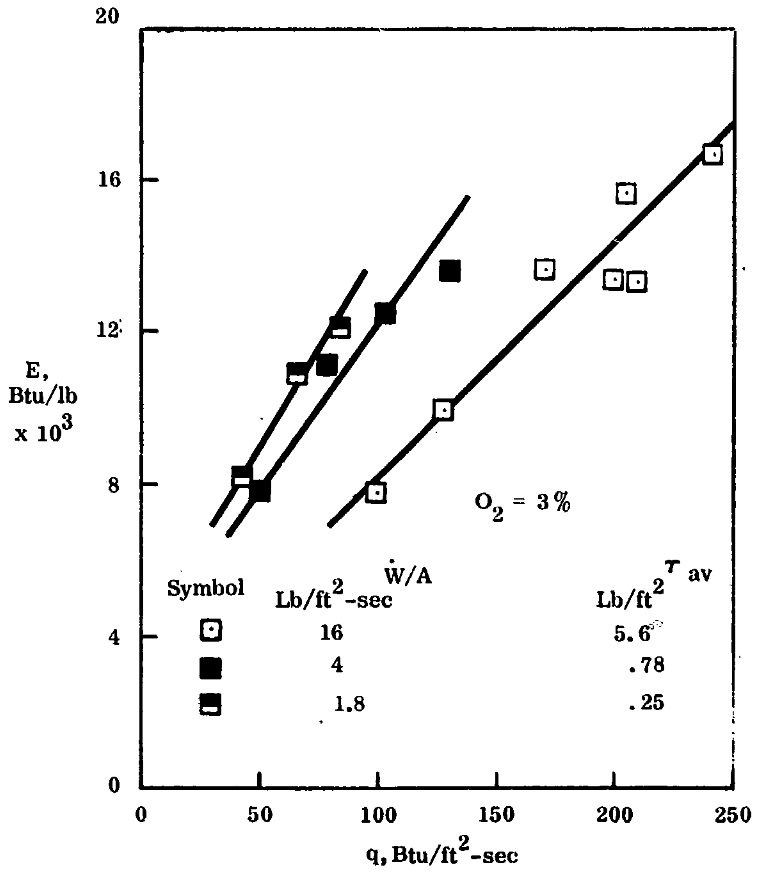

Figure 30.—Effectiveness of 36 lb/ft^3 phenolic-nylon as a function of heating rate, stream mass flow, and aerodynamic shear stress. Formulation 2.

Processing

The selected formula was combined with a silicone catalyst and a blowing agent. Foaming and curing can be accomplished between room temperature and 140° F to yield materials with densities ranging from 20 to 80 lbs. per cu. ft. A preferred density range is 23 to 66 lbs. per cu. ft.

The compositions are foamed in trays either with or without phenolic-glass honeycomb. A honeycomb reinforced composite is obtained by pouring the liquid formulation into a mold and forcing the glass-phenolic honeycomb into the resin until it seats on the lower surface of the mold. Foaming fills the honeycomb cells. Following the initial cure, the material is post-cured for ten hours at 300° F.

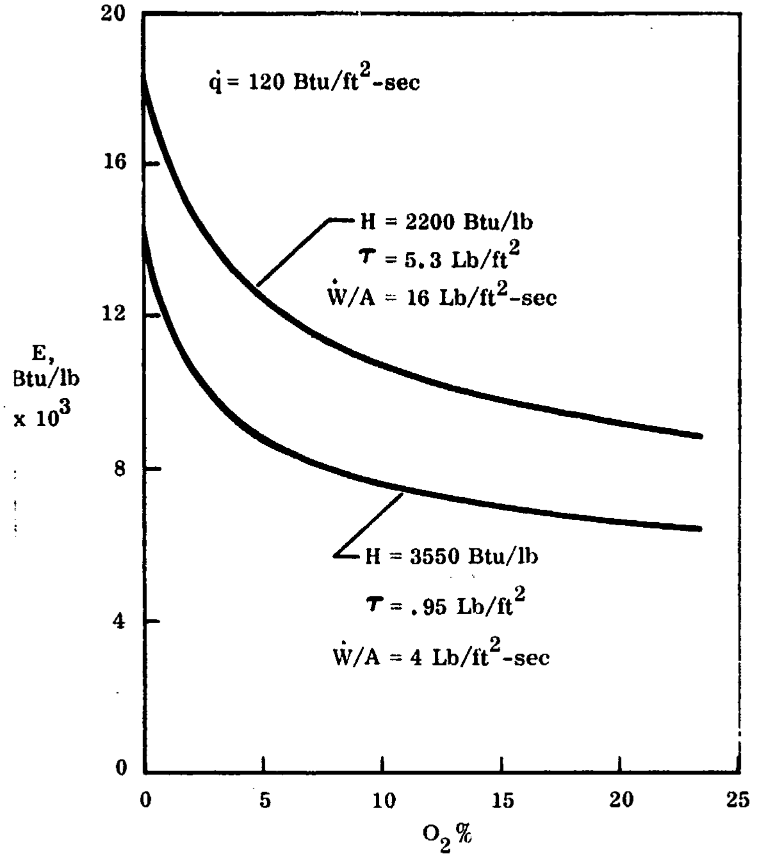

Figure 31.—Effectiveness of 36 lb/ft^3 phenolic-nylon as a function of stream chemistry, enthalpy, mass flow, and aerodynamic shear stress. Formulation 2.

Mechanical and Ablation Properties

Properties are presented in Tables 22 through 27 for both ESM 1001 P and ESM 1004 BP. The ultimate strengths of these at 77° F and at 300°F (Tables 22 and 23) are low which may account for their poor ablation effectiveness under high shear.

Thermophysical properties reported for ESM 1001 P and ESM 1004 BP include thermal conductivity and specific heat, presented in Tables 25 and 26.

Table 27 covers the ablative performance. By comparing these data with that of Table 19, it may be seen that ESM is similar to "Purple Blend" in ablative effectiveness. The ablative effectiveness of the unreinforced composition ESM 1004 BP appears to be sensitive to aerodynamic shear forces.

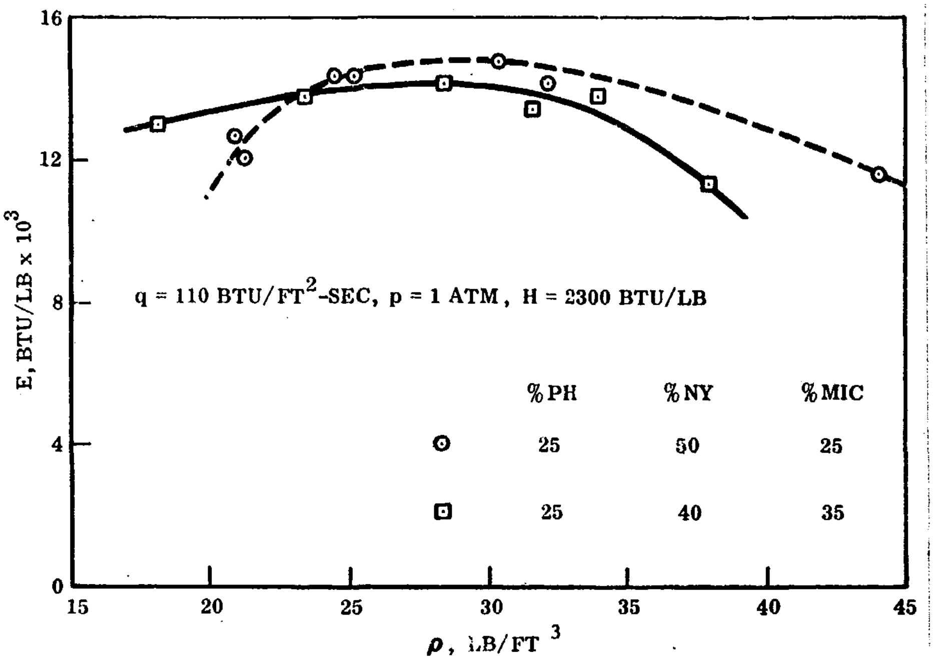

Figure 32.—Combined effect of density and composition on effectiveness.

Table 22.—Tensile Properties: ESM 1001 P and 1004 BP

Formulation	Temperature	Elastic Modulus, psi	Ultimate Strength, psi	% Strain at Failure
ESM 1001 P	-280° F	2.11 x 10^5	1500	0.83
	300	225	36.8	21.0
ESM 1004 BP	-280	2.11 x 10^5	1540	0.93
	-130	873	302	31.0
	- 35	296	86	30.0
	77	356	75	21.0

EPOXY-NOVOLAC BASED ABLATOR

The epoxy-novolac syntactic foam resin system, selected for the Apollo heat shield is a proprietary formula, AVCO 5026-39.

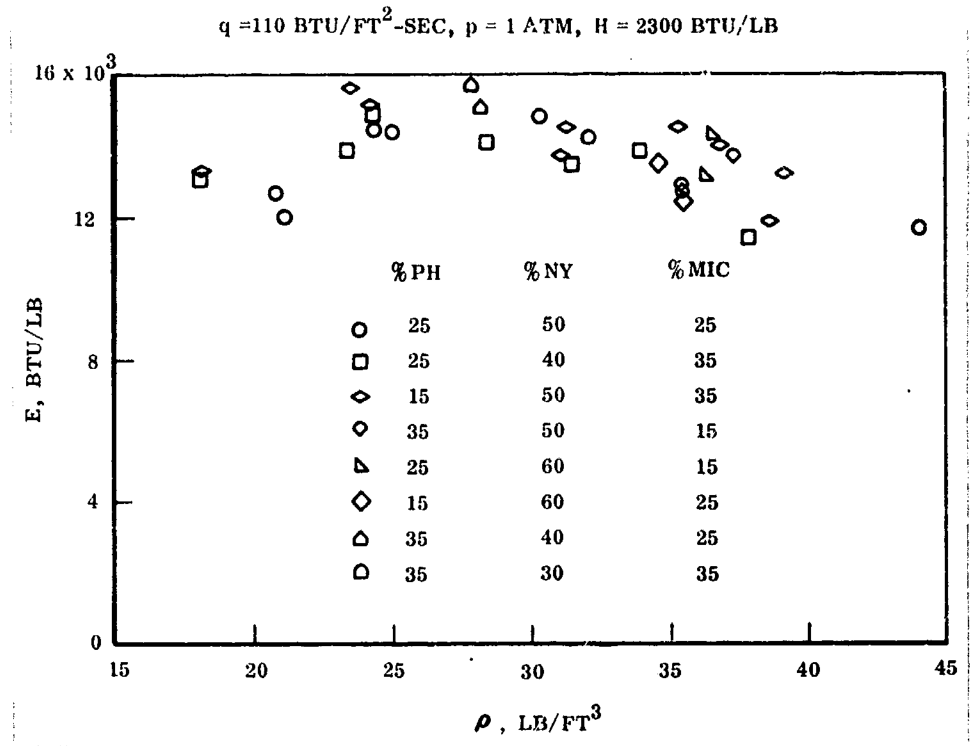

Figure 33.—Effect of density on the effectiveness of phenolic-nylon.

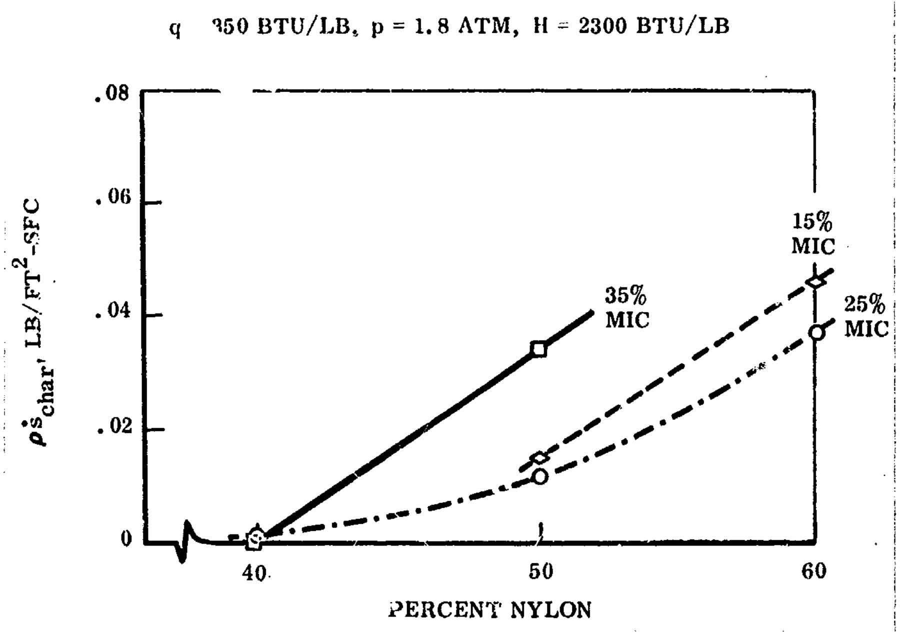

Figure 34.—Effect of nylon content on surface recession.

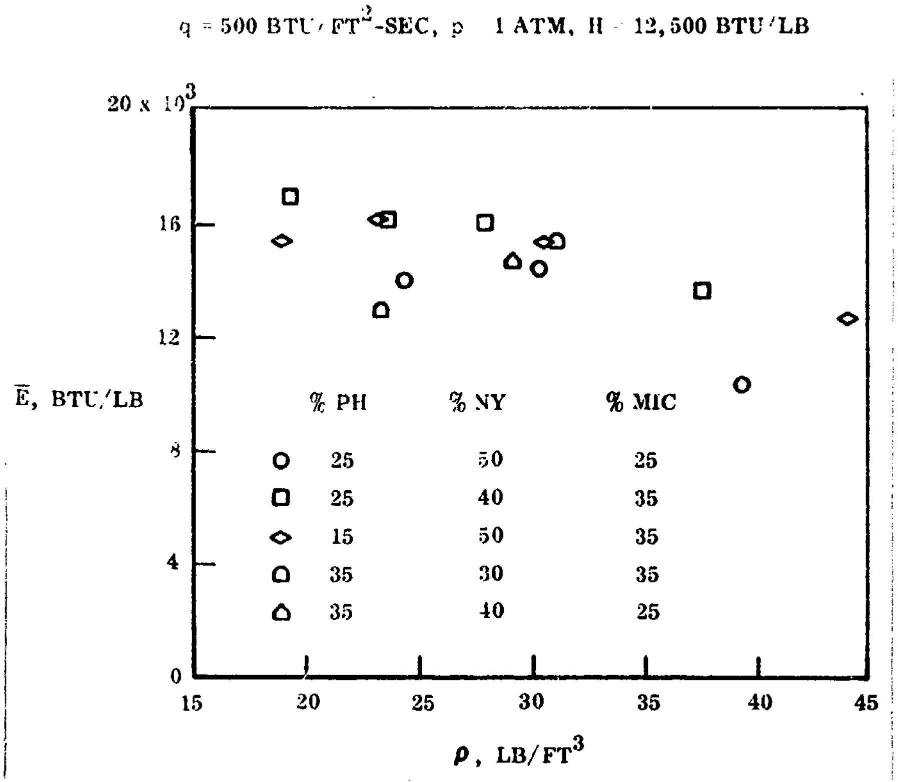

Figure 35.—Effect of density on effectiveness.

Table 23.—Tensile Shear Properties (Double Lap Shear)*

Formulation	Temperature, ^{o}F	Ultimate Strength, psi
ESM 1001 P	300	28.5
	77	28.7
	- 35	51.5
	-130	162.5
	-280	695.0
ESM 1004 BP	300	35.8
	RT	24.4
	- 35	64.9
	-130	223
	-280	940

*Bonded to aluminum with RTV-560; two-square-inch total cross-section

Table 24.—Compression Properties ESM 1001 P and 1004 BP

Formulation	Temperature, °F	Elastic modulus, psi	Stress at 25% deflection psi
ESM 1004 BP*	77	99	24
	130	88	20
	280	77	18
ESM 1001 P*	77	68	17
	130	105	24
	280	114	25
	-130**	116	23
	-160**	213	43

*Specimen size 1 x 1 x 1 inch
**Specimen size 6 x 6 x 0.25 inch

Table 25.—Thermal Conductivity of ESM 1001 P and 1004 BP

Material	Density, lb/ft^3	Temperature, °F	Thermal conductivity, Btu/ft^2-sec-°F
ESM 1001P	37.7	100	2.45×10^{-5}
		200	2.32×10^{-5}
		300	2.20×10^{-5}
		400	2.08×10^{-5}
		500	1.90×10^{-5}
		600	1.82×10^{-5}
ESM 1004 BP	39.0	100	3.00×10^{-5}
		200	2.88×10^{-5}
		300	2.78×10^{-5}
		400	2.66×10^{-5}
		500	2.54×10^{-5}

Table 26.—Specific Heat of ESM 1001 P and 1004 BP

Material	Density, lb/ft^3	Heating rate, °F/min.	Temp. range, °F	Specific heat, Btu/lb-°F
ESM 1001 P	37.7	5.2	-200 to +300	0.38
			300 to 600	0.50
ESM 1004 BP	39.0		-250 to +500	0.24 to 0.51

Table 27[4]. —Ablation Performances
Phenolic-Glass Honeycomb Reinforced ESM

Material	w	O_2%	t_{300}	$\dot{q}$	H	τ	$\dot{W}/A$	E
ESM 1001 P	2.95	3.5	304	111	3300	0.5	0.35	11,420
ESM 1001 P	2.98	3.7	320	126	3200	1.5	0.15	13,510
ESM 1001 P*	2.97	3.7	325	120	3200	1.5	0.15	13,100
ESM 1004 BP**		3.7	108	124	2700	4.5	0.35	4,400
ESM 1004 BP**		3.7	338	114	3200	1.5	0.15	13,200

*Split honeycomb for columnar reinforcement.
**Not reinforced.

Composition

Epoxy-novolac resin, filled with fibers and phenolic microspheres. The curing agent may be methyl nadic anhydride or a similar system to provide a high heat distortion temperature.

Cure

3/8" cell, phenolic fiberglass honeycomb reinforcement. The uncured filled resin is inserted into the honeycomb cells and the composite is then cured.

Density - 31 lbs. per cu. ft. (nominal)

The re-entry environment parameters are listed in Table 9. Extensive data have been developed to prove thermal insulative, shape stability and ablative performance and to meet the cold requirements of -150° F. Expansion-contraction stresses on the structure and heat transfer rates have been the subject of extensive testing.

Fabrication

High reliability has been a dominant goal in procedures for the fabrication and application of the heat shield. Vacuum bonding is used to anchor sized, molded-honeycomb sections of the heat shield to the substructure. After filling the cells with the resin ablator system, and curing, a final complex machining controls thickness and structural weight.

Storage and handling of the resin are closely controlled. The filled resin is stored in 1.5-inch diameter plastic cartridge tubes at 30° F. Before use the tubes are warmed in a dielectric oven, then the tube is inserted into the barrel of a gun heated by electrical tape. The gun nozzle is inserted in the honeycomb cell, air pressure is applied and the material is blown out in little globules deep into the cell.

Table 28[3]. —Mean Specific Heat Vs. Temperature:

AVCO 5026-39

Mean Temperature °F	Mean Specific Heat Btu/lb/°F
-124	0.19
+113	0.31
146	0.34
212	0.38

The 370,000 cells, with a cell size of 3/8 inch diameter, are each filled with ablative material. Thus far, the manual approach has the highest reliability. Electrical timing automatically measures the amounts of ablative material.

Thermophysical Properties

Thermophysical properties available for AVCO 5026-39 include mean specific heat (Table 28), and thermal conductivity (Figure 36). The mean specific heat is similar to that for DC 325 and NASA "Purple Blend."

SPRAYABLE SILICONE-BASED ABLATOR (MARTIN MA-25S)

The MA-25S ablator material is a proprietary two-part silicone elastomer system filled with microballoons. It was developed by Martin-Marietta, Baltimore, to expand the flight envelope of the X-15-2 hypersonic aircraft to Mach 8 by limiting the back side temperature to a design goal limit of 600-700°F.

Applications

The MA-25S material permits on-site application of refurbishable ablative coatings for space research vehicles for NASA FRC, Edwards AFB.[10] The MA-25S sprayable system was selected after a screening test program at the University of Dayton and arc tunnel tests and structural tests at Langley Research Center. The objectives were to acquire operational experience in rapid refurbishment by quick spray-on and removal of coatings and to achieve economy for recoverable vehicles by avoiding fabrication from more expensive structural materials.

The presence in one area of an FM radio type antenna with a 6-inch protrusion caused the high shear, high heat flux environment during flight, so a molded material with improved thermomechanical properties has been developed. This is fabricated from the same silicone elastomer, is filled with microballoons and reinforced with silica fibers. The material must not interfere with radio communication. It must be transparent to 250 megacycle and C-band 5700 megacycle frequencies.

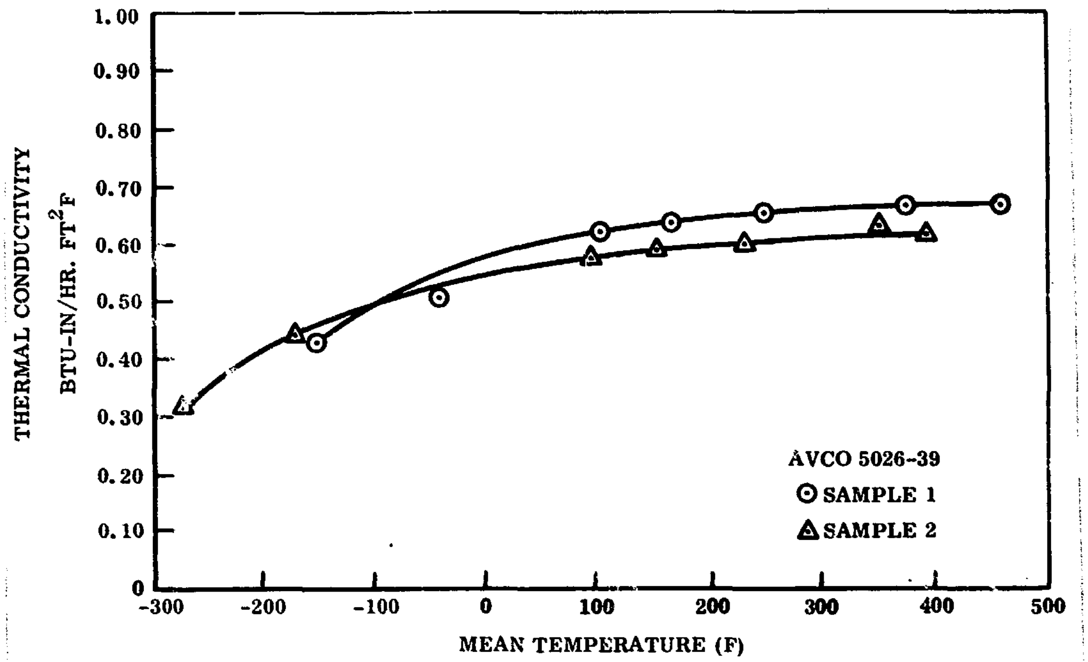

Figure 36.—Apparent thermal conductivity - versus - temperature (AVCO5026-39).

Total system weight of the applied protective coating is not less than 300 lbs. nor more than 400 lbs. Section thickness is built up to 1/2 inch along leading edges, wings and fins. The upper rear fuselage receives a very thin coating.

Process Application

The MA-25S is a solvent system. Spray processing technique involves two-component metering in the temperature range of 30 to 90°F. The proportion of catalyst delivered for mixing with the solvated resin in the head of the spray gun is regulated in relation to the ambient temperature, providing approximately uniform cure rates. Surfaces are primed with a silicone primer. For refurbishment, the ablated coating is removed manually down to the primer. Coating thickness depends on the number of spray passes.

Physical Properties

Physical properties for MA-25S are shown in Figures 37 and 38.

Thermophysical Properties

Thermal expansion, thermal conductivity and specific heat are presented in Figures 39, 40 and 41, respectively.

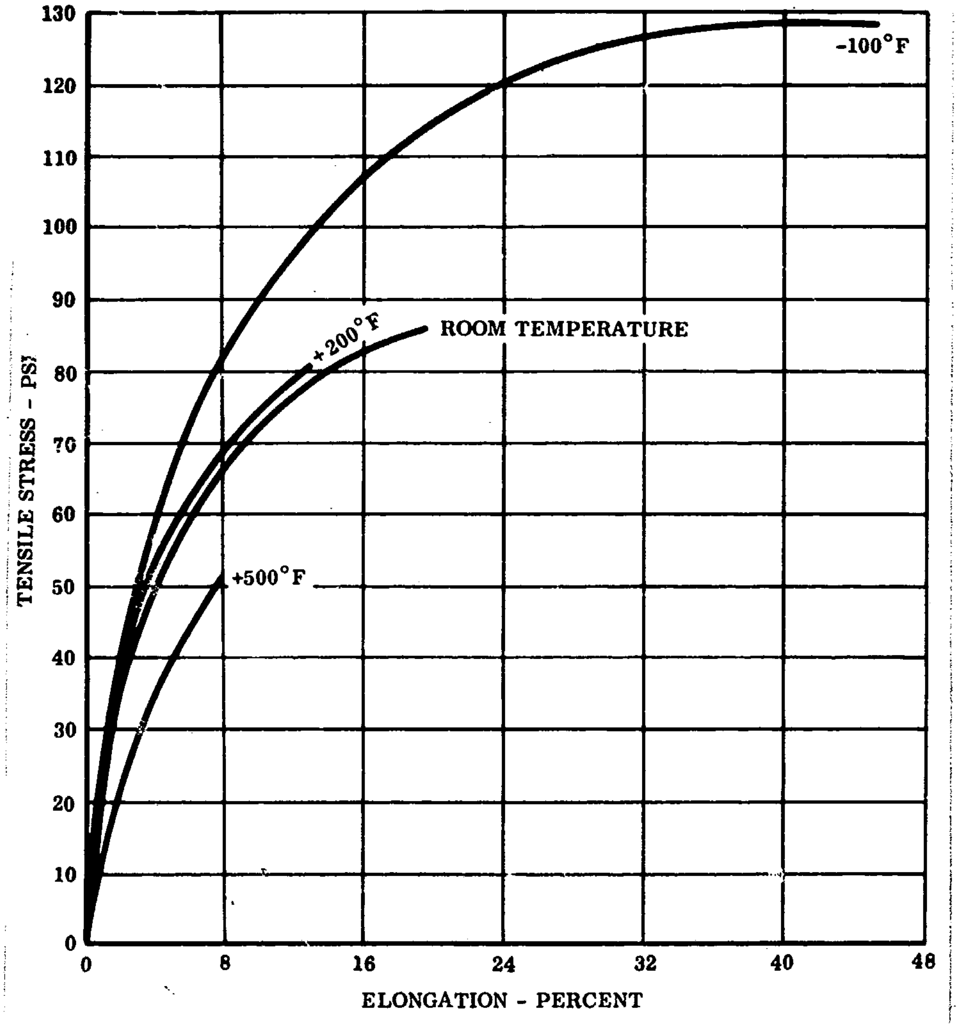

Figure 37.—Tensile properties of MA-25S stress versus strain

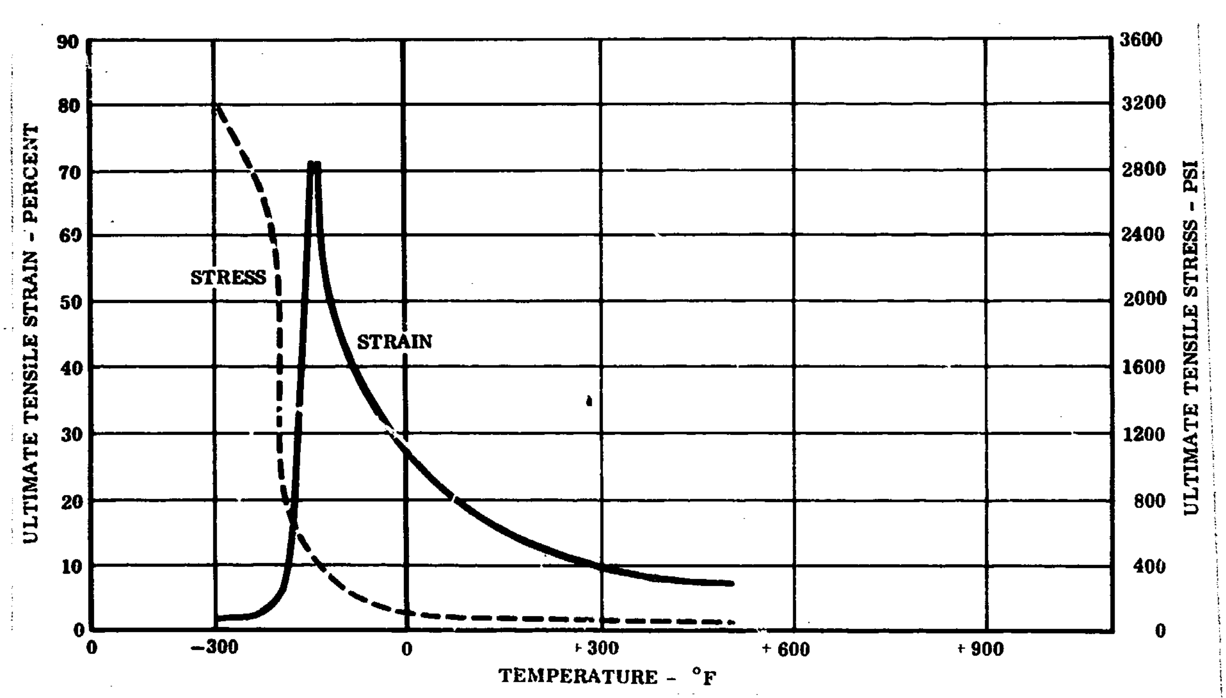

Figure 38.—Ultimate tensile properties of MA-25S versus temperature.

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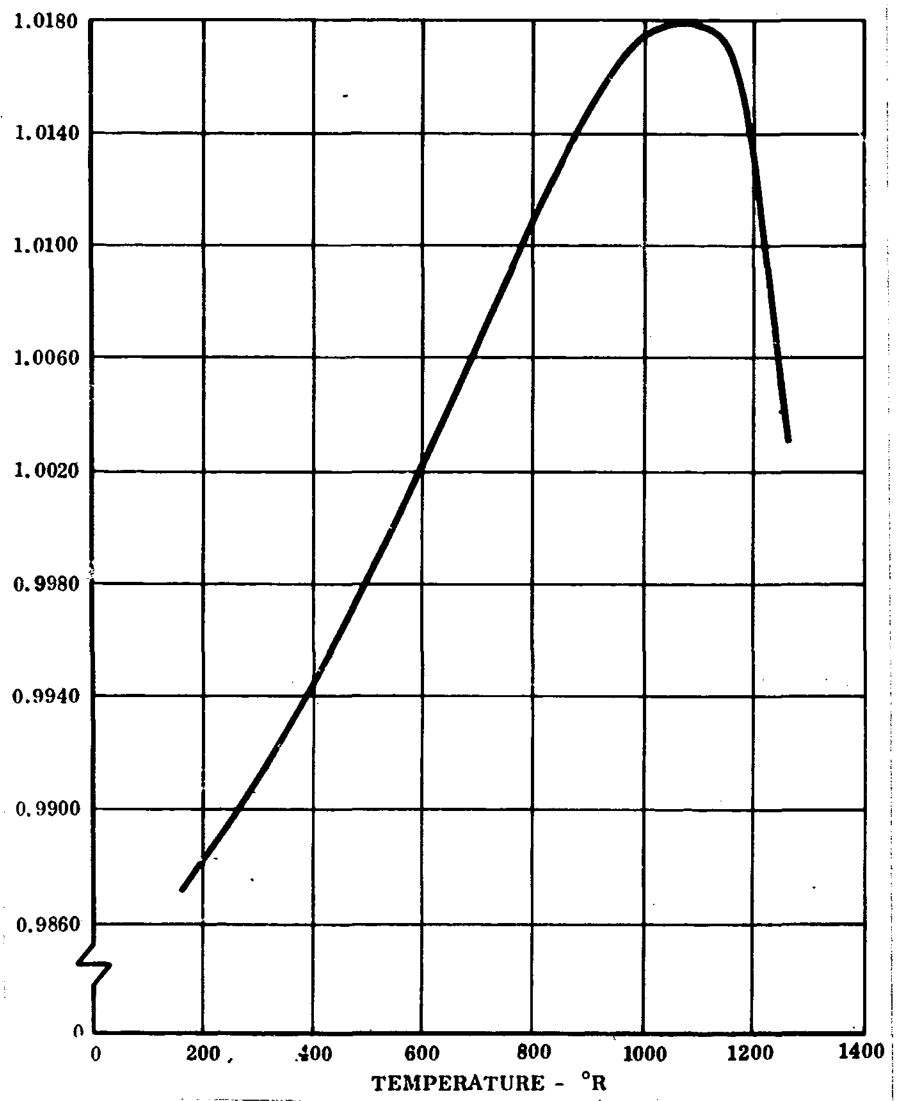

Figure 39.—Linear thermal expansion of MA-25S versus temperature.

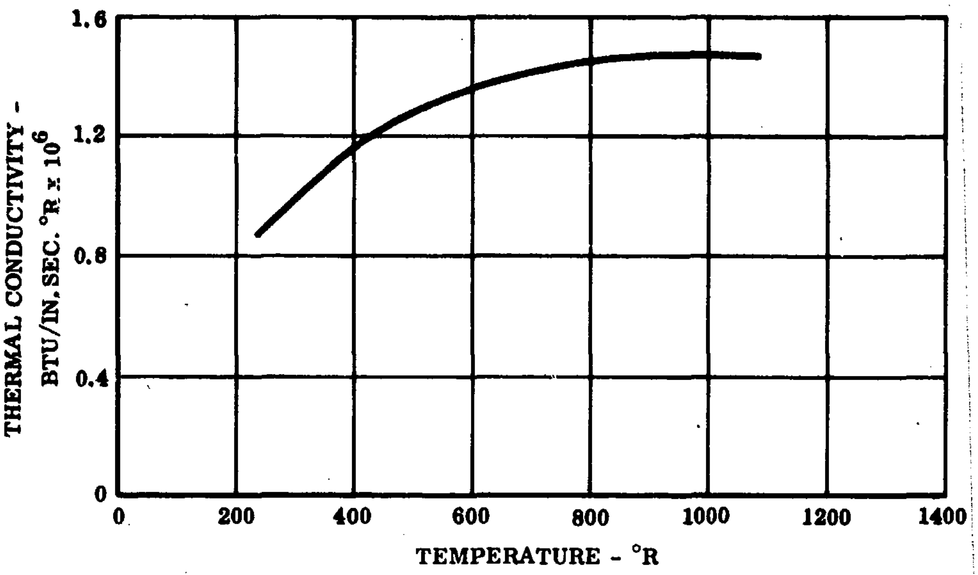

Figure 40.—Thermal conductivity of MA-25S vs mean temperature.

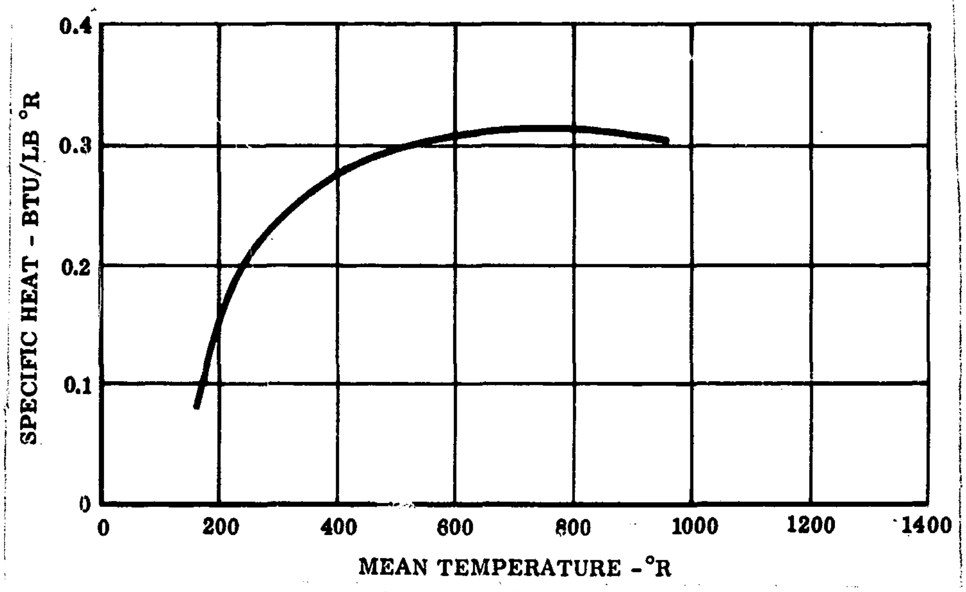

Figure 41.—Specific heat of MA-25S vs temperature.

REFERENCES

1. Wilson, R G.: Thermophysical Properties of Six Charring Ablators from 140° to 700°K and Two Chars from 800° to 30.00°K. Langley Research Center, NASA TN D-2991, October, 1965.

2. Dow Corning 325 Data Sheet, 1962.

3. Hogenson, P. A.: Apollo Alternate Heat-Shield Materials Investigation. North American Aviation, SDL 425, S&ID, 1964.

4. Dolan, C M.: Study for Development of Elastomeric Thermal Shield Materials. NASA CR-186, 1965.

5. Swann, R. T., et al.: Effect of Composition and Density on the Ablative Performance of Phenolic-Nylon. Presented at 8th National Meeting of SAMPE, 1965.

6. Chapman, A T.: Effect of Weight, Density, and Heat Load on Thermal-Shielding Performance of Phenolic-Nylon. NASA TN D-2196, 1964.

7. Clark, R. K.: Effect of Environmental Parameters on the Performance of Low-Density Silicone-Resin and Phenolic Nylon Ablation Materials. NASA TN D-2543, 1965.

8. Keller, L. B.: Development of Characterized and Reproducible Syntactic Foam of Phenolic-Nylon for Heat Shields. Hughes Aircraft Report P66-49, Dec. 1965.

9. Dolan, C. M., et al.: Elastomeric Thermal Shield System for Lifting Re-entry Vehicles. AIAA 6th Annual Structures and Materials Conference, 1965.

10. Private communication, Edwards Flight Research Center.

Chapter V

FOAM SYSTEMS FOR CRYOGENIC INSULATION

PERSPECTIVE

Foams are widely used to insulate launch vehicles that use cryogenic propellants. In particular, thermal protection for hydrogen propellant limits tank pressure rise and minimizes evaporative loss during prelaunch hold periods, the boost phase, and in space during sustained flights.

The two principal categories of cryogenic insulation for flight systems are rigid polyurethane foams combined with vapor barriers and multiple-layer, highly reflecting radiation shields separated by spacers or insulators in high vacuum. Thermal conductivities of foams are controlled by the interstitial gas and are much higher than that of insulation using vacuum. In spite of these factors, advantages of weight, cost, producibility, and reliability of current composite foam insulations account for their choice for short-term missions requiring space-borne liquid hydrogen tankage.

Thermal insulation for liquid hydrogen may be internal or external to the tank wall. The insulation should be provided with a barrier that prevents its filling with a liquid which would greatly reduce its effectiveness. Thus, for internal insulation, a hydrogen barrier is required; for external insulation, a barrier must exclude moisture or air which can cryopump into the insulation.

There are three basic types of foam insulation systems for liquid hydrogen tanks (Figure 42).[1] Internal sealed-foam insulation is utilized on the Saturn S-IV and S-IV-B stages. External foam insulation systems, as tested on the Centaur vehicle, are either helium purged or vapor sealed.

The final insulation configuration is specific for each system or mission. It is determined by a trade-off among, (1) minimum flight weight design, (2) effectiveness of the insulation, and (3) allowable propellant boil-off. The choices depend on the relative times involved in the hold, boost, and flight phases of the mission.

Varying concepts have been utilized to provide structural integrity of low density foam insulation and an effective barrier to fluid.

NASA's Lewis Research Center has investigated hermetically sealed foam insulation and has extended this to full-scale liquid hydrogen tank tests. A design goal is to obtain a thermal conductivity for the complete insulation system as low as that of the basic foam. A positive seal would insure that neither gas nor liquid is cryopumped into the insulation.

A lightweight insulation system developed by Lewis Research Center used panels of low density polyurethane foam hermetically sealed with a thin film laminate of Mylar and aluminum foil.[2] The panels were bonded and sealed to the outside walls of the tank and gained structural rigidity by a prestressed wrap of fiberglass yarn.

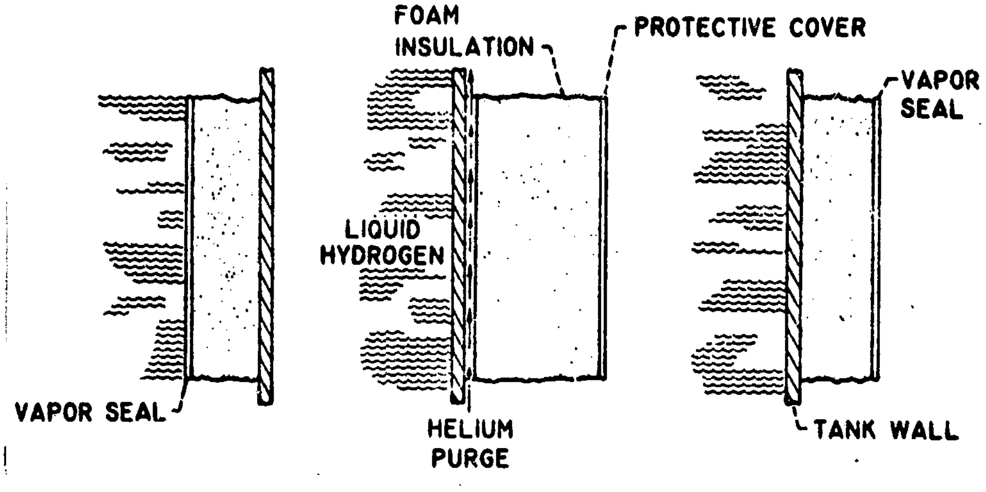

Figure 42.—Basic types of foam insulation systems for liquid hydrogen tanks.

Calorimeter tests measured the thermal conductivity of variations of the system. Subscale tank tests were used to develop insulation application techniques, to evaluate thermal and structural performance, and to determine the effects of aerodynamic forces and heating encountered during launch. Ground-hold boil-off tests were conducted on full-scale tanks. The insulation system finally developed was applied to a Centaur liquid hydrogen tank for test purposes.

The complexity and reliability requirements of current vehicle systems used in manned-space studies have increased holding periods. An analysis at Martin-Marietta Corporation, Denver,[3] concluded that, on a volumetric basis, the boil-off of liquid hydrogen would be 37.7 times as great as that of liquid oxygen in uninsulated tanks of equal size under normal atmospheric conditions. The behavior described points to the need for extremely effective insulations for liquid hydrogen propellant tanks (Figure 43).

INSULATION DESIGN FACTORS

The choice of insulation for a particular cryogenic application is generally a compromise between such factors as: (1) permanence of thermal properties, (2) insulation flight weight, (3) volume, (4) producibility, (5) capability of insulation to operate under ground and air-borne conditions, (6) reliability of insulation after handling and repeated use, (7) influence of insulation on other vehicle components and materials, (8) extent of auxiliary equipment required to make the insulation function effectively, (9) ease of maintenance, and (10) cost.

Table 29 presents data on thermal conductivity and density for a number of common insulation materials. Figure 43 summarizes in graphic form: (1) the insulation weight

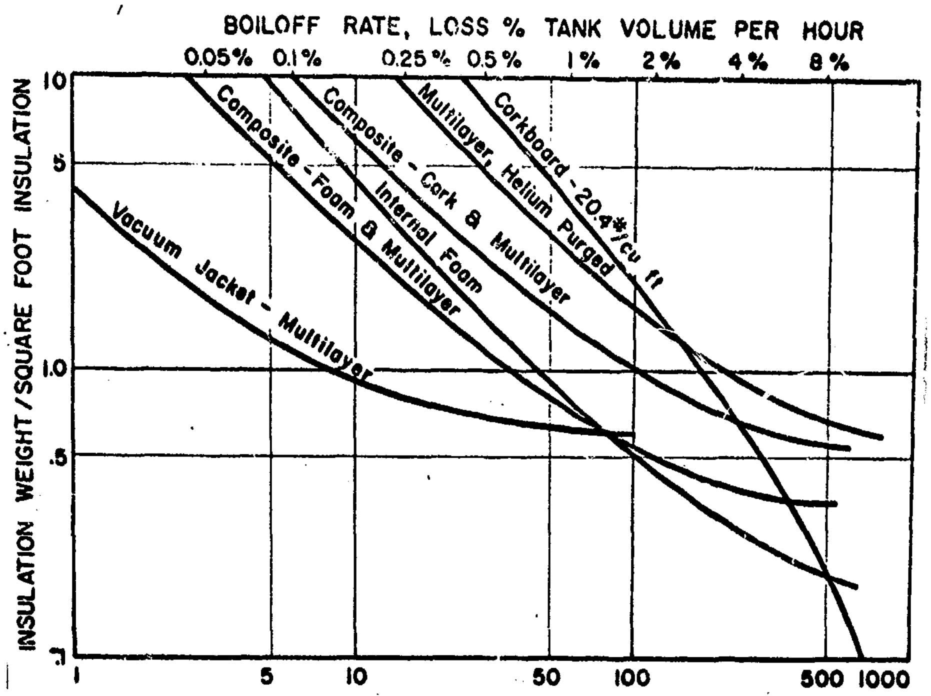

Figure 43.—A comparative study of airborne liquid-hydrogen tank insulation.

per square foot, (2) the heat transfer rate, and (3) the resulting liquid hydrogen boil-off, expressed as percent of tank volume per hour. These data are based on a tank 33 feet in diameter and 50 feet long, approximately to the liquid hydrogen tank size of the Saturn series of launch vehicles. An outside air heat transfer coefficient of 2 Btu/hour-ft^2-°F is assumed.

Effect of Cryopumping on Thermal Conductivity

The thermal conductivity of low density polyurethane foam is 0.11 Btu-in/hr-ft^2-°F, while the "K" factor for gaseous hydrogen approaches 0.65 Btu-in/hr-ft^2-°F. Assuming it is either impossible or impractical to keep gaseous hydrogen from entering polyurethane foam installed inside the cryogenic tankage, the foam insulation takes on the "K" factor of the saturating hydrogen gas. This degradation of the "K" factor from 0.11 to 0.65 is avoided by external sealed insulation systems. External insulation is susceptible to cryopumping problems, particularly in the event of handling damage and subsequent repair and checking procedures. Minimizing cryopumping generally requires a purge gas such as helium which, once it saturates the foam, degrades the "K" factor from 0.11 Btu-in/hr-ft^2-°R to 0.7 Btu-in/hr-ft^2-°R of the helium gas.

Table 29.—Properties of Various Insulating Materials

Insulation	k, Btu/hr-ft^2-°F/in.	ρ lb/ft^3	$k\rho$	Insulation pressure
Materials				
Silica Aerogel	0.12	8.5	1.02	Air environment
Polyurethane foam	0.20	2.0	0.40	1 atm
Kapok	0.24	0.88	0.21	
Corkboard	0.30	20.0	6.0	
Balsa wood	0.36	8.0	3.88	
Teflon	0.60	—	—	
Rubber	0.98	75.0	73.0	
Multilayer (S-I) Insulation				
S-I 10	0.00078	2.5	0.0020	10^{-4} mm Hg
S-I 12	0.00108	2.0	0.0020	10^{-4} mm Hg
S-I 44 (formerly 4)	0.00024	4.7	0.0011	10^{-4} mm Hg
S-I 62	0.00022	5.5	0.0012	10^{-4} mm Hg
S-I 62	0.0072	—	—	15 psi external load
S-I 91	0.00012	7.5	0.009	10^{-4} mm Hg
Opacified Powders				
Santocel "A"	0.0011	6.0	0.0066	10^{-4} mm Hg
Perlite	0.000864	8.0	0.0069	10^{-4} mm Hg
Cab-o-sil	0.0014	4.5	0.0063	10^{-4} mm Hg
Micro-cell	0.0042	—	—	10^{-4} mm Hg
Fiberglass				
AAAA 2.2 x 10^{-5} in. dia. fiber-heat felt	0.01	4.0	0.05	10^{-3} mm Hg
AAAA 2.2 x 10^{-5} in. dia. fiber-heat felt	0.03	1.04	0.03	10^{-3} mm Hg
AAAA 2.2 x 10^{-5} in. dia. heat felt	0.21	4.0	0.84	1 atm

EXTERNAL INSULATION—EVACUATED

If only thermal conductivity and the elimination of condensation are involved, evacuated multilayer insulation is far superior to all other insulation systems.[15] However, the problems and costs of fabricating and maintaining a vacuum-jacketed insulation severely restrict its use for flight vehicles. Although it is used for ground storage vessels for liquid hydrogen, for space vehicles, a means must be provided to maintain a vacuum in this type of insulation jacket during ground hold and boost through the atmosphere. Rigid foams are suitable for use as the core material, since they readily sustain loads imposed by evacuation. Low outgassing in a hard vacuum is an important criterion in selecting such foams.

The vacuum jacket insulation system is also susceptible to puncture. The requirements for repair, bakeout, and re-evacuation constitute further limitations in the application of this insulation system on current space vehicles that may use in excess of 5000 square feet of insulation.

Foam Insulation in Saturn Vehicles

The cryogenic foam insulations found in the various stages of the Saturn family of vehicles are summarized in Table 30.

The treatment of vehicle insulations will be presented according to foam location, whether internal or external to the tank wall.

INTERNAL FOAM INSULATION

This concept places the insulation material within the tank wall, to which it is adhesively bonded. The insulation is neither evacuated nor cryopumped, and radiation shields are eliminated. Three concepts are considered for classification.

In the first, an open-cell foam is covered by a liner or barrier which is permeated by hydrogen gas, but impermeable to liquid hydrogen. Such a barrier is termed "fly screen" by designers. The liner must withstand the static pressure involved, but not the large differential pressure caused by tank pressurization. By applying the foam as shingle blocks and bonding these at liner joints with a rubbery urethane adhesive, a structural joint is made which can withstand the thermal stresses imposed. As in the case of helium-purged insulation, foam which has become permeated by gaseous hydrogen will tend to assume the thermal conductivity of the contained hydrogen gas.

A second configuration of internal insulation assures that all cells are axial to the tank wall. End-grain Balsa wood and honeycomb core filled with foam are examples. The heat transferred through the cell is again primarily the result of gaseous hydrogen.

The third insulation concept employs a liner or barrier which is impermeable to both liquid and gaseous hydrogen. Hence, it must withstand forces generated by the gaseous and liquid hydrogen and remain sufficiently elastic at cryogenic temperatures to withstand the temperature gradients developed. A closed-cell foam with or without an elastic bladder would serve as an example.

The internal foam insulation adopted for the S-IV/Saturn I and S-IV-B/Saturn V stages was of the first configuration. In these structures the foam insulation is covered with a "fly screen" liner which permits entry of the gaseous hydrogen, but prevents permeation of the liquid hydrogen.

The development of such an internally bonded insulation offered (1) less difficulty in bonding insulation internally to a surface above -100°F than in bonding externally to a surface at -423°F, (2) no cryopumping of air and no increased heat transfer rate caused by the presence of liquid air, (3) minimizing of liquid hydrogen boil-off during loading, and (4) better ground handling and ground environmental protective characteristics.

Table 30.—Summary of Vehicles, Contractors and Type of Cryogenic Insulation Utilized

Vehicle	Designation	Contractor	Type insulation	Location	Typical boost time
Saturn 1	S-1	1st stage, Chrysler Corp.	3-D Fiberglass reinforced polyurethane foam	Internal	5-10 minutes
	S-IV	2nd stage, Douglas Aircraft Co.			
Saturn 1B	S-I-B	1st stage, Chrysler Corp.	3-D Fiberglass reinforced polyurethane foam	Internal	0.5 to 4.5 hours
	S-IV-B	2nd stage, Douglas Aircraft Co.			
Saturn V	S-I-C	1st stage, Boeing Aircraft Co.			155 secs.
	S-II	2nd stage, North American Aviation	Polyurethane foam in 3/4" Phenolic-glass honeycomb	External non-jettisonable	190 secs.
	S-IV-C	3rd stage, Douglas Aircraft Co.	3-D Fiberglass reinforced polyurethane foam	Internal	

Saturn Third Stage, S-IV-B/V Insulation

The S-IV-B third stage of the Saturn V uses both liquid hydrogen and liquid oxygen cryogenic propellants to provide escape velocity for large payloads such as the Apollo spacecraft. The S-IV-B vehicle, developed and manufactured by the Missile and Space Division of Douglas Aircraft Co., is 22 feet in diameter and 58 feet in length. The tankage capacity approximates 230,000 pounds of propellant. The stage has stop and restart capability.

The liquid hydrogen tank of the S-IV-B stage is internally insulated with a polyurethane foam.

The components of the composite insulation for liquid hydrogen are:

(1) A foam core which serves as the primary thermal barrier and which has sufficient structural integrity. The foam used is a CPR (Division of Upjohn Co.), Series 20, 3 pcf. density polyether polyurethane, closed cell, Freon blown system which is cured at room temperature. This foam is reinforced in the "X," "Y" and "Z" axes with fiberglass threads. The density of the glass reinforced foam is 5.2 lb/ft^3. The two-part polyurethane system is cast into a block in the three planes and is then fabricated into insulation tiles (Figures 44 and 45).[5] The disposition of the filament reinforcement has led to the descriptive name of "three-dimensionally reinforced foam" or simply "3-D foam."

(2) A liner that physically ties together the individual foam segments, prevents surface cracking in the core, and acts as a base for a seal coat. The liner for the S-IV-B consists of a No. 116 fiberglass cloth impregnated with a polyurethane resin.

(3) A polyurethane resin sealer that acts as a barrier to retard hydrogen permeation and prevent moisture penetration.

It is helpful to visualize the dome and common bulkhead design of the vehicle to appreciate the methods of installation and attachment of the foam tiles. The S-IV-B

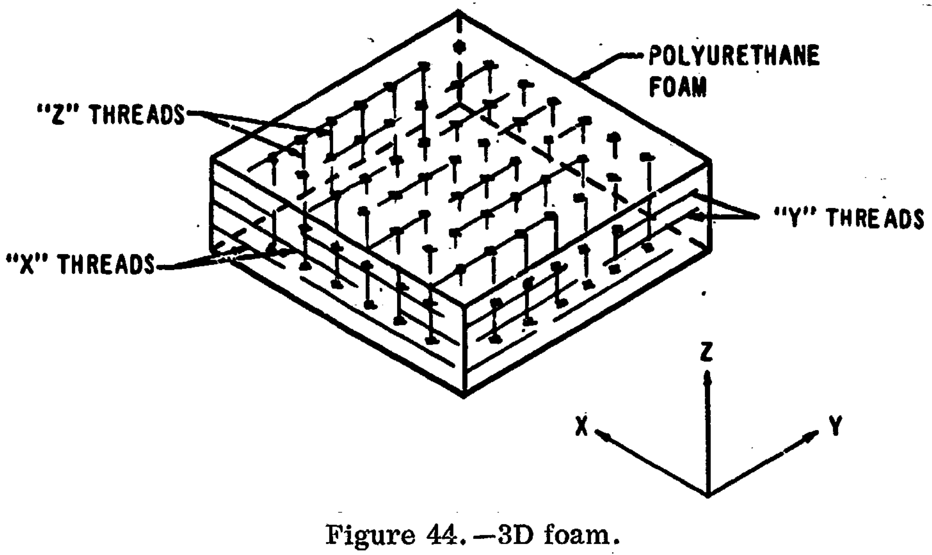

Figure 44.—3D foam.

5-7

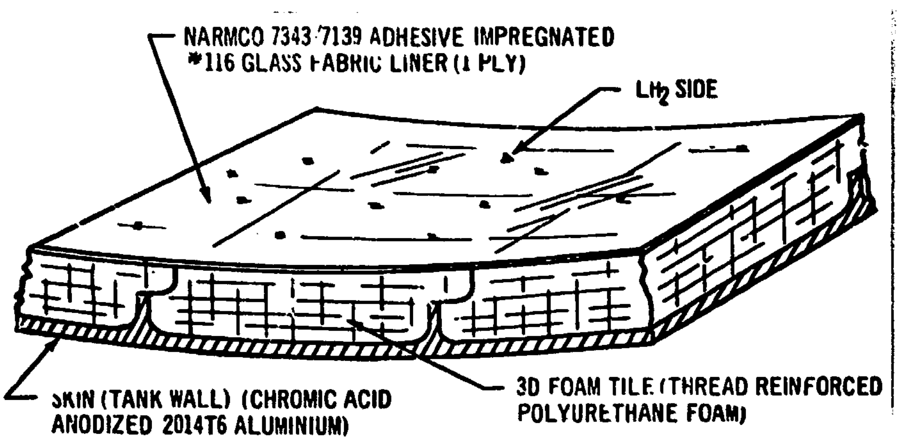

Figure 45.—Internal insulation.

system of LOX and liquid hydrogen tanks is fabricated with a common bulkhead. The hydrogen forward dome, the LOX tank aft dome, and the common bulkhead domes are hemispherically shaped aluminum structures with nine gore segments. The common bulkhead has a forward and aft dome with a 1-3/4-inch layer of fiberglass phenolic honeycomb core bonded between the dome.

The liquid hydrogen tank is fabricated from seven welded, chem-milled 2014 aluminum alloy sections. The chem-milling results in an integrally stiffened 9" x 9" geodesic structure which presents a very complex inner tank surface to which the foam insulation must be adhesively bonded. This surface is shown in Figure 46 where the cylindrical skin section of the LH_2 tank is being coordinated to the LOX tank. After assembly, the metallic structure is hydrostatically tested.

Each vehicle has approximately 4300 sculptured "3-D" foam insulation tiles. The composite foam and reinforcement has a density of 5.2 pounds per ft^3. The first step in the production of the reinforced foam is the insertion of the "X" and "Y" fiberglass threads. The weaving machine for placing warp threads about special peripheral frames (13" x 13") is shown in Figure 47. These frames are alternately stacked at right angles to each other to arrange reinforcing threads in two of the three axes. A second weaving machine inserts the "Z" axis reinforcement.[4]

The details of the reinforcement are as follows:

Axis	Distribution ends per in^2	Reinforcement	Wt. oz.
X	25-30	CAP ECG 150 -1/0	1.0
Y	25-30	CAP ECG 150 -1/0	1.0
Z	25-30	CAP ECG 140 -3/2	3.8

The glass thread reinforcements were supplied by Owens Corning Fiberglass Corp., with an epoxy compatible finish such as EGP-682.

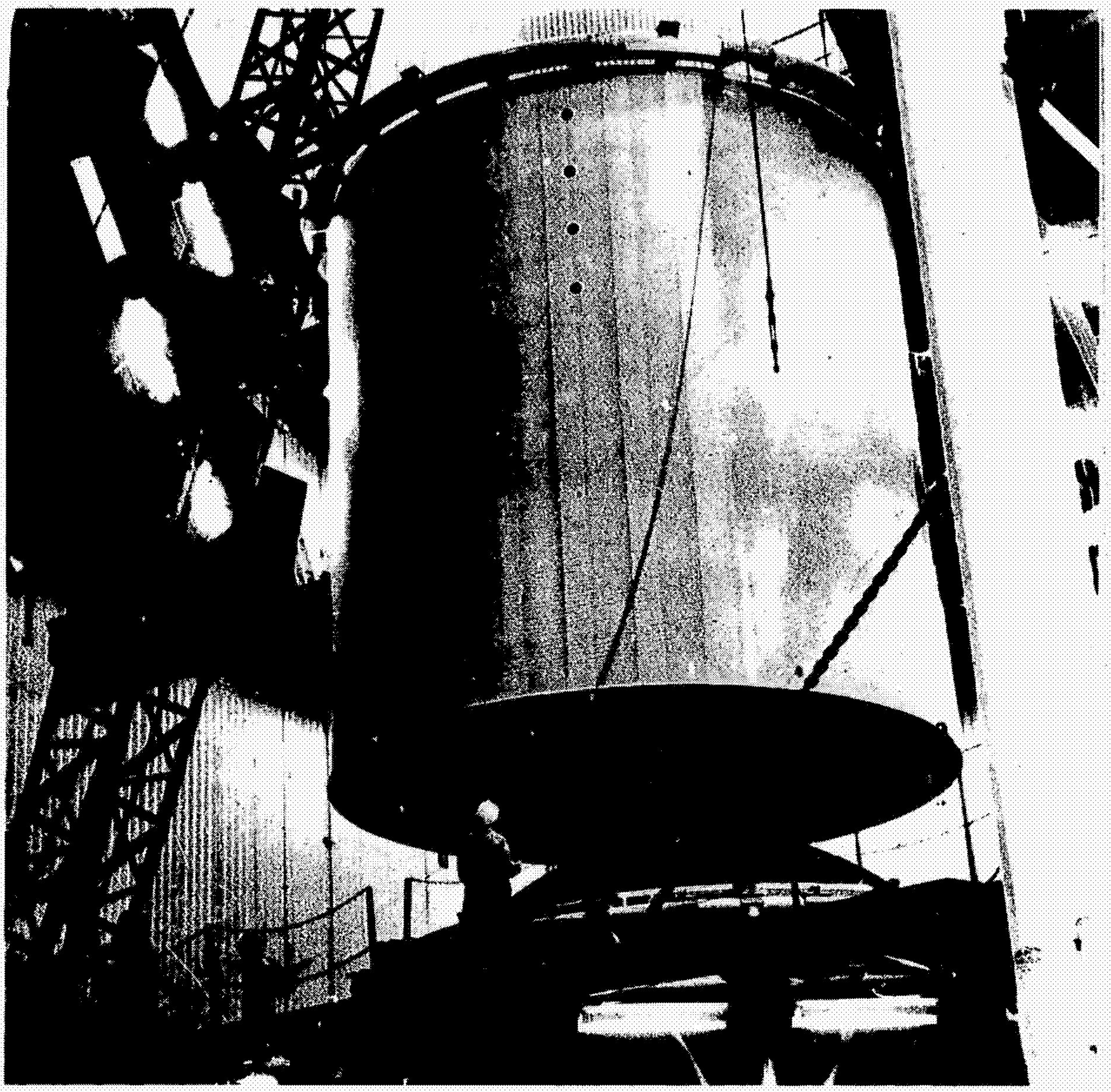

Figure 46. —Cylindrical LH_2 tank skin section.

After the thread frames were stacked to 7-1/2 inches, and the "Z" threads woven into place, a demountable mold was placed around the frame stack and the polyurethane reactants poured into the mold and foamed in place up through the specially distributed reinforcing threads. After the foam formed it was cured at room temperature and subsequently removed from the mold. A standard foam block size is 13" x 13" x 7-1/2".

Next, the reinforced foam block is either band-sawed into slices for turning or cut on a 130-inch radius to conform to the cylinder sidewall shape.

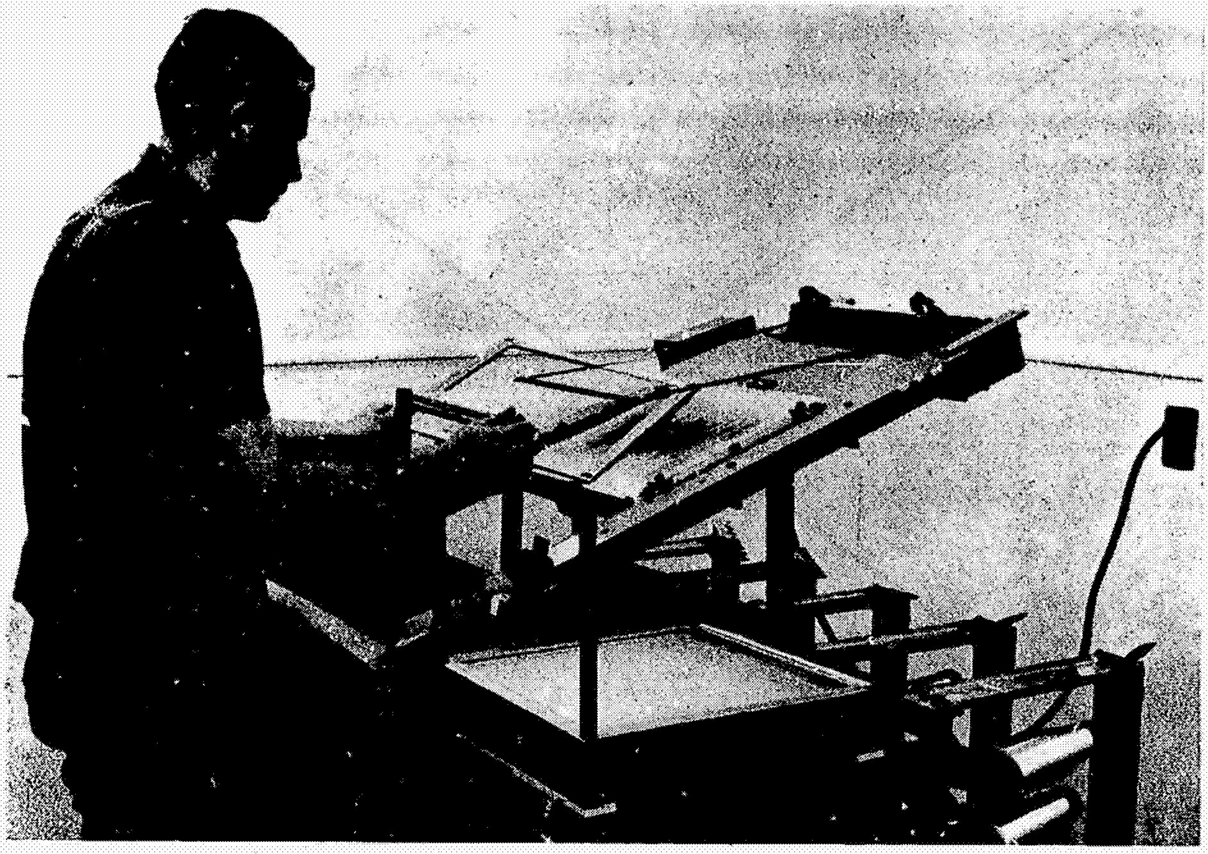

Figure 47.—Tile insulation fabrication "X" - "Y" weaving machine.

Various tiles fabricated from the rough "3-D" foam block are pictured in Figure 48. Tile block sizes are generally 9" x 9" x 1" thick. Thickness sections of 1/2" to 3/4" are cut for special areas.

For installation, the tank is mounted and the tiles are delivered by conveyor through the door in the upper dome into the liquid hydrogen tank itself. There are two distinct operations: (1) tile bonding to the aluminum tank using the epoxy adhesive and (2) application of the protective liner using the polyurethane adhesive. Limited pot life of the adhesive and the large size of the tanks requires each of these operations to be accomplished incrementally.

"3-D" foam tiles are then progressively installed within the tank. The assembly chamber temperature is held at 55 to 65°F to extend the life of the catalyzed adhesive. For curing a polyvinyl chloride vacuum bag at a pressure of 15 inches of mercury is used to press the tile against the inner tank surface, while the temperatures in the tank and chamber are increased to 110°F.

The inner surface of the installed tile is covered with an 0.005-inch-thick protective liner composed of #116 fiberglass cloth (0.004 inch) laminated in position with a 60-percent polyurethane resin- (Narmco 7343/7139) to-glass ratio by weight.

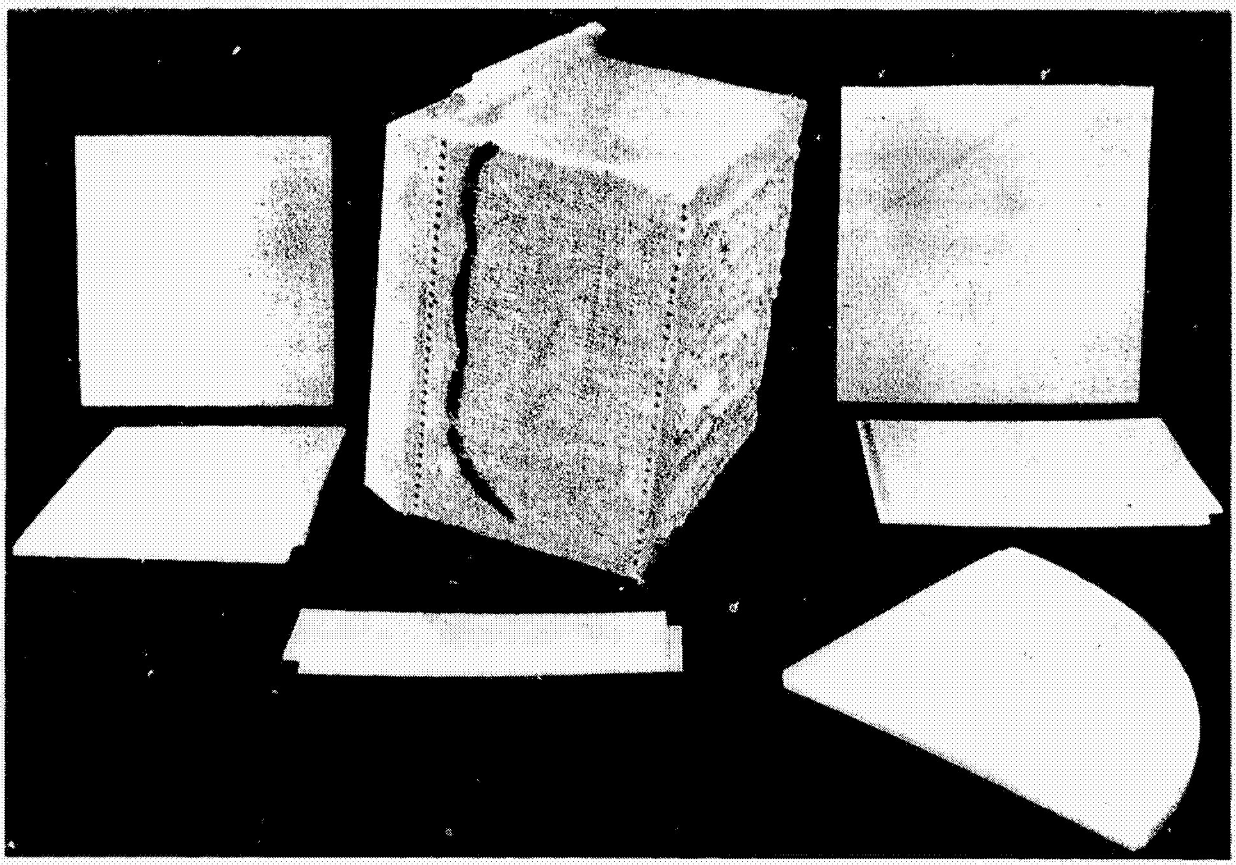

Figure 48. —Tile fabrication display.

The overlay barrier is permeable to gaseous hydrogen, but not to liquid hydrogen. This effect is known as the "fly screen" effect, and assists foam survival. The tank is finally postcured at 160°F for 24 hours, given a final cleaning, the probes installed and the tank sealed.

The development of the "3-D" fiberglass reinforced polyurethane foam tile by Douglas Aircraft Co. is an example of a practical solution to the problems of cracking, splitting, and separation.

The composite insulation has been tested for structural integrity under vibration, temperature and pressure environments simulating Saturn S-IV and S-IV-B flight conditions. Structural property data at liquid hydrogen temperatures are as follows:

	Without fiberglass reinforcement	Reinforced
Average compressive strength, psi	75	220
Average tensile strength, psi	50	160
Modulus of elasticity, psi	--	2.1×10^3

The thermal conductivity of the "3-D" foam has been reported[3] to range from 0.14 to 0.23 Btu-in/hr-ft^2-°F, 0.2 representing a working average. Upon filling the tank with liquid hydrogen, simulating a ground hold, draining the tank and repeating this cycle, the overall heat transfer coefficient U changes to 0.4 for two cycles, equivalent to that of hydrogen gas (Figure 49).

A relationship to predict transient heating rates during the 4.5-hour orbital time of the S-IV-B stage has been developed (Figure 50). The mean temperature of the insulation varies between -170°F and -350°F.

EXTERNAL FOAM INSULATION—GAS-PURGED

An external gas-purged foam insulation for cryogenic tankage must be covered with some form of vapor barrier or shroud. The space between the tank wall and the shroud is ordinarily purged with helium gas to eliminate air condensation. Helium gas, because of its low boiling point (-452.1°F), remains gaseous even adjacent to liquid hydrogen (B. Pt. -423.2°F). Unfortunately, the insulation then has the approximate thermal conductivity helium ("K" = 0.7 - 0.8 Btu/hr-ft^2-°F).

If the insulating system combines multiple radiation shields with a foam layer both perform best in vacuum. The purge gas concept eliminates some of the vacuum problems; however, its poor thermal conducitivity limits the system.

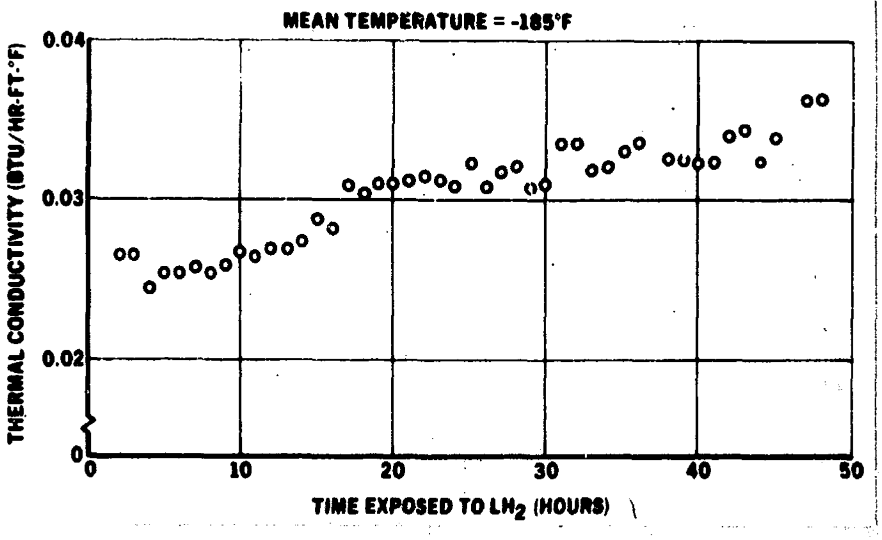

Figure 49.—Saturn S-IVB LH_2 tank internal insulation thermal conductivity.

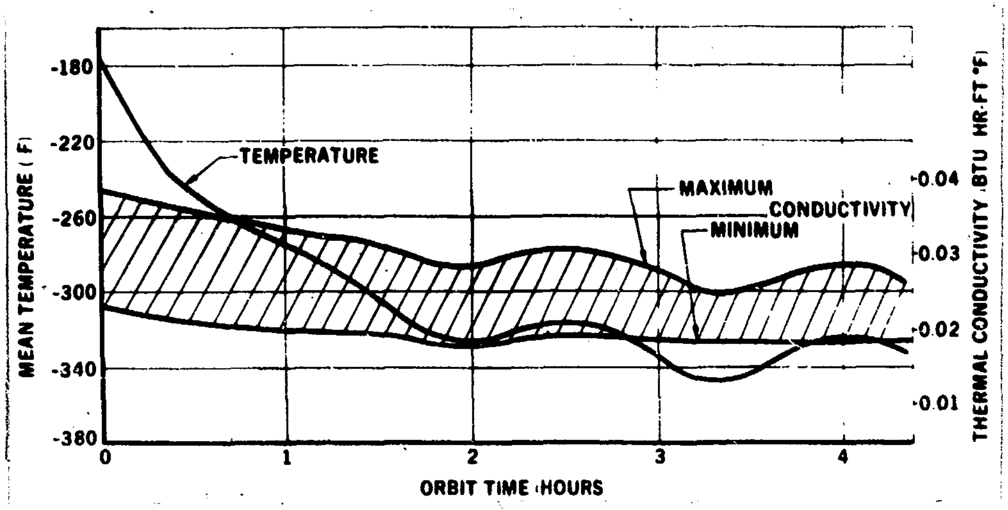

Figure 50.—Saturn S-IVB LH_2 tank insulation temperature and thermal conductivity.

External Insulation for the S-II Vehicle

The insulation for the S-II stage of the Saturn V vehicle is external and purged with helium gas.[7] Purging overcomes two problems, first the cryopumping of air through minute holes in the outside surface laminate and through inadequately sealed areas and, second, the possible presence of liquid oxygen, caused by fractionation of cryopumped air. The foam is LOX-incompatible, and the cryopumped air, on vaporization, expands 800-fold, so damage could occur.

The insulation is a 1.6-inch thick HRP (heat resistant phenolic) honeycomb core with a 3/4 inch cell size and 1.9 lbs/ft^3 density. The cells are filled with 2 lbs/ft^3, Freon-blown, rigid polyurethane foam (CPR-9005-2 DAC).

The foam cell size is less than 1/32 inch diameter. The polyurethane foam is a polyether type based on a polymethylene polyphenyl-isocyanate. The foam material is produced by a one-shot process in block form. The foams have excellent flame-retardant properties and remain stable at high temperatures.

The CPR-9005-2 DAC foam has sufficient rigidity to permit pressing the foam into the honeycomb cells without tearing.

The outer shroud is 0.002-inch Tedlar film, heat sealed to a two-ply nylon-phenolic laminate. The laminate is bonded to the core with an epoxy-phenolic adhesive. The thermal conductivity of the system without helium purging is 0.25 Btu-in/ft^2-hr.-°F.

Aerodynamic heating at a major surface may cause the temperature to rise to +365°F during the flight time of about 190 seconds. In contrast, the inside tank temperature is at -423°F, so there is a temperature differential of about 790°F across a 1.6-inch thickness. In localized regions, where shock waves may boost the temperature to 700°F, a thicker section of foam of even smaller cell size than the 1/32 inch diameter is applied.

Thermal stability of the foam material is thus of considerable importance. A characteristic temperature-time profile of the insulation surface is shown in Figure 51. The foam functions by storing heat and transmitting it at an acceptable slow rate for the 190 seconds boost period.

The temperature effect on the external insulation of the S-II after launch is not as severe as for an upper stage with a longer flight time. The S-II is to be fired immediately after the S-I-C firing which has a duration of about 155 seconds. Thus, the total flight heating time for the S-II is approximately 345 seconds.

The communication required between the honeycomb cells for the helium purge was provided by saw cuts 1/16 inch wide and 3/16 inch deep into the walls of the honeycomb adjacent to the tank. These slits, on 3/4 inch centers, were made in the X- and Y-axes, forming an intersecting manifold network.

The cuts (a) provide a helium path for purging, (b) keep the pressure differential at a minimum, (c) permit leak detection, and (d) provide insulation.

For the primary insulation of the S-II, polystyrene bead board has been suggested. The thermal efficiency and cost weight data are attractive but the aerodynamic heat generated in the airborne trajectory and the low heat distortion temperature could eliminate this material.

The original insulation concept for the S-II booster was a composite of rigid polyurethane foam (2 lbs/ft^3) supported in 3/4-inch cell size, fiberglass, phenolic honeycomb core and bonded to the exterior of the liquid hydrogen tank wall. The initial design minimized hydrogen boil-off. Subsequent data and analysis by NAA (S&ID)[8] on stratification in liquid hydrogen necessitated redesign to limit heat leak during the boost phase. In the redesign, the foam fill was reduced to 40-50 percent of the honeycomb volume. The remaining foam was disposed at the center of each cell, gaseous helium occupying the space on either side of the foam (Figure 52). This appears to involve a new technique for insertion of the premolded foam. The fuel saving gained by this weight reduction is considerable since one pound of structural weight is equivalent to 50 pounds of fuel.

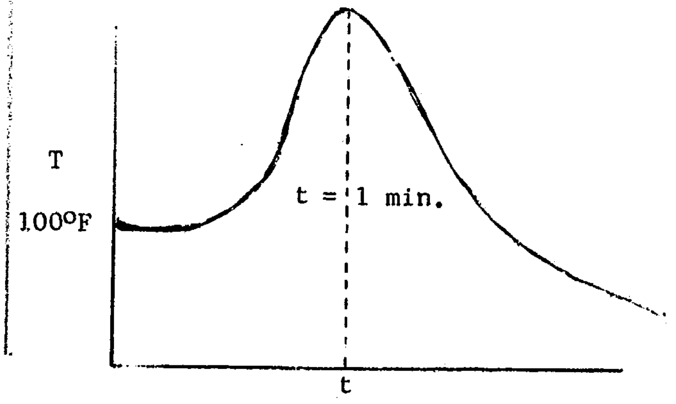

Figure 51.—Illustration of temperature-time profile for S-II insulation during boost.

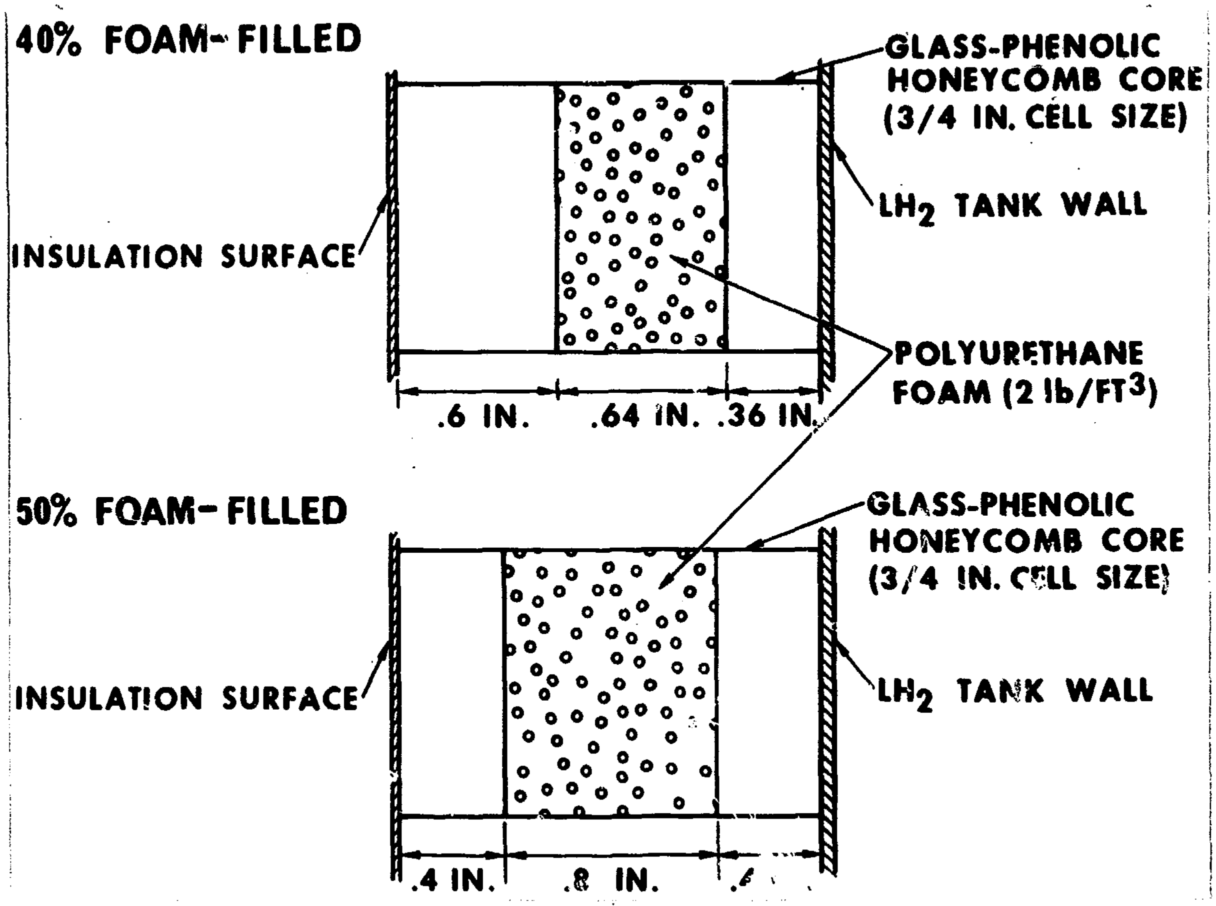

Figure 52.—Optimized 40 and 50 percent partial-foam insulation.

The design study included development of a mathematical model for thermal conductivity of partially foam filled honeycomb. Samples were evaluated in a thermal conductivity apparatus. Experimental values of effective thermal conductivity of 1.2 - 1.3 Btu-in/ft^2-hr.-°F, for a 40 percent foam-filled honeycomb, were obtained, confirming the theoretical analysis.

The foam was installed in the center 0.8 inch of 1.6-inch high fiberglass phenolic honeycomb core having a cell size of 0.75 inch. The remainder of the cells were flooded with helium gas to avoid the combustion hazard of cryopumped liquid oxygen from potential leaks in the Tedlar-nylon phenolic outer barrier. The partially foam-filled honeycomb cells gave a "K" factor substantially the same as for helium gas ("K" for helium—1.1 Btu-in/ft^2-hr.-°F at a mean temperature of 145° F). Leaks can be located in the outer barrier when "sniffed" with a helium detector.

EXTERNAL FOAM INSULATION—SEALED

The following section describes cryogenic insulation when the foam, within an impermeable membrane, is attached outside the LH_2 tank to function without a gaseous purge.

The use of low-density polyurethane foams in sealed cryogenic insulation systems, such as the Centaur lightweight insulation, has been investigated by Goodyear Aerospace Corporation.[9] The objectives were to optimize the material, the configuration, and the vapor-barrier seal. The investigations covered (1) optimum hole pattern in the perforated foam, (2) outgassing characteristics, (3) effects of cell structure, and (4) compression characteristics. The helium permeability of vapor barrier films and adhesives was measured by mass spectrometer techniques.

Outgassing Characteristics

Goodyear analyzed foam for outgassing characteristics, to develop optimum techniques for preconditioning the foam. Outgassing is important when foams are installed as sealed insulation and subject to vacuum from cryopumping. The tests included vacuum conditioning at room and elevated temperatures and alteration of foam formulations to eliminate constituents which would outgas at vapor pressures of 10^{-4} torr or less. The weight-loss equipment consisted of an automatic recording vacuum balance, pumping system, specimen chamber, and vacuum-monitoring gauges.

The test samples, 2-inch x 8-inch in area, varied from 0.020 to 0.060 inch in thickness. The specimens were preconditioned for 16 hours at 75°F and 45 percent relative humidity. Vacuum was reduced stepwise and weight loss recorded for one hour. Elevated temperature test samples were maintained at 300°F during the vacuum cycle. Preliminary tests reduced the rigid polyurethane foam candidates to four:

(1) 2 pf.^{3} white closed cell by GAC (Goodyear Aircraft Corp.)
(2) #107754-3, 2.31 pf^3 open cell by Mobay Chemical Co.
(3) #107754-7, 2.18 pf^3 open cell by Mobay Chemical Co.
(4) 1S1080, 1.7 pf^3 open cell by Upjohn Co., Carwin Division.

The results are summarized in Table 31. A typical outgassing weight loss curve for Mobay Chemical Co. #107754 foam is shown in Figure 53. The greatest weight loss occurs in the 500 micron to 10 micron pressure range. By the time 10^{-4} to 10^{-6} torr is reached, all the volatiles appear to have left the system. Foams exposed to both vacuum and temperature environments experienced greater weight losses.

Effects of Foam Cell Structure

During Goodyear's evaluation it was noted that reticulated flexible foams possess an almost ideal cell structure. It is so open that preinstallation outgassing is easy. Several attempts were made to rigidize the flexible foam structure by impregnation with rigid polyurethane varnish and other agents. This approach was later abandoned in favor of finding a suitable rigid open-cell formulation. Radiation cross-linking was not considered.

Table 31.—Summary of Foam Weight Loss Measurements Due to Vacuum Preconditioning at Room Temperature and 300°F

Foam	GAC		Mobay #107754-7		Mobay #107754-3		Carwin #TS1080	
Test condition	Vacuum only	Vacuum +300°F	Vacuum only	Vacuum +300°F	Vacuum only	Vacuum +300°F	Vacuum only	Vacuum +300°F
Weight in air (mg)	2695.2	2681.76	3609.7	3548.7	Did not run	3518.2	3270.5	3257.8
Finish weight (mg)	2662.92	2622.75	3586.3	3458.51		3449.7	3225.1	3179.7
Weight loss (mg)	32.28	59.01	23.4	63.19		68.5	45.4	60.1
% weight loss	1.21	2.18	0.654	1.78		1.92	1.39	1.85
Weight after N2 backfill (mg)			3484.28			3448.42		

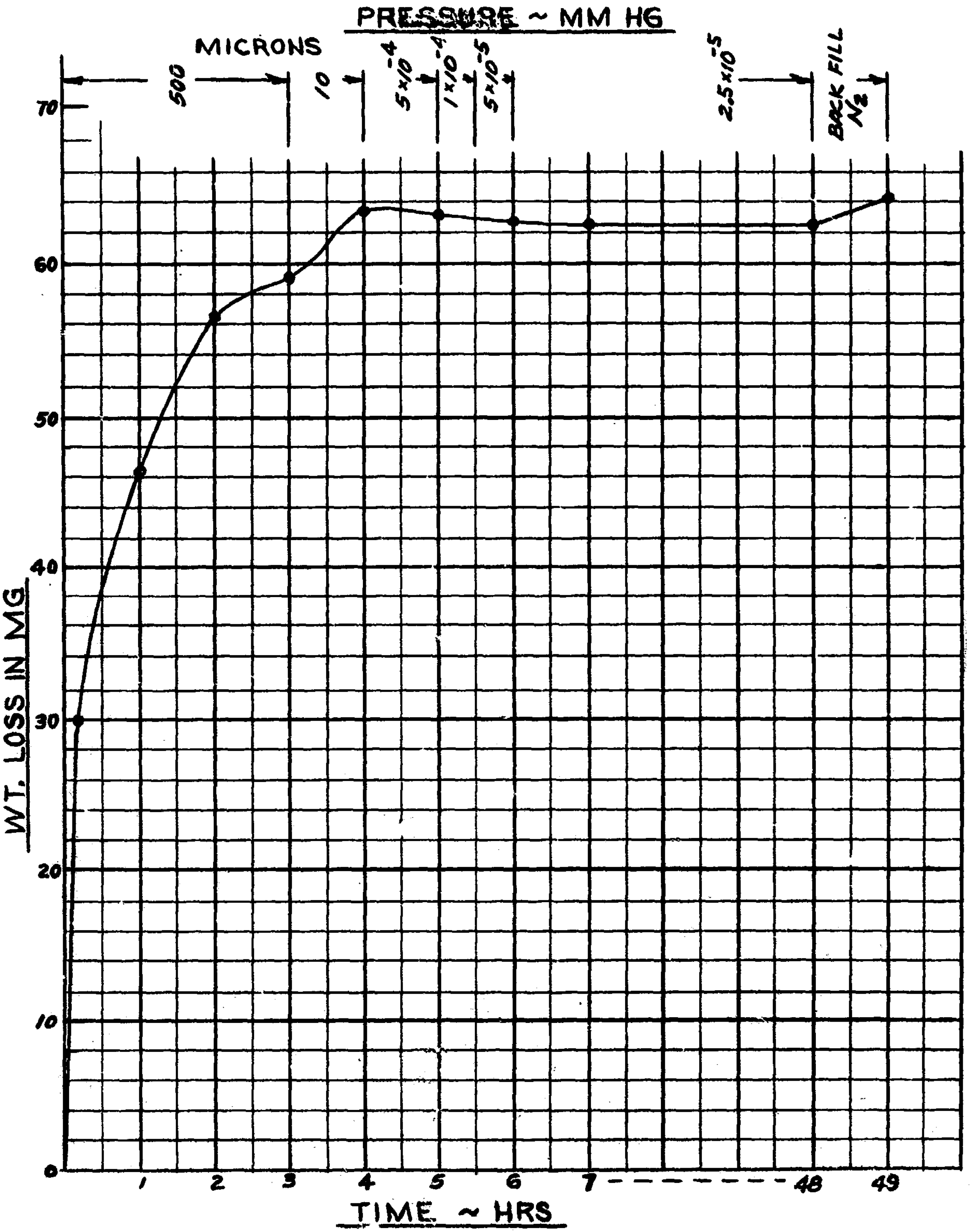

Figure 53.—Mobay Chem. No. 7—300°F (temp. increased ambient to 300°F in 1st hr).

A survey was made of available open-cell foams to determine if a rigid polyurethane foam could be formulated which would eliminate volatile reactants. It was concluded that little or no outgassing of the urethane polymers occurs; resins present are thoroughly reacted into polymer. Hence, the weight loss would be more properly attributed to catalysts and nonreactive stabilizers present. To reduce outgassing, tertiary amine catalysts could be substituted by less volatile catalysts, such as dibutyl tin dilaurate. The nonreactive, vacuum-volatile foam cell stabilizers, such as the silicones, might be replaced by a hydroxy-substituted silicone that can be tied into the polymer. A blowing agent, whether Freon or carbon dioxide, when trapped in a closed cell can diffuse slowly through the cell walls, especially in a vacuum. An open-cell foam does not have trapped cell gas.

The Corwin Division of the Upjohn Company and the Mobay Chemical Company supplied rigid, polyurethane foams having 90 percent open cells. However, the cells were open by virtue of ruptured cell walls, rather than by the completely removed cell walls of a reticulated foam. The Mobay foam proved to have the best physical properties, obtained by adding a small amount of aluminum flake to a rigid foam formulation. The best molding characteristics were found in the Mobay formulation shown in Table 32. The choice of stabilizer, level of stabilizer, and level of aluminum are decisive factors in noncollapsing, open-cell foam. The molded material could be cut into thin slices without crumbling.

Compression Characteristics

The compression deflection characteristics of candidate foam materials were evaluated for test samples with alternating layers of 0.020"-thick foam slices and 1/4-mil aluminized Mylar. The stack was 0.350" thick, measured 2" x 2" in area, and consisted of ten layers of foam and nine layers of aluminized Mylar.

Five foam-film composites were compression and thermally cycled. These included:

Table 32.—Mobay Formulation

Component 107754-7	Parts by weight
PeP 450, polyol	100.0
Freon 11 blowing agent	30.0
L 530 stabilizer	2.0
TMBDA catalyst	1.5
#422 aluminum flake cell opener	1.0
Mondur MR isocyanate	136.0

GAC white 2 pf^3 rigid polyurethane Mobay Chemical #107754-7 - open cell rigid polyurethane
Mobay Chemical #107745-3 open cell rigid polyurethane
U.S. Gypsum "Zero Cell" 1.7 pf^3 rigid polyurethane
Carwin Chemical #TS 1080, open cell rigid polyurethane

The room-temperature compression-load-deflection curves for Mobay Chemical #107754-7 urethane are shown in Figure 54, low temperature (-320°F) and room temperature load deflection characteristics in Figure 55, and ultimate compressive strength in Figure 56. Yield point at -320°F was approximately 32 psi. This is slightly greater than twice the maximum pressure on self-evacuation insulation panels.

Vapor-Barrier Materials and Fabrication Techniques

Maximum permeability allowable for a vacuum jacket was 2.2×10^{-10} cc helium per second per square inch at standard conditions. Permeability data for vapor-barrier material selection are listed in Table 33.

The test fixture shown in Figure 57 was used with a mass spectrometer to determine the helium leakage through the seam of a 3-inch back-to-back adhesively bonded joint. These data are presented in Table 34.

EXTERNAL FOAM INSULATION—NON-POROUS, SEALED, CONSTRICTIVE WRAP

During launch, the constrictive-wrap sealed-foam insulation system of the Centaur vehicle is exposed to aerodynamic heating and erosion. A sector tank installation was conceived to test the insulation in the NASA Lewis Research Center 8' x 6" wind tunnel under flight conditions. Two opposite sections from a 60-inch radius tank wall, approximately 4' x 5', were brought together and faired to resemble an airfoil section in general appearance.

Constrictive-wrap sealed-foam insulation panels were fabricated by Goodyear Aerospace Co., conforming to the 60-inch sector tank.[10]

The tank top was insulated with a 0.4-inch-thick sealed panel covered with 0.56-inch-thick polyurethane unsealed foam built up to simulate a fairing to encapsulate a wiring harness under the constrictive wrap. The tank bottom was covered with four identical rectangular panels of 0.4-inch-thick sealed polyurethane foam.

The constrictive wrap was an 8-end S/HTS fiberglass epoxy prepreg roving applied by filament winding at a 6° helix angle with 0.25 inch spacing between the rovings.

High temperature blister tests were performed on Freon-blown and water-blown 2 lb/ft^3 density, rigid polyurethane core stock, with and without post curing. A 15-inch cubic block of each foam was poured and cured for one hour at 180°F. The water-blown foam was additionally cured for two hours at 275°F. Both blocks were split and half of each block was post cured as follows: 150°F, 4 hours; 230°F, 8 hours; 300°F, 8 hours. The blocks were then sawed into slabs and 0.4" x 10" x 10" sealed-foam test

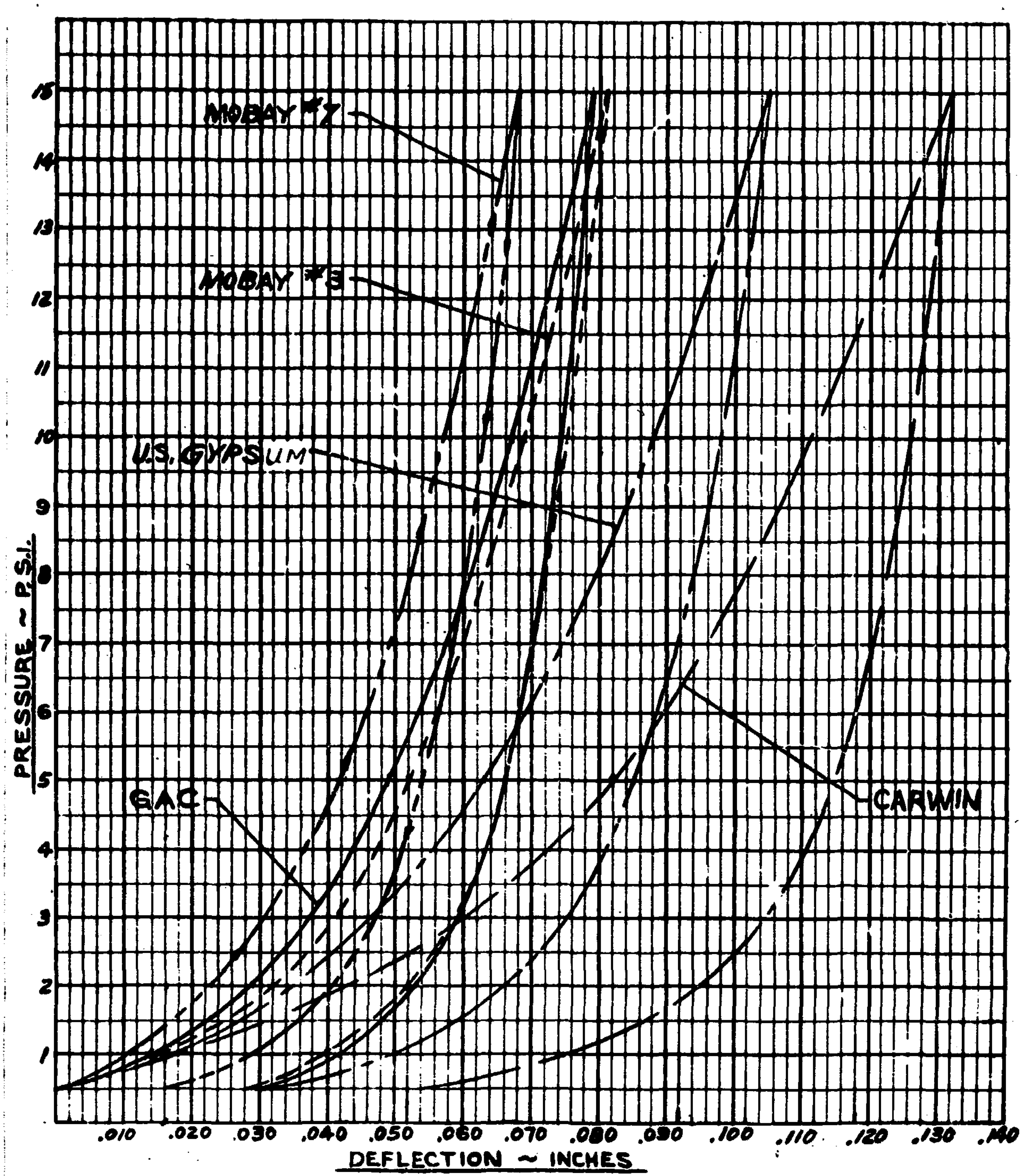

Figure 54.—Typ. compression load–deflection curves foam and film at room temp.

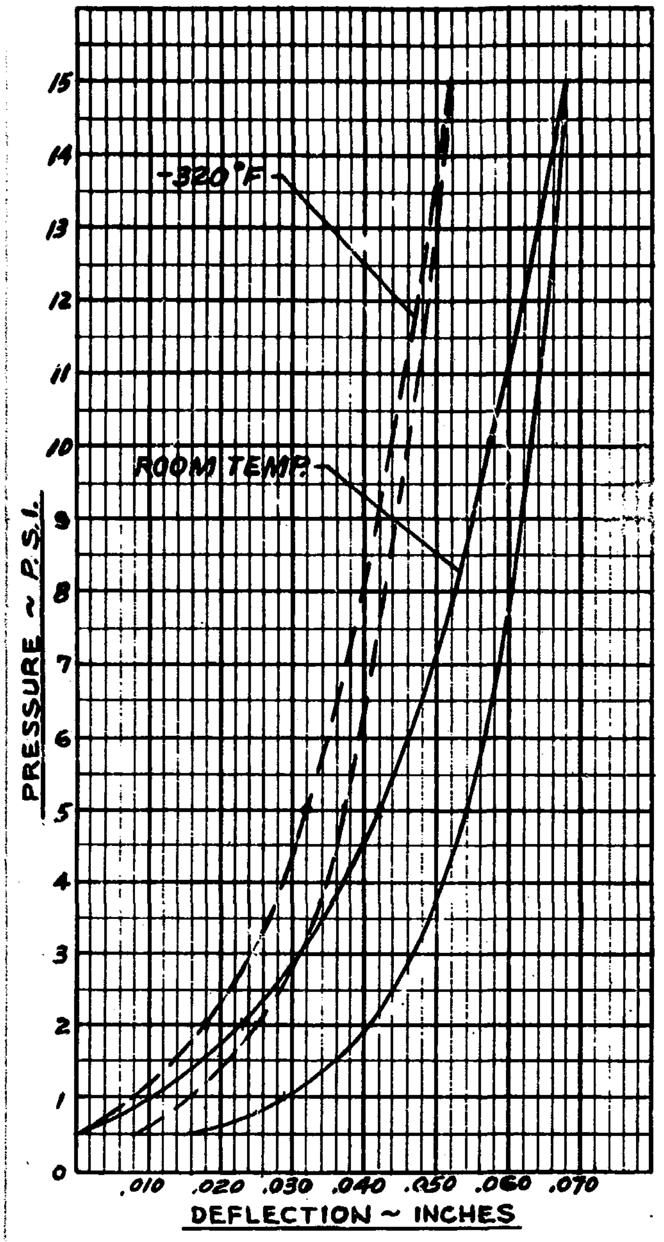

Figure 55.—Typ. compression load—deflection curves Mobay #7 foam and film at -320° F and room temp.

panels were fabricated. The 2-psi constrictive wrap load on the panel was simulated by vacuum bagging the panel with PVA film applied over fiberglass bleeder cloth and decreasing the pressure by 2 psi. Panels were placed in a circulated-air oven. A push rod and dial gauge operating outside the oven contacted an aluminum plate, which was placed over the bagged assembly, indicated blisters which formed.

The Freon-blown panel, without a post cure, blistered and showed a 10-percent-thickness thermal expansion. The postcured, Freon-blown panels expanded 7 percent in thickness, but did not blister. The postcured water-blown foam panel shrank 7-percent which would cause some loss in tension. Therefore, postcured Freon-blown rigid polyurethane foam having a density of 2 lbs/ft^3 was chosen for the sector panels.

All areas not covered by sealed insulation panels were covered by laminating two layers of 16-lb/ft^3 sheet cork. The cork was vacuum bagged and bonded to the tank using Epon 828 (65 parts), Versamid 125 (35 parts), and curing at room temperature.

All sealed-foam insulation was tested for leak tightness after covering with MAM (1/2 mil Mylar-Aluminum-1/2 mil Mylar) by immersion for 5 minutes in liquid nitrogen.

The panels were bonded to the tank wall with a 5-inch grid-pattern glue line of Narmco 7343/7139 polyurethane adhesive by vacuum bagging and curing for sixteen hours at room temperature. The insulation on the sector tank is shown in Figure 58. The constrictive wrap roving at 2 psi provided 2 psi normal load to the insulation and an 0.88 strain in the glass roving. An edge view of the finished tank is shown in Figure 59.

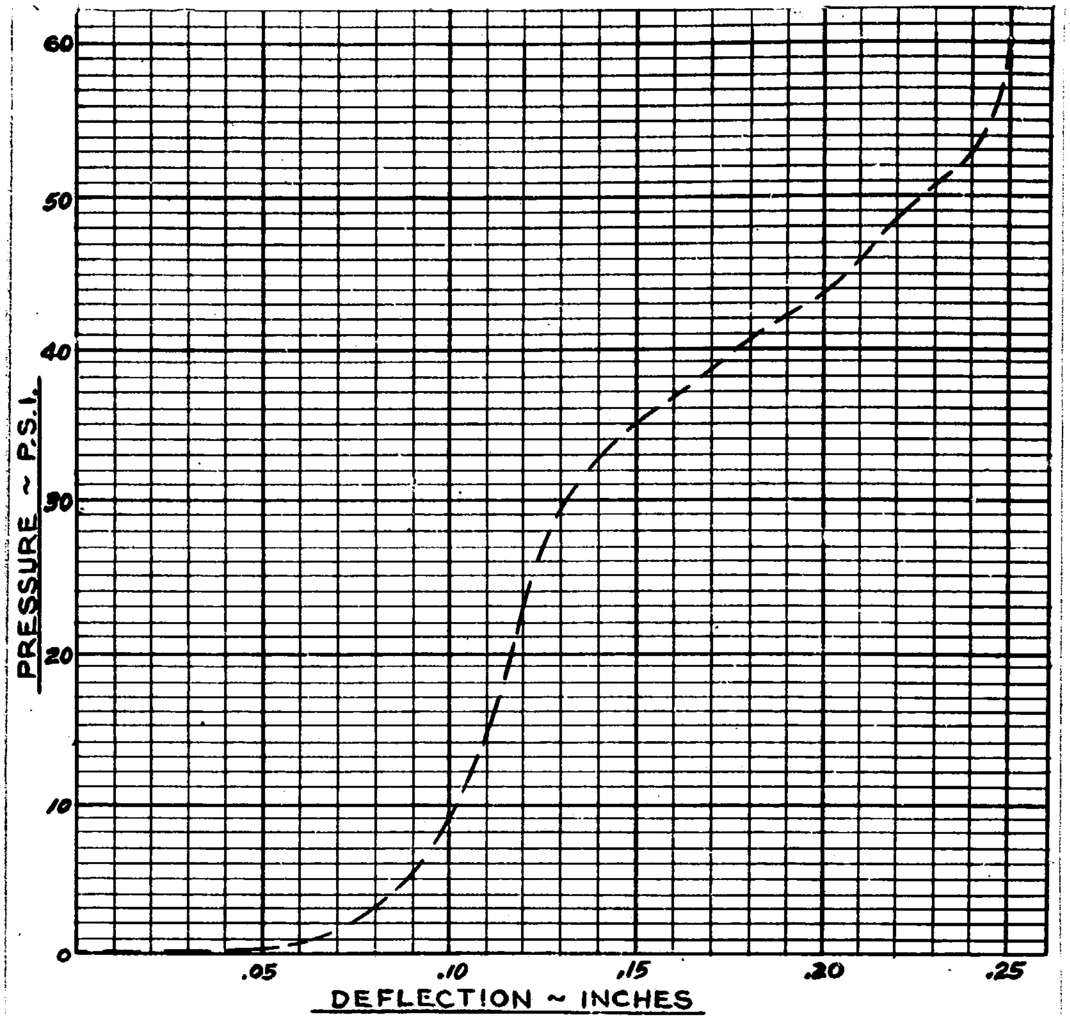

Figure 56.—Ultimate compression curve Mobay No. 7 foam and film at -320°F.

EXTERNAL FOAM INSULATION—SEALED, CONSTRICTIVE-WRAPPED, JETTISONABLE

Goodyear Aerospace Co. investigated jettisonable insulation, which was fabricated for a 60-inch radius sector tank for the Centaur. Flexible, linear-shaped charges were incorporated to sever the fiberglass constrictive wrap which secured the tank insulation. The construction and material were the same as for constrictive wrap, except for placement of the shaped explosive charges and an expeller bag of Mylar-Dacron placed within the MAM envelope. The latter may be inflated simultaneously with the firing of the flexible linear-shaped charge and the attendant cutting of both the MAM moisture-vapor sealing envelope and the fiberglass constrictive wrap. The external appearance of the jettisonable sealed insulation was identical to the wind-tunnel segment tank previously illustrated except for the absence of the external thermocouple leads.

Table 33.—Vapor-Barrier Data

Material	Construction	Source	Thickness in.	Weight lbs/ft^2	Helium permeability cc/sec-in^2
MAAM	1/2-mil Mylar, 0.35 mil aluminum, 2-plys, Type 34322	Dobeckmun Co.	.002	.0187	1X-10^{-10}
MAAM	1/2-mil Mylar, 0.35-mil aluminum, Type 34322	Dobeckmun Co.	.0027	.023	1X 10^{-10}
MLM	1-mil Mylar, 0.8-mil lead	G.T. Schjeldahl Co.	.0047	.0703	2.7×10^{-10}
MAM	1/2-mil Mylar, 1/2-mil aluminum, 1/2-mil Mylar	Continental Co.	.0017	.0132	8.2×10^{-10}

Table 34.—Vapor-Barrier Adhesive Seam Data

Material	Adhesive	Cure	Helium permeability cc/Sec/14.7 psi
MAAM	Goodyear G-207, 3" seam length	Heat seal 275°F by hand iron	1.2×10^{-9}
MAAM	Adiprene L100/Moca, 3" seam length	16 hrs. room temperature	1×10^{-10}

EXTERNAL FOAM INSULATION—SEALED CONSTRICTIVE-WRAPPED—FOR FULL-SCALE CENTAUR TANK

The object of this program was to develop, fabricate and install a sealed, lightweight, vapor-tight, foam-jacketed insulation system on the exterior surface of an experimental, full-scale Centaur liquid hydrogen tank[12] approximately 10' diameter x 24' long. Preliminary investigations dealt with materials selection, fabrication techniques, wrapping, etc.

The full-scale Centaur tank required twenty sealed-foam insulation panels to cover the cylinder wall. Eight panels contained protuberances and had to be hand tailored in the areas where bosses extended through the insulation.

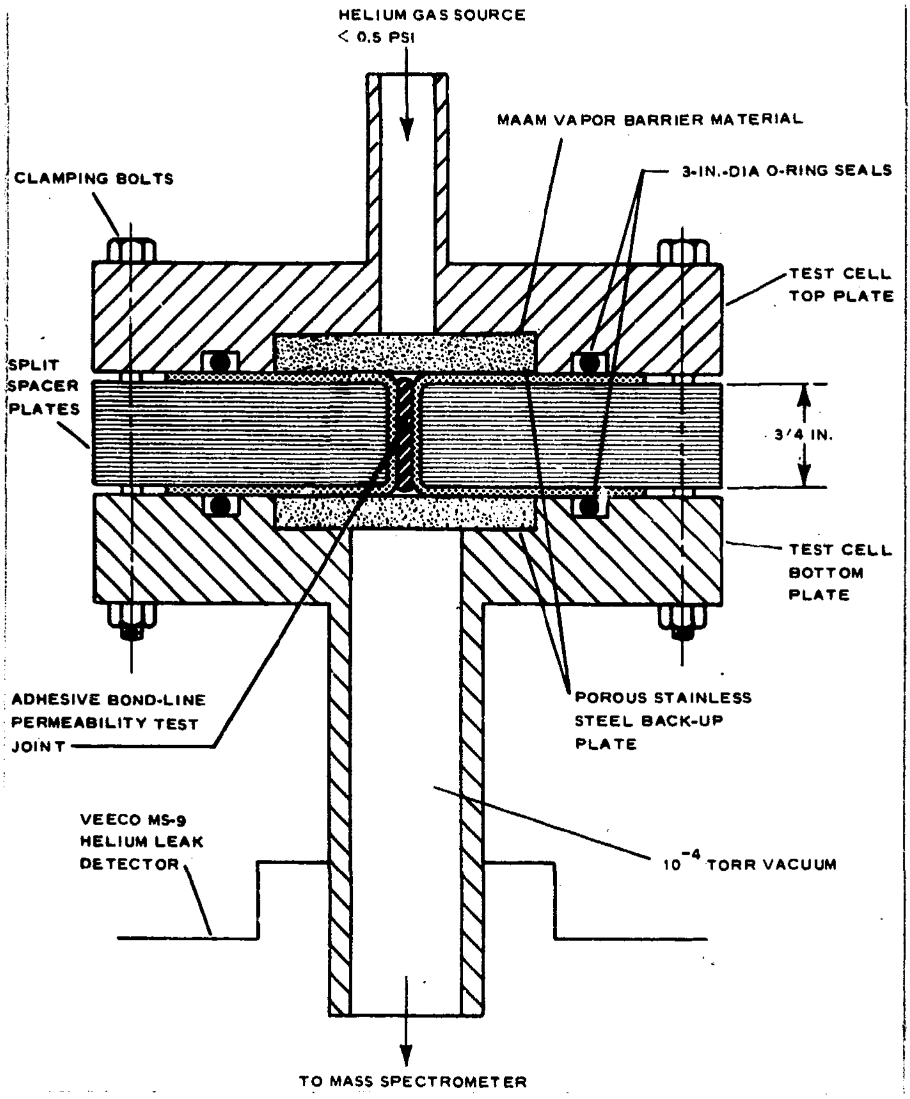

Figure 57.—Helium leak-detector technique for evaluating vapor barrier seams.

Both Freon-blown and carbon dioxide-blown foam, having a density of 2 lbs/ft^3 were evaluated. The Freon-blown foam was chosen for the full-scale tank insulation. Formulations and typical properties of the two types of foam are given in tables 35 and 36. The Freon-blown foam has better handling characteristics, dimensional stability, and a lower "K" factor.

While several constructions were evaluated for encapsulating the foam, 0.0015 Mylar-aluminum-Mylar barrier film was chosen because it had satisfactory properties and was of minimum weight. A 0.002-inch Mylar film was used as the edge channel about the perimeter of each panel. This material also proved to be adequate for cap strips and doublers between adjacent panels.

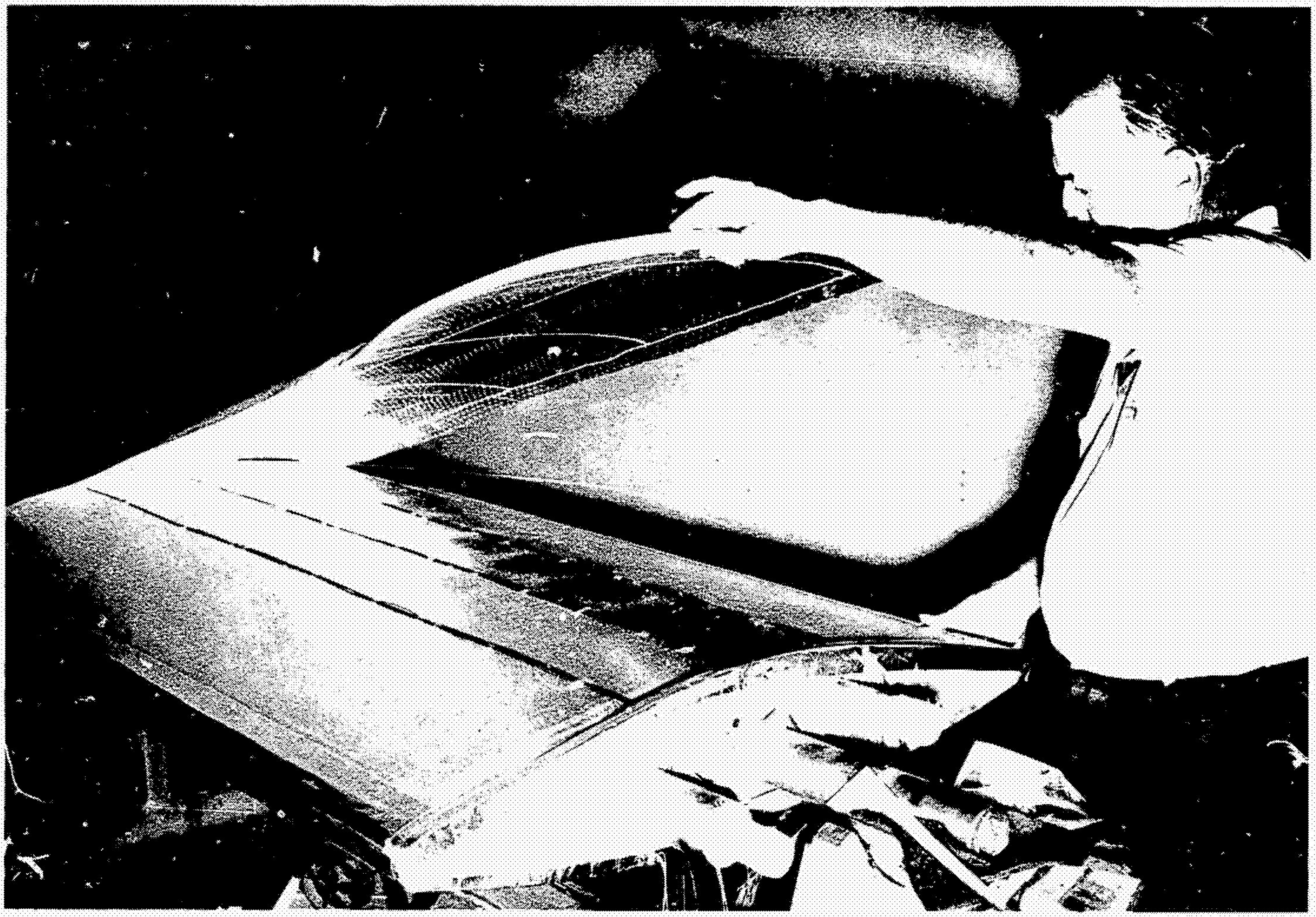

Figure 58. —Installation of wiring harness panel.

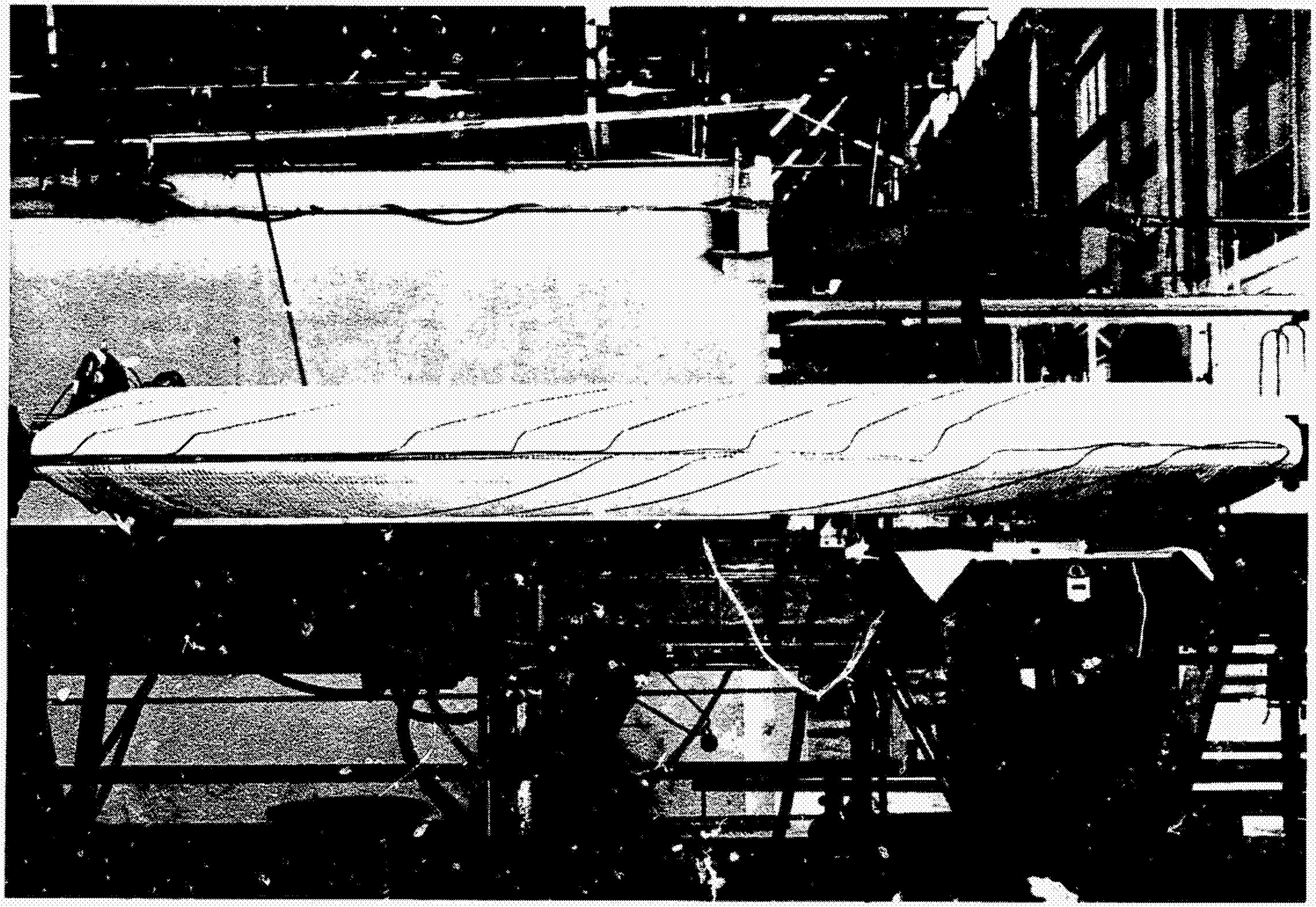

Figure 59. —Edge view of completed constrictive wrap showing typical routing of thermocouple wires.

Table 35. —Typical Rigid Foam Formulations

Material	Supplier	Parts per hundred	
		Freon-blown	CO_2-blown
PFR6, polyester resin	Allied Chemical Corp	100	100
Dabco 33LV, amine catalyst	Houdry Process Corp	0.6	0.6
L-521, silicone surfactant	Union Carbide Corp	1.5	1.5
Water	. . .	...	5.0
RCR5043, TDI prepolymer	The Glidden Co.	110	183
R-11, Freon blowing agent	E. I. duPont de Nemours and Co.	30	...

Table 36.—Physical Properties of Gas-Blown Foams

Property	Freon-blown	Carbon dioxide blown
Density, pcf	2.0	2.0
Heat transfer (k) factor (Btuh/sq ft/F/in.)	0.14	0.22
Closed cells, percent	90.0	85.0
Tensile strength, psi	60.0	58.0
Compression strength, psi:		
10-percent deformation	47.0	32.0
30-percent deformation	45.0	28.0
Yield point	46.0	30.0
Heat distortion temperature, fahrenheit	250.0	300.0
Dimensional stability	Superior	.....
Handling ease	Superior	.....

The Mylar-aluminum-Mylar vapor barrier was bonded with Vitel (Type PE 207, a heat-sealable polyester adhesive by Goodyear Tire & Rubber Co) to the rigid polyurethane panels which were cut to 0.400-inch (±0.008 inch) thickness from 99- by 42- by 10-inch foam blocks. A back-lighted glass table was used to determine the uniformity of foam structure. Density was held to 1.8 to 2.0 lbs/ft^3.

Narmco polyurethane adhesive system 7343/7139 was applied over Vitel PE 207 which acted as a primer on the surface of the tank. This served to insure a vapor tight bond and prevent cryopumping of air.

Precut foam filler strips were found most effective for insertion in joints between adjacent panels since problems of dimensional stability and density control proved troublesome using foam-in-place techniques.

The constrictive wrap for attaching the insulation panels on the Centaur tank consisted of S/HTS fiberglass roving applied as a cinch wrap. The tension was held at greater than two pounds during filament winding to provide a 2-psi load normal to the insulation panel and an 0.88-percent strain in the glass roving. The effect of protuberances on the pattern of helical wrap is shown in Figure 60.

Based upon estimated weight, the polyurethane foam constituted 38 pounds of the 81.65 pounds of gross weight of the insulation panels.

EXTERNAL FOAM INSULATION—SEALED, CONSTRICTIVE-WRAPPED FOR LIQUID HYDROGEN TANKS OF BOOST VEHICLES

Full-scale qualification tests for the external insulation system for Centaur liquid hydrogen tanks have been conducted by Lewis Research Center.[2] A comparison is made below between the insulation performance and payload weight characteristics of the lightweight, nonjettisonable insulation system and a flight-tested jettisonable insulation.

Insulation Performance Under Thermal Conditions of Boost Phase

An experimental investigation based upon a computer study of a typical Atlas-Centaur trajectory. Calculations were made of the heat flow into the insulation and, the liquid hydrogen propellant.

Two insulations were examined, a jettisonable insulation and the lightweight, sealed, nonjettisonable insulation. The sealed, wrapped insulation was a 0.4-inch-thick foam panel covered with a laminate of aluminum and Mylar, with a 0.0005-inch layer of Mylar on each side of a 0.0005-inch layer of aluminum. The laminate was assumed to have a density of 115 pounds per cubic foot, a specific heat of 0.25 Btu/lb/°F, and a thermal conductivity of 1.548 Btu-in/ft^2-hr-°F. The foam core was assumed to have a density of 2 lb/ft^2, a specific heat of 0.4 Btu/lb/°R, and a thermal conductivity varying with temperature according to the upper boundary of the region shown in Figure 61.

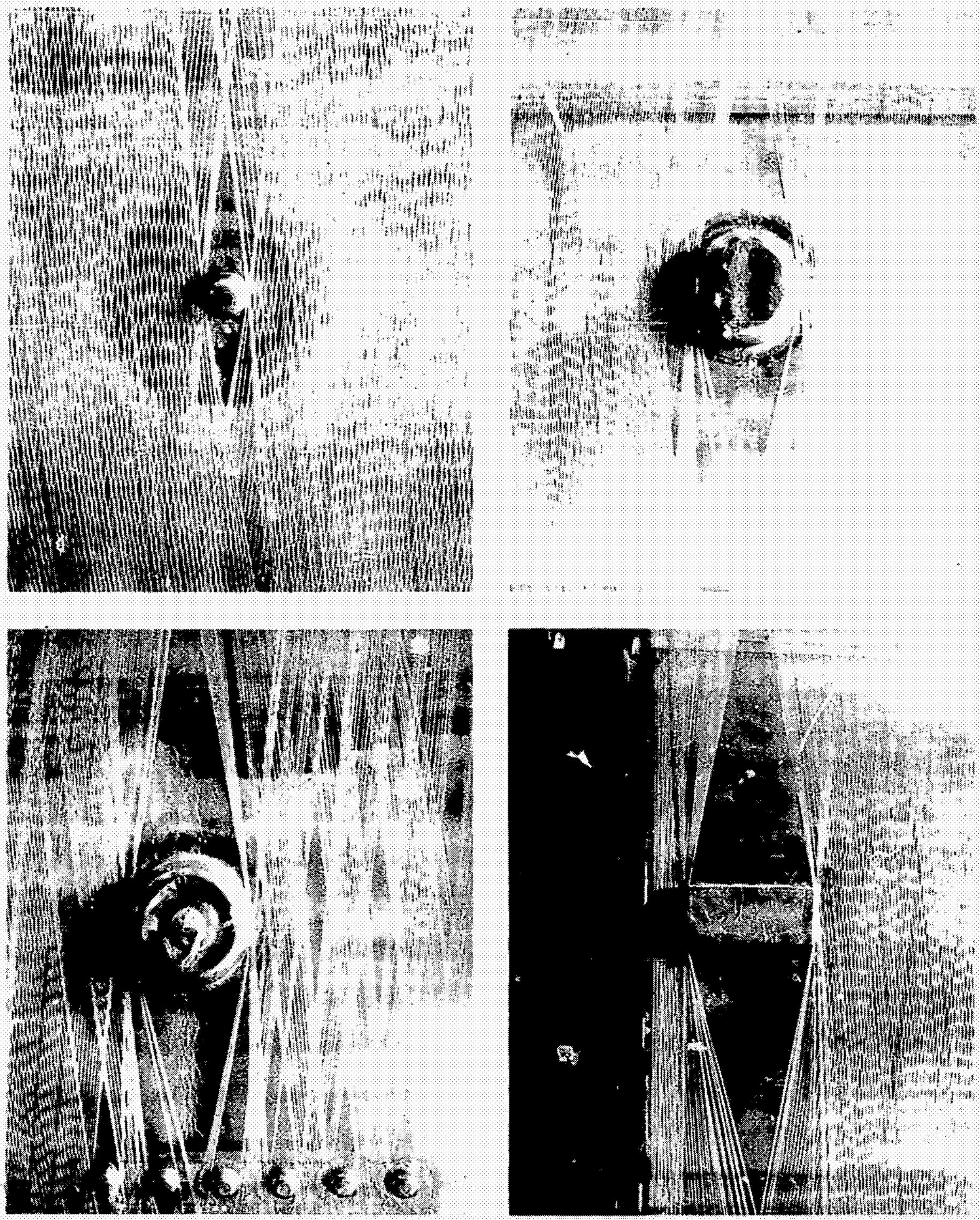

Figure 60.—Effect of protuberances on helical wrap.

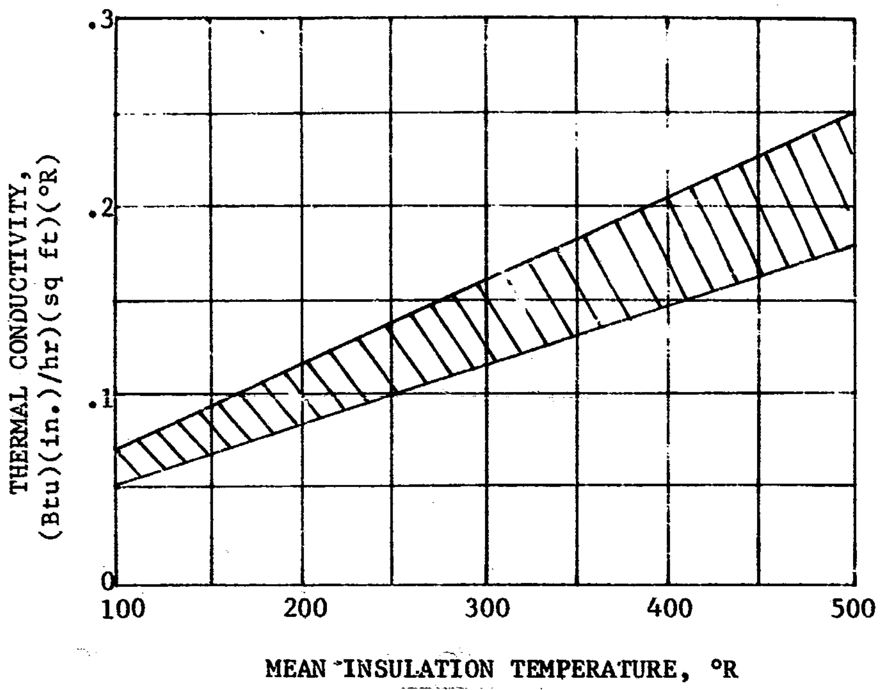

Figure 61.—Thermal conductivity range of polyurethane foam as function of mean insulation temperature.

Centaur Flight Model Insulation System

The jettisonable insulation was assumed to be 1.0 inch thick foam-filled honeycomb structure with faces of 0.015 inch fiberglass laminate. The foam core was assumed to have a density of 4.2 lb/ft^3 and specific heat and thermal conductivities as given in Table 37. The fiberglass laminate was assumed to have a density of 120 lb/ft^3 and the specific heat and thermal conductivity listed in Table 38. The tank wall was assumed to remain at liquid hydrogen temperature. The insulation was assumed to be separated from the tank wall by a 0.1 inch helium-filled gap. A heat-transfer coefficient of 2.56 Btu per hour per square foot per °R was used for the heat flow across the helium gap. At 173 seconds, the insulation was assumed to be jettisoned.

In making calculations for both insulations, an initial wetted area of 485 square feet was used. A length of 10 feet was used in determining the Reynolds number for the aerodynamic heat-transfer coefficient. Figure 62 shows heating rate incident on the outer surface of the sealed, wrapped insulation due to aerodynamic heating, plus averaged radiant heat from the sun. Also shown are the heat radiated away from the surface of the insulation and the net heat that actually enters the insulation.

Because of the thermal lag, not all of the heat that actually enters the insulation gets through to the liquid hydrogen on the inside. The total heat input to the hydrogen from 0 to 675 seconds was calculated to be about 13,300 Btu.

In addition to the heating rate, the temperature of the insulation is significant because of its effect on physical properties. Figure 63 shows the variation of the

Table 37.—Specific Heat and Thermal Conductivity of Foam Core

Temperature, °R	Specific heat, c_p, Btu/(lb)(°R)	Thermal conductivity, k, (Btu)(in.)/(sq ft)(hr)(°R)
40	0.283	0.037
160	-----	.147
180	-----	.162
220	.295	-----
360	.303	-----
500	.312	-----
760	-----	.503
1500	.378	-----

Table 38.—Specific Heat and Thermal Conductivity of Fiber-Glass Laminate

Temperature, °R	Specific heat, c_p, Btu/(lb)(°R)	Thermal conductivity, k, (Btu)(in.)/(sq ft)(hr)(°R)
400	0.2220	1.615
500	.2340	1.701
600	.2460	1.788
700	.2580	1.860
800	.2700	1.945
900	.2820	2.029
1000	.2940	2.122

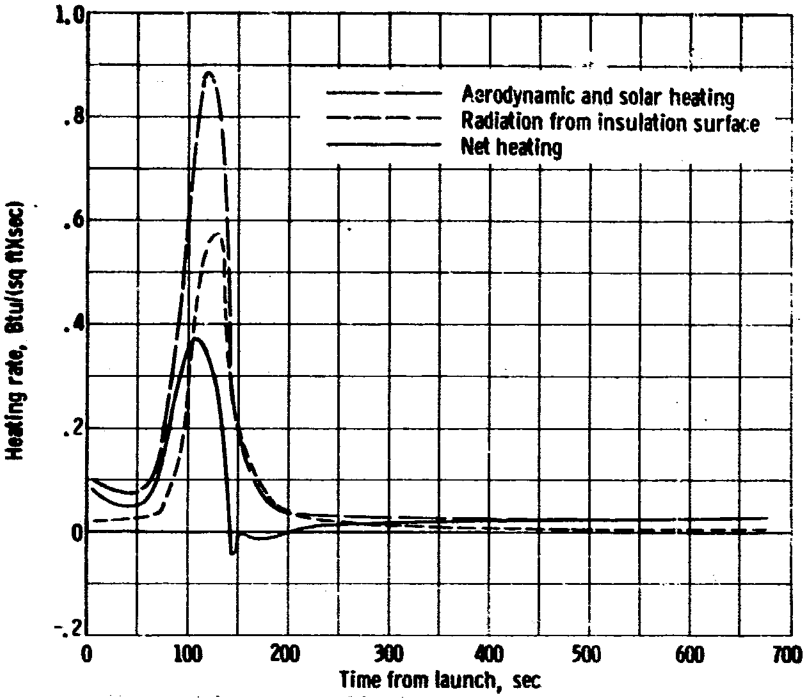

Figure 62.—Aerodynamic and solar heating, radiant heat from insulation, and net heating rate.

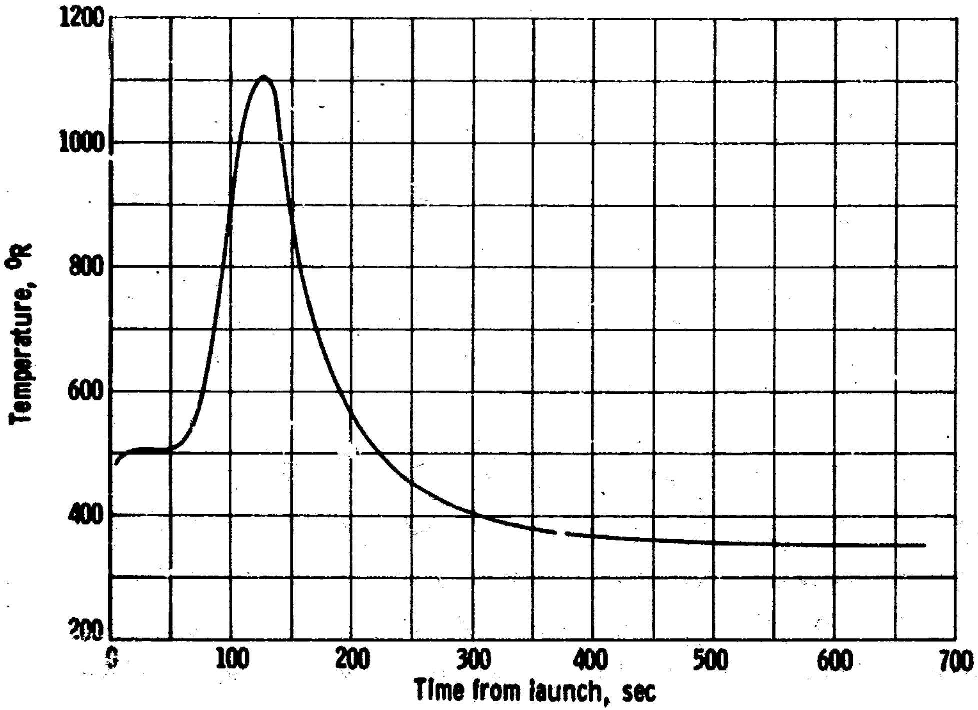

Figure 63.—Surface temperature.

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temperature of the outer surface of the insulation during the first 675 seconds of flight. The curve peaks at 127 seconds and reaches a maximum value of slightly over 1100° R. The temperature is above 800° R for approximately 65 seconds.

Dynamic pressure $(1/2)\rho V^2$ (where ρ is the local density and V is the freestream velocity), as well as temperature, is important in its effect on the durability of the insulation. The maximum values of temperature and dynamic pressure are substantially separated in time. The maximum dynamic pressure (860 lb/sq. ft.) occurs while the temperature is quite low, about 600° F. Fortunately, by the time maximum temperature is reached, the dynamic pressure is only about 17 percent of its maximum value.

The comparison analysis showed that the sealed, wrapped, nonjettisonable insulation allows more than twice the amount of heat to get into the hydrogen during the first 675 seconds of flight as does the jettisonable insulation system. The maximum possible boiloff is about 69 pounds for the sealed, wrapped insulation and about 33 pounds for the jettisonable insulation.

Thermal Conductivity Tests

Thermal conductivity tests were conducted on 0.4-inch-thick, sealed, closed-cell polyurethane foam specimens fabricated for NASA Lewis Research Center by Goodyear Aerospace Corp. A double-guarded, cold-plate, thermal conductivity apparatus, built by Arthur D. Little, Inc., under contract number NASw-615, was used. Runs were made at 2 psi and 15 psi compressive loads. The lesser pressure corresponds to the loads imposed by the constrictive wrap while the 15 psi represents loads imposed by evacuation from cryopumping. The average value of overall thermal conductivity, where the insulation panels were directly in contact with the cold plate, was 0.145 Btu-in/hr-ft^2-°R at a mean temperature of -178°F (282°R). The imposed loads of 2 and 15 psi did not significantly change the contact resistance between the sealed foam insulation and the cold plate.

Liquid Oxygen Impact Sensitivity

If a sealed panel developed a leak through the puncture of the encapsulating Mylar under cryopumped conditions, air drawn into the evacuated foam panels might condense as liquid air or even as liquid oxygen.

Drop-impact tests were therefore performed at Marshall Space Flight Center to determine compatibility or sensitivity to impact when submerged in liquid oxygen, using an impact sensitivity test apparatus (88 ft-lbs-energy).[13] The resulting data are summarized in Table 39. In tests on the basic foam material itself, only three, barely visible reactions occurred in 15 tests, indicating comparative insensitivity to impact. Also, high resistance to permeation of air through the closed cell structure would restrict cryopumping to a very localized area. Therefore, even if reaction from impact occurred, it is highly unlikely that damage beyond the immediate area would be sustained. Only one test in 40 showed a bright flash and signs of a sustained reaction. Substitution of other species of the same generic materials might not yield the same results.

Table 39.—Drop-Impact Tests on Polyurethane Foam Insulation Samples

Sample number	Group number	Sample description	Environment	Relative intensity of reaction
1	I	Plain polyurethane foam	Liquid oxygen	No visible reaction
2				Barely visible reaction
3				Barely visible reaction
4				No visible reaction
5				
6				
7				
8				
9			Gaseous oxygen	
10			Gaseous oxygen	
11	II	Polyurethane foam with MAM layers glued to top and bottom surfaces with Vitel PE 207 adhesive	Liquid oxygen	Very bright reaction with sustained combustion
12				
13				No visible reaction
14				
15				
16				
17				
18				
19			Gaseous oxygen	
20			Gaseous oxygen	
21	III	Polyurethane foam with MAM layers removed, but with some glue residue	Liquid oxygen	No visible reaction
22				No visible reaction
23				Plainly visible reaction
24				Relatively bright reaction
25				Plainly visible reaction
26				No visible reaction
27				No visible reaction
28				No visible reaction
29	IV	MAM-covered polyurethane foam with three longitudinally drilled holes under striker pin	Liquid oxygen	Relatively bright reaction
30				No visible reaction
31				Relatively bright reaction
32				No visible reaction
33	V	MAM-covered polyurethane foam with holes through sample perpendicular to MAM layers and directly under striker pin	Liquid oxygen	No visible reaction
34				No visible reaction
35				Barely visible reaction
36	VI	Plain polyurethane foam with three longitudinal holes through sample and under striker pin	Liquid oxygen	No visible reaction
37				Barely visible reaction
38				No visible reaction
39				No visible reaction
40				No visible reaction

Sub-Scale Insulated Tank Tests

In sub-scale tank tests[14] with the insulation systems developed, it was noted that design, bonding, protuberances, and panel edge seals had little effect on thermal performance. The sub-scale-test insulation values were in substantial agreement with the measurements made on flat panels.

Simulated aerodynamic heating tests were conducted with gas-stream temperatures up to 840°F and dynamic pressures up to 1300 lbs/ft^2 in wind tunnels. Four variations of the insulation system and two methods of handling the constrictive wrap around external protuberances were investigated. In general, the tests showed that this type of insulation system was applicable under operational conditions.

REFERENCES

1. Perkins, P. J. Jr.; and Esgar, J. B.: A Lightweight Insulation System for Liquid Hydrogen Tanks of Boost Vehicles. NASA LERC, Publication CP-8, AIAA Fifth Annual Structures and Materials Conference, Palm Springs, Calif., Apr. 1-3, 1964.
2. Sealed-Foam, Constrictive-Wrapped External Insulation System for Liquid Hydrogen Tanks of Boost Vehicles, NASA TN D-2685, 1965.
3. McGrew, J. L.: A Comparative Study of Air-Borne Liquid Hydrogen Tank Insulation. Martin-Marietta Corp., Advances in Cryogenic Engineering, vol. 8, pp. 387-392 (1963).
4. Boucher, K. H.: Saturn Third Stage, SIVB Manufacturing. Douglas Aircraft Co., paper presented at National Aeronautic and Space Engineering and Manufacturing Meeting, Los Angeles, Calif., Oct. 4-8, 1965.
5. Ollensis, G. H.; and Rumenopp, H. E.: Lefkoweld 109/LM-52 and Narmco 7343/7139 Bond Strength to 3D Foam at 25°C and -196°C. Douglas Aircraft Co., Report No. SM-48414, Sept. 25, 1965.
6. Dearing, D. L.: Development of the Saturn S-IV and S-IVB Liquid Hydrogen Tank Internal Insulation. Douglas Aircraft Inc., Advances in Cryogenic Engineering (Plenum Press, New York) vol. 11, pp. 89-97 (1966).
7. Private communication, North American Aviation, Space & Information Division.
8. Taylor, B. N.; and Mack, F. E.: Effect of Convection in Helium-Charged, Partial Foam Insulations for Liquid Hydrogen Propellant Tanks. North American Aviation, Inc., paper presented at the 1965 Cryogenic Conference, Aug. 23-25, 1965, Houston, Texas, NASA Contract NAS 7-200.
9. Shriver, C. B.: Investigation of Fabrication and Processing Parameters Associated with Use of Polyurethane Foams in Sealed Cryogenic Insulation. Goodyear Aerospace Corp., Final Report GER-12249, NASA Contract NAS 3-5646, June 25, 1965.
10. Shriver, C. B.: Insulation Fabrication for Wind Tunnel Test Tank. Goodyear Aerospace Corp., Final Report GER-12214 under NASA Contract NAS 3-5646, June 2, 1965.

11. Shriver, C. B.: Insulation Fabrication for Jettisonable Insulation Test Tank. Goodyear Aerospace Corp., Final Report GER-12157, NASA Contract NAS 3-5646, Apr. 8, 1965.
12. Burkley, R. A.; and Shriver, C. B.: Centaur Insulation Study Program. Goodyear Aerospace Corp., Final Report GER-11193, NASA Contract NAS 3-3238, Nov. 1, 1963.
13. Key, C. F.; and Riehl, W. A.: Compatibility of Materials with Liquid Oxygen. NASA TM X-54611, 1963.
14. Heidelberg, L. J.: Evaluation of a Subscale Internally Insulated Fiberglass Propellant Tank for Liquid. NASA TN D-3068, 1965.
15. Knoll, R. H.; and Oglebay, J. C.: Lightweight Thermal Protection Systems for Space Vehicle Propellant Tanks, NASA, paper 746C, International Automotive Eng. Congress, Detroit, Mich., Jan. 11-15, 1965 (reprint from 1964 SAE Transactions).

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Chapter VI

ELECTRICAL ENCAPSULATION WITH FOAMS

PERSPECTIVE

Effective insulation and protection of electronic circuits and packages in the space environment imposes stringent requirements. Materials and processes used for the embedment of components or the encapsulation of circuitry have, for the most part, been supplied as proprietary or special formulations by industrial companies. The unique electrical properties and the low densities of foamed plastics make them especially useful in aerospace electronic applications. Trends to miniaturization and lightweight electronic devices have led to an increasing emphasis on foams.

Current trends in aerospace electronics are toward the use of d-c, or low frequency a-c, circuits of the order of less than 2400 Hz. The d-c solid state circuits for control or logic operate on a supply voltage of 28 volts. Intermediate or high voltage networks exist, as for example, in the traveling wave tube amplifier (1500-6000 volts) and the klystron oscillator and amplifier (at less than 400 volts). High frequencies (136 to 260 MHz) and high voltages prevail in RF equipment where high power is transmitted. In S-band transmission at 2200 MHz, corona effects with an attendant avalanche breakdown in connectors have been significant in some studies.

The technology for radar antennas has been advanced mainly by Air Force investigation. Silicone or polyester resins are preferred over epoxy resins, since the latter display a high dissipation factor or loss tangent. The use of polyurethane foams as enclosures for radomes has been gaining momentum.

The two general uses of cellular materials in space equipment are electric wire and cable insulation and embedment of electronic modules. Foamed plastics for cable insulation, such as the polyolefin or FEP fluorocarbons, have a lower loss factor and dielectric constant (low capacitance) than their solid equivalents because part of the plastic is replaced with a gas of a lower dielectric constant. This type of insulation is provided commercially as extruded stock and its electrical and mechanical properties are well known.

The use of foamed plastics for spaceborne rigid assemblies is governed by mechanical, physical, and electrical design criteria, as well as weight reduction, repairability of the package, and environmental protection requirements. The most important properties for dielectrics are the dielectric constant and loss tangent. For spacecraft and satellites, foamed-in-place liquid resins fill voids, provide good adhesive bonds to mating surfaces, and in many cases are repairable.

An encapsulated spacecraft electronic package may either be exposed to the space environment or be shielded by a hermetically sealed and pressurized canister or the cabin of a manned spacecraft. Materials for space-vacuum application must have low outgassing characteristics and must not release condensible volatiles which might deposit on solar cells or connectors. Radiation effects should not degrade the electrical and mechanical properties and, in the case of sealed equipment, corrosive gases should not be generated and the canister pressure should be kept within limits. Since Freon-11-foamed polyurethane might degrade into chemically reactive gases,[1] the CO_2-blown system has generally been chosen. It has proven satisfactory in laboratory simulation tests. The absence of vibration and an atmosphere in space, on the other hand, provides some advantages in equipment life. In the space cabin, foam encapsulation materials are disqualified if they produce objectionable odors or toxic gases.

Rigid urethane or epoxy foams have been applied as encapsulants for multilayer, printed-circuit board assemblies and for cordwood welded modules with low voltage circuits. They have also proven feasible for high voltage, low-energy networks in the 1- to 5-KV (RMS) range.[2] Foam materials have been very effective dielectrics in such cases, while providing structural rigidity and mechanical positioning of electrical connections.

Goddard Space Flight Center has estimated that approximately 65 percent of an encapsulation involves foam materials. In general, three density levels are employed, for sounding rockets, 4-6 lbs/ft^3; for smaller satellites, 6-8 lbs/ft^3; and for the OGO spacecraft, 8-10 lbs/ft^3.

DESIGN CONSIDERATIONS

In electronic module packaging for space equipment, good electrical insulation and mechanical support must be provided. Design criteria are based on

(1) electrical, mechanical and thermal properties,
(2) weight considerations,
(3) void volume in the package to be filled with dielectric,
(4) processing requirements,
(5) environmental conditions:
    (a) induced vibration, acceleration loading and temperature during ascent,
    (b) exposure to the vacuum, thermal, and radiation conditions in space,
    (c) exposure to operational temperatures and 5-psi oxygen atmosphere in the capsule of a manned spacecraft,
(6) accessibility for replacement or repair,
(7) costs of the package.

The design goals of reduced weight, repairability, elimination of conventional mechanical supports, ease of processing, and low dielectric constant and dissipation factors have made the foam-in-place and syntactic foam materials attractive for packaging space electronic equipment.

Molded urethane foam supports used in place of thin mechanical isolators offer increased design flexibility. Advantages obtained include foam conformance to the structure, maximum load distribution over the surface, and complete coverage of components.

A distinctive feature of foam materials is the variation of the mechanical properties with density.[4] In general, tensile strength, compressive strength, modulus, impact resistance, and flexural strength increase with increasing density. Density can be controlled within the required limits by the chemical formulation and process conditions during foaming and curing.

Properties

Desirable properties include low dielectric constant and low dissipation factor in the required frequency range, and high insulation resistance. In general, the dielectric constant and dissipation factors for foams are intermediate in value between those of the solid polymer and air. Thus, values will range from a dielectric constant (gas) of near 1.0 to a dielectric constant (solid polymer) of 2.5-6.0. A foamed plastic has a lower dielectric constant at a given frequency and temperature than the corresponding unfoamed, solid polymer, but higher than air.

Electrical data for castor oil, polyester, and polyether rigid foam have been reported. Polyether urethanes usually have a lower dielectric constant and lower dissipation factor than polyester urethanes. These electrical properties, as well as the power factor and dielectric strength, vary both with foam density and the frequency in a-c circuitry.

For electrical circuits above ~275 volts RMS, dielectric strength and dielectric breakdown characteristics become especially significant.[5] Dielectrics in satellites and space vehicles must be reliable for periods from 14 days to 2 years (see Table 46). Voltages in the range of 3 to 5 KV RMS appear to be attainable without adverse corona effects.

Compressive strength and tensile shear properties are especially important for dielectrics. Compressive strength versus density and compressive strength/weight ratio versus density are shown in Figures 64 and 65. The mechanical properties are governed by the type of resin used, by the cell structure, and by the foam density. The strength of low density, blown foams is less than that of the syntactic foams which contain a hollow, microballoon filler.

The foam structure must be able to protect the package from mechanical shock by (a) provision of structural support for and (b) delaying the arrival of transferred shock impulses. Under forced vibration the mechanical criterion of failure is fatigue. Since foams can be chosen with high internal hysteresis, the dynamic or resonant stress can be kept within acceptable limits.

The low static properties (for example, the compressive yield of foamed plastic structural members) require that the material be encased in a thin metal skin to avoid local high stress points. Silicones are particularly low in compressive strength compared to urethane or epoxy foams. The packaging engineer selects the module geometry or mounting system to assure maximum protection from vibration.[6]

In Syncoms 2 and 3, the telemetry-and-command and transponder subsystems have met the qualification level of vibration of 1.5 times that expected for twice the

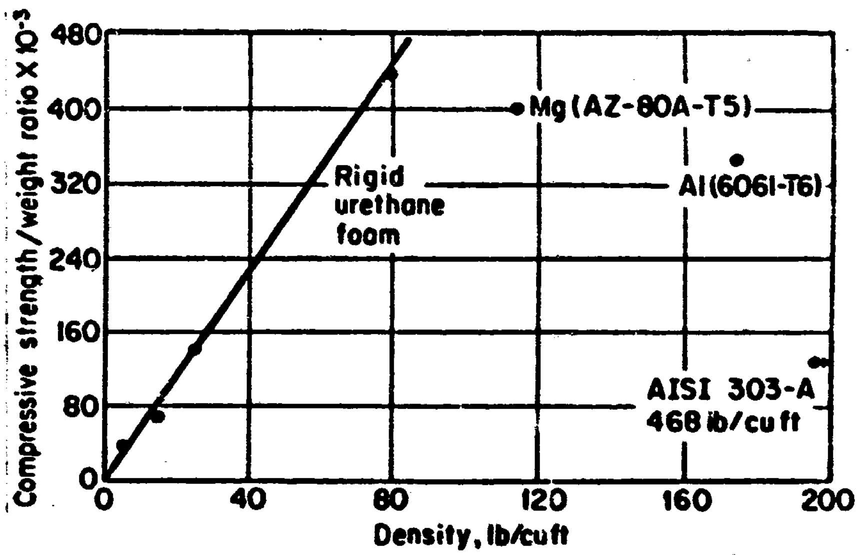

Figure 64.—Compressive strength-to-weight ratios of rigid urethane foams vs density.

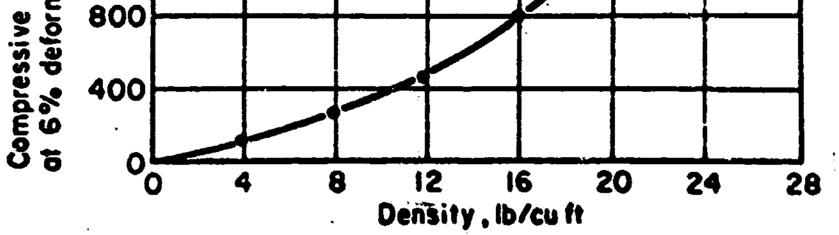

Figure 65.—Compressive strengths vs densities for a typical rigid foam.

duration of flight. The expected amplitude levels were for random vibration at 6 g and for acceleration at 15 g.

Several examples will illustrate the effectiveness of foam materials in packages subjected to high g loading.

(1) Dummy welded cordwood electronic modules embedded with the syntactic epoxy foam, Stycast 1090/11 (Emerson & Cuming), have survived impacts in a horizontal impact machine at levels in excess of 10,000 g's average amplitude from 200 ft/second.[7]

(2) A welded cordwood module, embedded in a rigid polyurethane foam cured at 200°F after applying an epoxy-amine "freeze coat" to the circuitry structure and encasing in an aluminum envelope with all voids filled, has survived vibrational loadings up to 90 g's.[8]

Because electrical insulating materials, including foams, are invariably poor heat conductors, the electronic package is designed to distribute heat loads, to create short heat paths by placing "hot" components in close proximity to the dense outer shell of the module, and to apply heat sinks that collect heat transmitted along component leads. An effective heat dissipation technique, employed by McDonnell Aircraft for Gemini equipment,[9] was to cast a thermally conductive RTV silicone pad over the printed circuit sides of a three-card assembly. The silicone rubber casting accommodated both variations in height (caused by buildup in tolerances) and vibration isolation.

Thermal conduction through the gas phase is generally the largest single contribution to the k (thermal conductivity) of foamed plastics of less than 5 lb/ft^2 density.[10] The thermal conductivities of the potential blowing agents for cellular plastics are shown in Table 40. The k of CO_2 is approximately twice that of Freon 11 (CCl_3F), which is commonly used as a blowing agent in thermal insulation foam systems. A CO_2-blown system for electrical encapsulation foams will therefore dissipate heat more effectively.

Table 40.—Thermal Conductivity of Potential Blowing Agents

Compound	Commercial designation	Thermal conductivity Btu/°F-sq. ft.-hr./in.		
		32°F	68°F	86°F
CCl_3F	F-11	.054	.057	.058
CCl_2F_2	F-12	.058	.064	.067
$C_2Cl_3F_3$	F-113	.046	.051	.054
$C_2Cl_2F_4$	F-114	.054	.061	.065(?)
$CHCl_2F$	F-21	.064	.067	.068
Isobutane		.096	.112	
CO_2		.101	.117	
Air		.168	.180	

Factors other than polymer and gas composition which affect the k of foamed plastics are density, cell size, environmental temperature, and aging conditions. Conductivity generally increases with increasing density and increased cell size. The effect of prolonged aging of unsealed foams, especially at elevated temperature, is to allow diffusion of air or water vapor or both into the closed cells. This not only results in an increase in the k value but also may adversely affect electrical insulation properties.

Internally generated heat, even at low power levels, may raise the operating temperature because of the close packing of the components and the low k of the encapsulant. Space environment may require service temperatures ranging upward from -70° F. The effects of elevated temperature on properties, for example embrittlement on prolonged exposure, could be a potential cause of failure, especially for thermoset plastics to which class the foam embedment materials usually belong. Temperatures up to 260°F may be reached in the lunar environment, for example. Temperature limits in cislunar space can be controlled by an active or passive temperature control system.

Thermal Stability

The thermal stability of a number of representative materials is given in Table 41. These temperatures are not absolutely limiting where only brief exposure is required. Package design criteria for continuous use at the temperature limits include outgassing and dimensional stability. Thermal stability is related not only to the chemistry of the polymer or resin system, but also to the permeability of gas through the cell wall. (The phenomenon of diffusion of blowing gases and the related outgassing effects are discussed in the section on "Diffusion of Gases in Polymeric Foams.")

The thermal stability of the foam materials will vary depending on whether the environment is air, a hard vacuum, or a space cabin atmosphere of 5-psi oxygen. In the case of embedment of the Gemini Time Correlation Buffer, very stringent temperature requirements were imposed for the epoxy embedment.[9] None of the materials could reach or require processing at temperatures above 200° F (93°C) but had to be capable of continuous operation at 200° F and also qualify for cabin use in the spacecraft. The standard exotherm test for the epoxy foam used, Ablestik I, resulted in a maximum temperature of 106° C, above that specified. In this test, the temperature rise of a homogeneous mass of foam is measured. Process temperature however, was limited in this case to 70° C because the embedded components acted as heat sinks.

A preferred practice, even for most room-temperature curing resins such as polyurethanes and RTV silicones, is to post-cure, to upgrade both thermal stability and mechanical properties, at a temperature which is higher than that of the subsequent exposure. For example, CPR-302 polyurethane foam used in the low-voltage digital equipment of the ATS (Applications Technology Satellite) was cured at 10-20° F above the expected use temperature to stabilize the foam against subsequent dimensional change. In this case, a 200°F cure also resulted in the foam being stable at 350°F at 10^{-10} torr and at 400°F in air.

Table 41. —Material and Process Specifications for Embedment or Encapsulating Materials

Specification No.	Title	Material Types	Cure	Material
MSFC-PROC-422 (4/20/1965)	Procedure - Use of Foamed-in-Place Polyurethane, for Electronic Equipment	Type I-107°C. Max.	21-27°C, 24 hrs. or 66°C, 1 hr.	See MFSC Spec 418
		Type II-135°C. Max.	21-27°C, 3 hrs. and 149°C, 3 hrs.	See MFSC Spec 418
MFSC-SPEC-418 (2/15/1966)	Polyurethane Foams for Electronic Equipment	Type I-107°C. Max. Classes 1,2,3,4 (2,4,6,8 pcf density)	Type I-PROC-442	Eccofoam FP (Emerson & Cuming)
		Type II-135°C. Max. Classes 1,2,3,4 (2,4,6,8 pcf density)	Type II-PROC-422	Eccofoam FPH (Emerson & Cuming)
		Type III-163°C. Max. Class 5 (10 pcf density)	177°C., 2 hrs. PROC 310	Nopcofoam B-610 (Nopco Chemical Co.)
Goddard SFC X-723-65-450 (Nov. 1965)	Encapsulation Electronics, Eccofoam 11	$\not>$50°C circuitry		Eccofoam FP 12-6 catalyst
Goddard SFC X-723-65-406 (Oct. 1964)	Encapsulation of MOFSETS* Circuitry 12	$\not>$125°C circuitry	50 ±5°C, 1 hr.	Eccofoam FPH 6-10 pcf
NAA, S&ID-MA0105-045	Foaming of Polyurethane Resin	MB0130-046 Spec.	70-80° F & post-cure	Rigid
NAA, S&ID-MB0130-046	Polyurethane, Foam, Rigid, Structural	Type IV-4 pcf density Grades 1 and 2 Type IV-6 pcf density Grade 1 - 40-110°F use Grade 2 - 40-160°F use		
NAA, S&ID-MA0105-033	Process-Fabrication of Flexible Polyurethane Foam Inserts	MB0130-039 3 pcf density, Max.	77°F - 12 hrs. 200°F - 1 hr.	
NAA, S&ID-MB0130-039 (8/3/65) (ref. SID 62-823-4, 7/20/64)	Foam, Polyurethane, Flexible, Low Density (3 pcf Max.)	Use, - 50°F to +150°F Instrumentation, vibration and shock	70 ±10°F 24 hrs. Min.	Uralane 577-1 (Furane Plastics)
GE P 50 GN 36453 (12/2/63)	Foaming of Gemini Fuel Cell Battery Section Assembly	Spec. A50GN307	70-80°F	Vultafoam 15-F-1502 (General Latex Chemical Corp.)

*MOFSETS - Metal Oxide Field Effect Transistor

Internal Stresses

Since electronic packages contain sensitive components, shrinkage of the embedding resins resulting from processing, curing, and subsequent aging is especially significant. Embedment problems may exist due to pressure sensitive or heat sensitive components, leads or joints. For glass, ceramic, or metal embedded components the crack resistance of the embedment package, especially upon low temperature exposure, is critical. Trends toward integrated circuits and replacement of heat-sensitive germanium by silicon in semi-conductor devices have reduced the extent of the problem.

The higher coefficients of expansion of urethane foams[13] (compared to metals) have to be taken into account when temperature changes occur, particularly low temperatures, to preclude development of high stresses. For pressure-sensitive components, one must avoid excessive internal stresses due to shrinkage of resins resulting from polymerization. Resin systems have much higher coefficients of thermal expansion than glass and metals, thus, as temperature decreases, the increasing differential strain results in progressively higher stresses. These stress problems can occur with either solid or foam resin embedments in electronic packages.

Internal stresses developed in the epoxy syntactic Stycast 1090 embedment of a model electronic module have recently been measured and evaluated at Northrop Space laboratories.[14] Stycast 1090 is a candidate material for sterilized electronic assemblies. The Stycast 1090 encapsulated module received a final cure at 275°F for 2 hours followed by three thermal sterilization cycles each at 293° F for 40 hours. Internal "bulk" type or volume effect pressures, exerted on all sides of the test sensor, were measured by means of embedded carbon-composition resistors. These resistor sensors gave results about equivalent to those obtained by the thermometry method. Residual internal pressures measured at room temperature after the above thermal treatment, were of the order of 800-1200 psi.

Package Design

Package design for circuits and components is largely based on welded or soldered "cordwood" structure and printed circuit board arrays. Repairability of modules is desirable.[15] A particular criterion at Hughes Aircraft was to limit welded module construction to a component holder type configuration[8] to facilitate component removal after welding the circuitry, in spite of limiting the component packing density.

Three different packaging systems were adopted to allow pre-embedment, electrical checkout and repairs as necessary. These are:

(1) Use of epoxy syntactic foam (20 lbs/ft^3, cured at 250°F) to produce the component holder (Figure 66),[8] followed by additional foam to fill the mold cavity (Figure 67), and encasement in an epoxy shell (0.050 inch thick) (Figure 68).

(2) A polyethylene component holder that is removed after welding, and an epoxy "freeze coat" for the welded circuitry. A polyurethane foam-in-place material

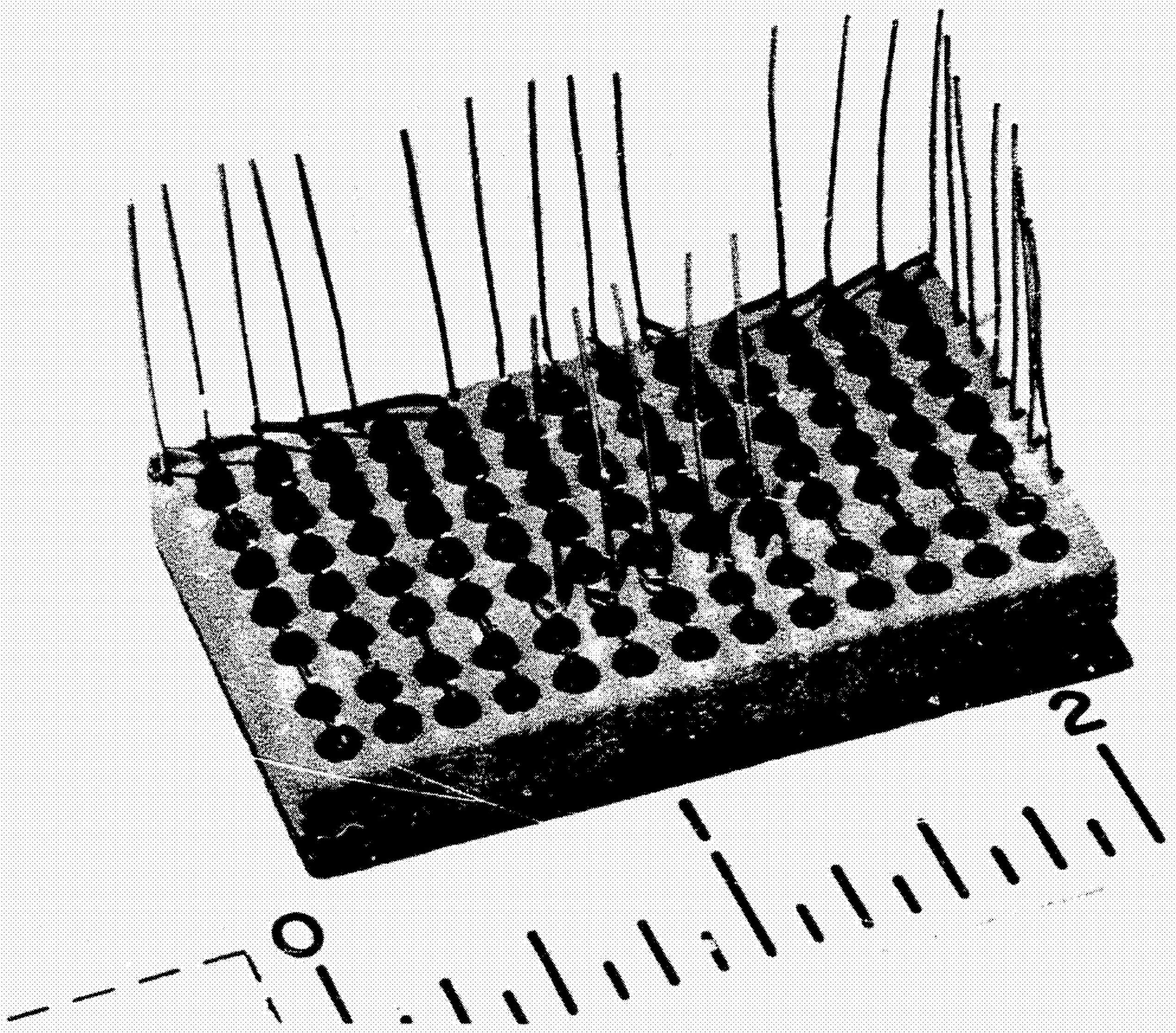

Figure 66. —Syntactic foam component holder and welded circuitry.

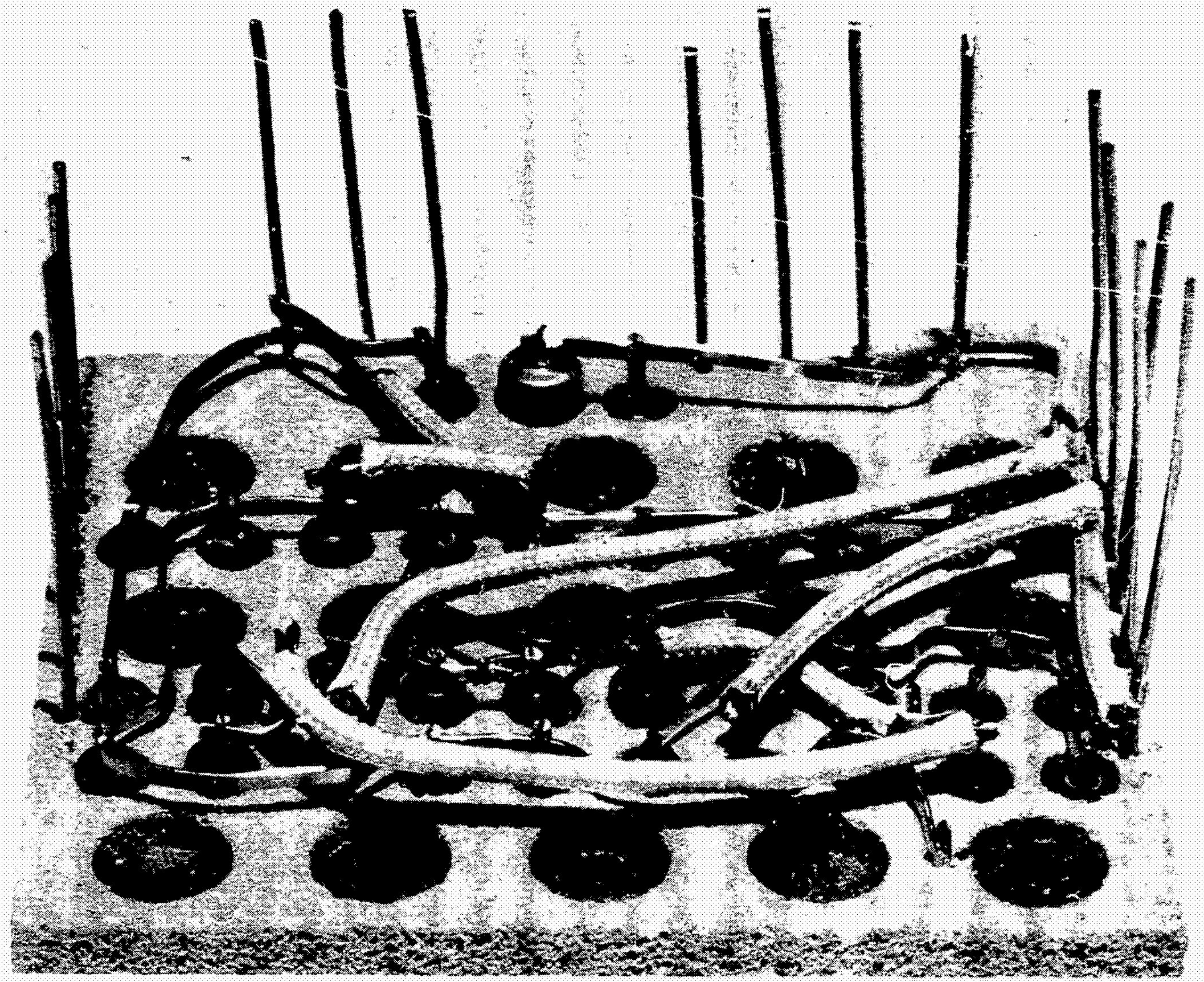

Figure 67. —Syntactic foam component holder and welded circuitry.

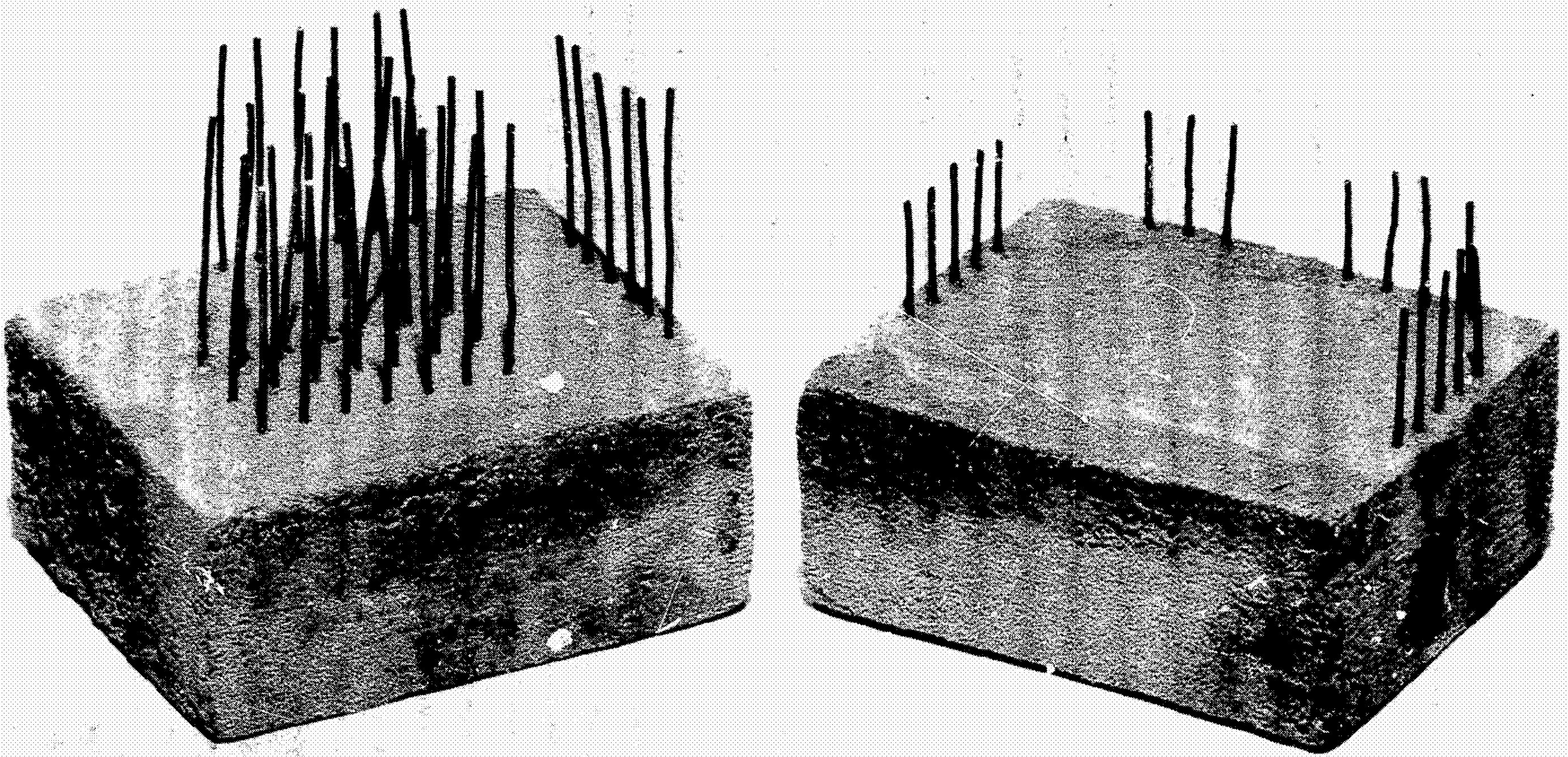

Figure 68. —Syntactic foamed modules prior to encapsulation with final shell.

is used for the embedment (Figure 69). After testing, the module is placed in its aluminum container and the remaining void is filled with more foam (Figures 70 and 71).

(3) A combination of the features of the (1) and (2) systems. This method uses the individual module concept on a rigid substrate with insulation provided by epoxy coatings and foam-in-place polyurethanes (Figures 72 and 73).

Vacuum Outgassing of Foam Encapsulants[16]

Data on the stability of one epoxy and several polyurethane foams exposed to a vacuum of 10^{-7} torr at room temperature are summarized in Table 42. These foams are of the closed-cell type used as encapsulants for electronic modules. Test specimens were 2" x 2" x 2" blocks. All of the foams tested showed good stability.

TYPES OF FOAM SYSTEMS AND RESIN CLASSES

Material Selection

A particular foam material for electronic applications is usually selected by low density, low outgassing and the specific dielectric properties required. Generally a compromise is required in terms of heat dissipation, weight, and structural strength. Thermal, vacuum-thermal, and radiation stability are further property requirements.

The specifications on foam materials and their processing requirements in Table 41 provide examples of commercial products found to be acceptable for different encapsulant applications. Products of this nature have been formulated for processing by foam-in-place methods and to provide relatively uniform properties. Major efforts have been expended by NASA to determine the property data, processing technology and reliability for their use in space electronics. This information is rather extensively spread throughout many organizations active in this area.

The two types of lightweight foam systems used for embedment or encapsulation of electronic packages are syntactic foams, formulated with a liquid resin and low-density microballoon filler, and atactic low-density blown-resin foams. Polyurethane and epoxy foams are the most widely used. The syntactic foams are generally used at a specific gravity between 0.6 and 0.8, whereas the polyurethane or epoxy foams are commonly used in the 2 to 10 pcf. density range. Polyurethane foams are used where maximum weight reduction is required and, in most cases, where the environmental requirements are not as severe as for the syntactic foams.

Polyurethane foams are usually a resin/catalyst and blowing agent foamed in place at room temperature either as casting or in a mold. Post-curing is generally desirable to obtain optimum physical properties and to reduce outgassing. In epoxy foams there is a higher cure temperature and reaction exotherm. The epoxy reaction and gas liberation or foaming reaction must be simultaneous, thus imposing

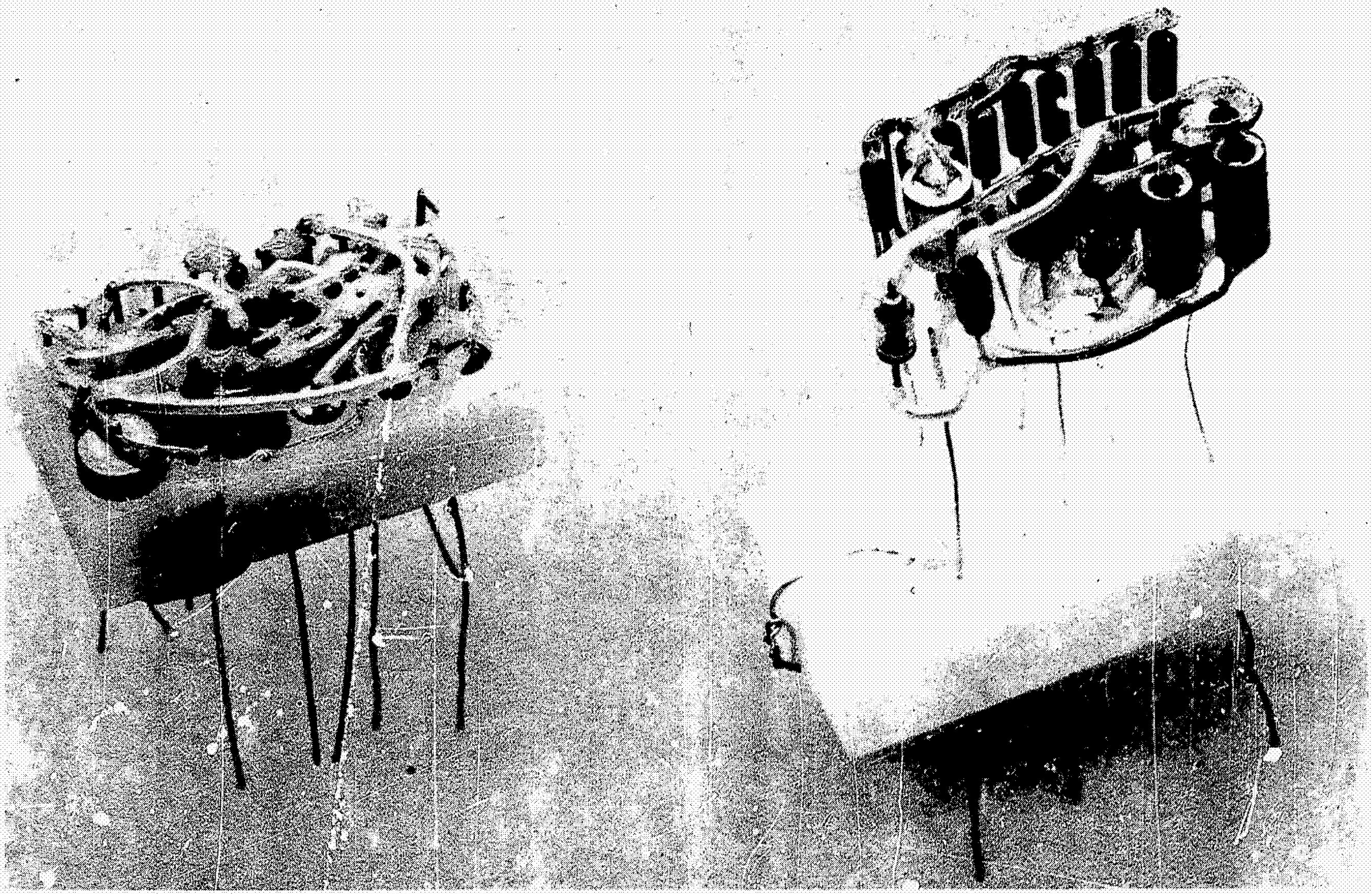

Figure 69. —Welded module with and without component polyethylene holder.

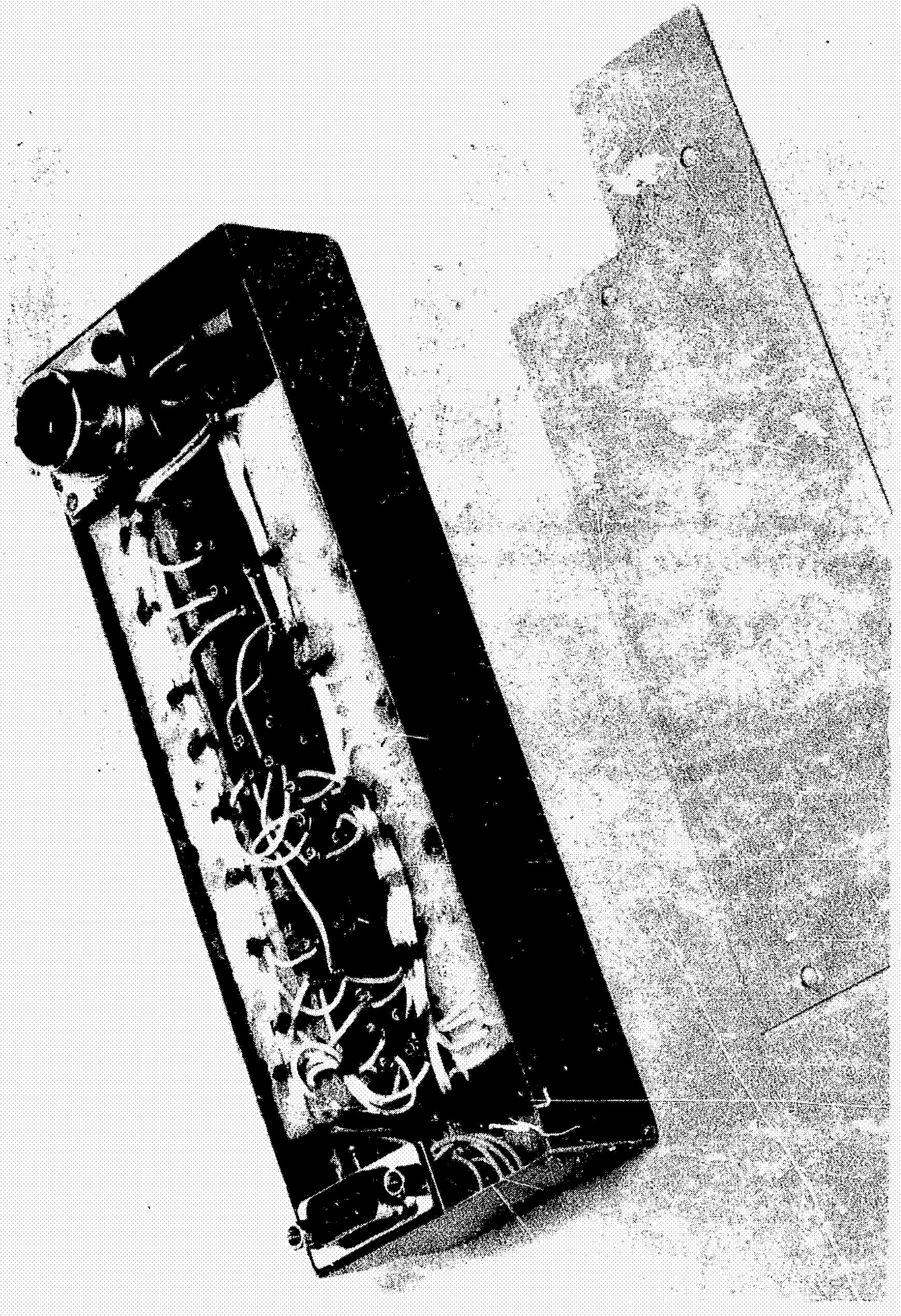

Figure 70.—Foamed modules placed in aluminum container.

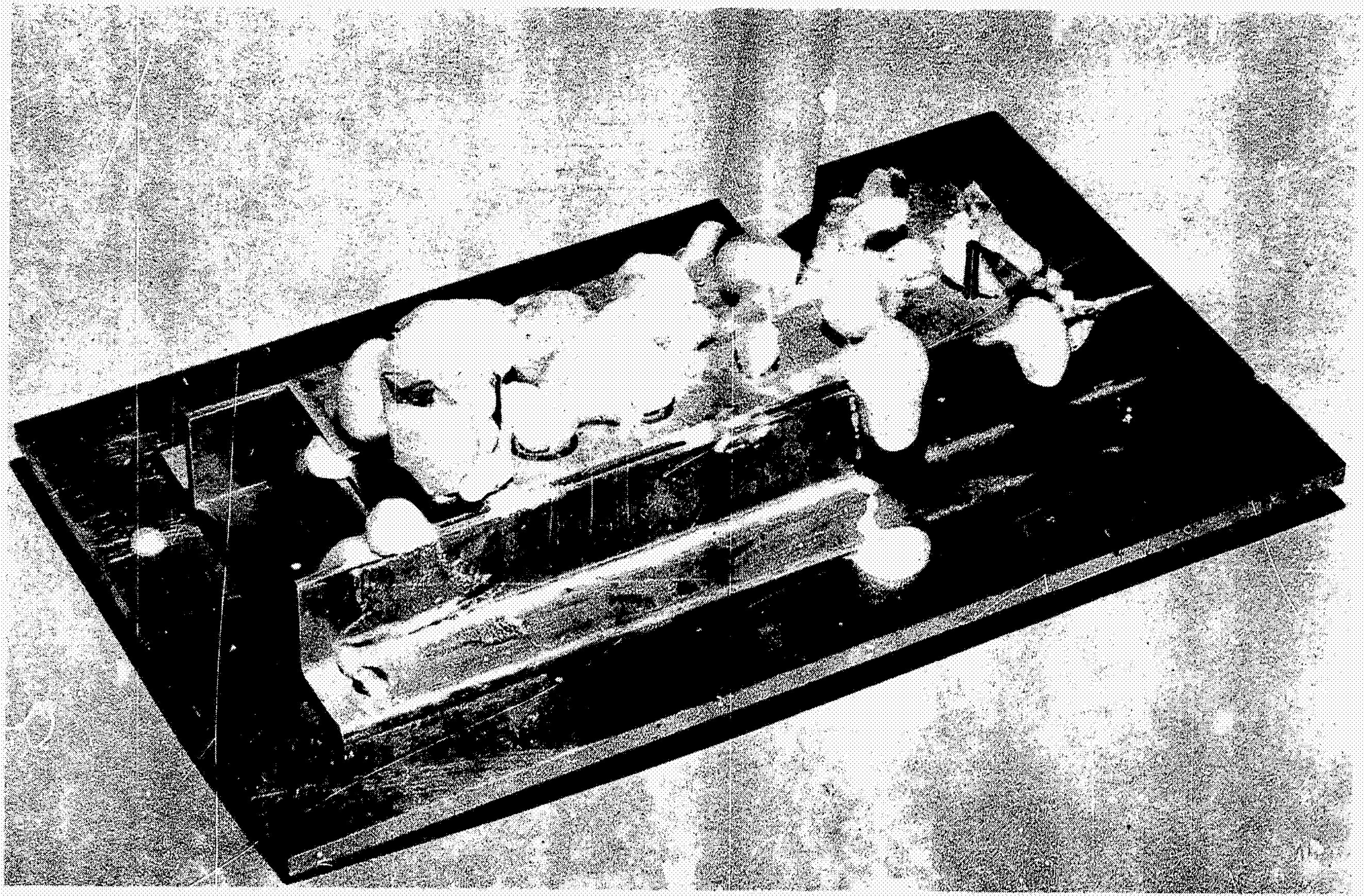

Figure 71.—Assembly being potted en masse with a urethane foam.

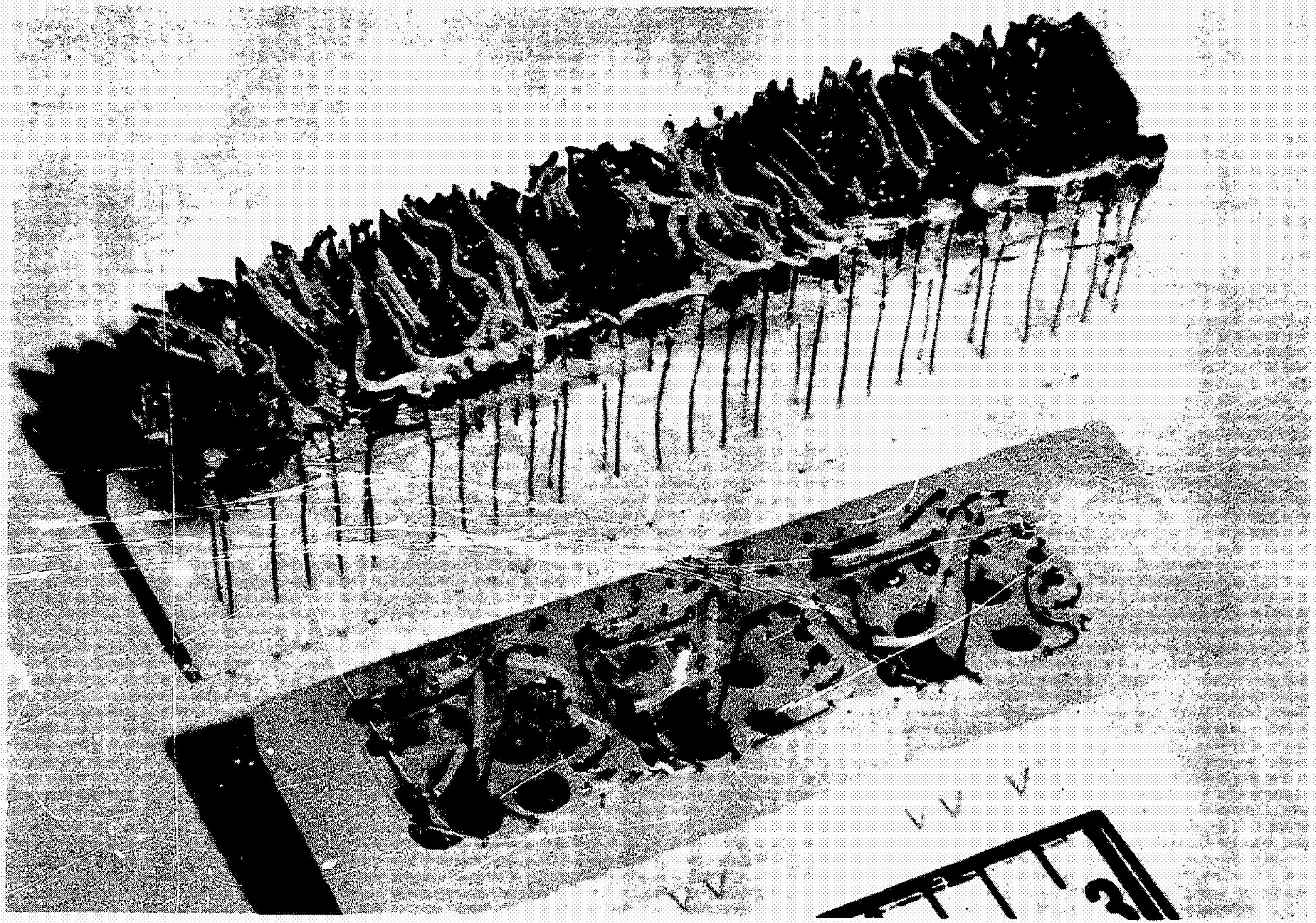

Figure 72. —Close-up of welded module showing the component holder and freeze coating.

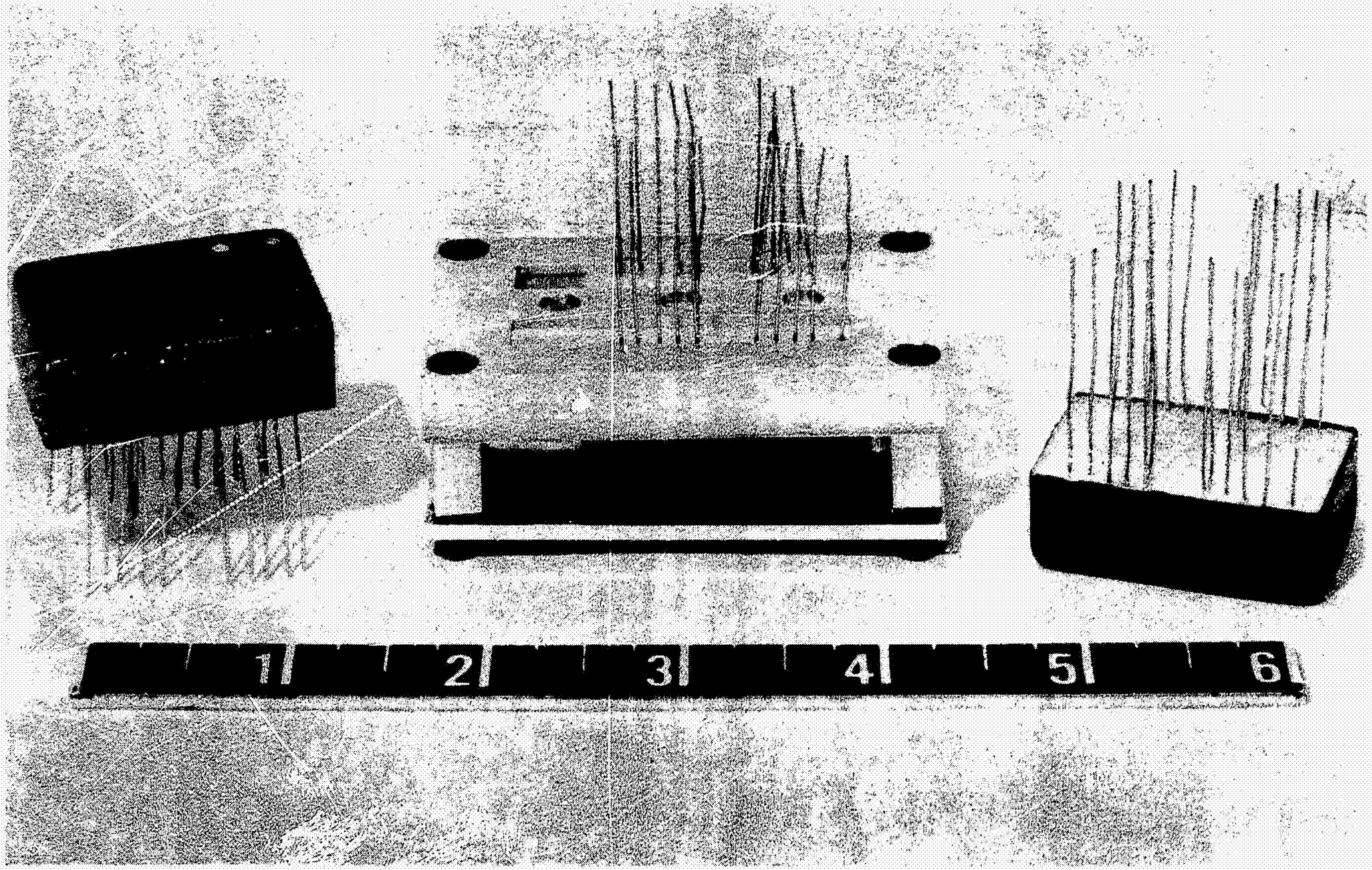

Figure 73.--Urethane foam potted modules showing combination foaming and electrical check-out tool.

Table 42.—Results of Vacuum Exposure on Foam-in-Place Encapsulating Materials

Foam	Chemical type	Before exposure		After 100 hours in vacuum at room temperature		
		Nominal density, (lb/cu. ft.)	Measured density, (lb/cu. ft.)	Weight loss, (percent)	Maximum dimensional expansion, (percent)	Decrease in density, (percent)
Stafoam AA-402	Polyurethane	2	1.64	2.35	0.77	2.75
Eccofoam FPH 12-24	Polyurethane	2	1.65	4.05	0.73	3.60
Polytron 2	Polyurethane	2	2.02	1.65	0.49	1.88
Stafoam AA-602	Polyurethane	2	2.06	2.32	0.05	1.16
Stafoam AA-1702	Polyurethane	2	3.15	0.92	0.25	0.53
Scotchcast 603	Epoxy	6	7.55	0.49	0.49	0.26
Eccofoam FP 12-10	Polyurethane	12	13.72	0.83	0.49	0.17
Stafoam AA-1710	Polyurethane	10	14.58	0.75	0.00	0.05
Stafoam AA-1720	Polyurethane	20	16.2	0.67	0.25	0.09

rigorous control on the resin, hardness, temperature, viscosities and other variables. The toughest epoxy foams are produced by baking for several hours at about 100°C to insure complete cure.

Silicone-foam encapsulants for space-borne electronics are, at present, in limited use or under development. Urethane foams have several advantages: (1) wide range of useable densities, 2-10 lb/ft^3; (2) rapid processing; (3) room-temperature cure and easily regulated post-cure; (4) less critical exotherm in filling small void volumes; and (5) they are easily repaired.

An epoxy foam, Ablefoam 1 (15 lb/ft^3 density), was chosen as embedment material for the Time Correlation Buffer (Table 43) used in the cabin of the Gemini spacecraft.[9] This epoxy foam had these advantages: (1) easy to use one-component foam, stored at -40° F and thawed for delivery into the mold cavity just before use; (2) lower pressure generated during the foaming reaction thus requiring less expensive tooling; and (3) significantly higher thermal conductivity than an otherwise acceptable 10-pcf.-density polyurethane foam; e.g., k (epoxy)/k (urethane) ratio of 0.39/0.28 Btu-inch/ft^2-hour-° F. This is the epoxy shown in Table 43.

Foamed plastics for foam-in-place electronic applications are closed-cell (unicellular) rigid foams for mechanical support. A unicellular structure will provide a uniform gaseous structure within the plastic matrix and effectively confine the gas used as the blowing agent, thus providing relatively uniform and predictable properties. The rigid foams usually have a closed-cell structure.

Table 43.—Evaluation of Foam Materials for Time Correlation Buffer[12]

Characteristic	Material requirements	Silicone	Polyurethane			Epoxy
			1	2	3	
Cure Temp., °C	93	25	93	66	93	66
Density, lb/ft^3	10-15	15	5	10	6	15
Thermal Cond., Btu/(hr)(ft^2) (°F/in)	0.7	0.26	0.27	0.25	0.28	0.39
Time for application	Several minutes	30 sec.	30 sec.	30 sec.	30 sec.	45 min.
Repairable	Yes	Marginally	Yes	Yes	Yes	Yes
Foaming action	Slow	Rapid	Rapid	Medium	Rapid	Slow
Odor	None	Failed	Failed	Failed	None	None
Exotherm, total temp., °C	93°C total	Eliminated	Eliminated	Eliminated	104	106*

* Exotherm measurements made on a dummy assembly showed that the highest temperature produced during curing was 70°C.

The closed-cell structure also provides protection against humidity damage to the foam's electrical properties. This protection is not complete since closed-cell foams generally have from ~30 percent open cells (for "semi-rigids'") to ~5 to 15 percent open cells (for the "rigids"); and permeation of water vapor through the polymer membrane of the cell wall can occur in time. This situation generally calls for sealing, as with a coating such as an epoxy or polyurethane film.

Polyurethane Foams

Urethane foams may be either polyester or polyether-based. The polyether type has a smoother compression load resistance curve with very little "plateau" effect, better low-temperature flexibility (below 0° F) and greater humidity and solvent resistance. The polyester-type has greater compressive strength (at yield) and better mechanical strength properties especially at elevated temperatures. For example, CPR-23 series, heat-cured, two-component, polyurethane foam at 7 to 8 lb/ft^3 density has improved mechanical properties in electrical packaging. In this series cured foam below 8 pcf density can be removed for repair.[17]

The mechanical strength of most rigid urethane foams decreases slightly between ambient temperature and 200°F. The use temperature is often limited to 210-225°F for continuous service because of a decrease in mechanical properties and dimensional stability at higher temperatures. One exception is Eccofoam FPH polyurethane which can withstand continuous exposure at 300°F.

A typical widely used foam formulation is Eccofoam FP, which is a liquid, foam-in-place, toluene-diisocyanate (TDI)/castor-oil copolymer. This prepolymer is reacted with water in the presence of a catalyst and a surface active agent to produce a foam. Encapsulant applications of foams in satellites are shown in Table 44.

Radiation resistance of a CO_2-foamed polyurethane, Eccofoam FPH (4.3 lb/ft^3) has proven to be satisfactory to encapsulate not only the subassemblies and circuits but the entire canister of the Telstar satellite.[1] At Bell Telephone Laboratories a sample was irradiated with 1-MEV electrons for 5 hours with a total flux of 2.9×10^{16} electrons/cm^2. Table 45 shows the effect of irradiation.

In another experiment the foam was reduced to a powder, charged into a sealed container and irradiated in a gamma cell for about 3 hours at 6×10^5 R/hour. This was to simulate an anticipated radiation level of nearly 2×10^6 R/year for Telstar. No significant pressure change occurred in the canister as a result of the radiation.

Although Fluorocarbon-11 is the preferred blowing agent for rigid urethane foams with densities below 4 lb/ft^3, used for thermal insulation, the low-density foams for structural support are expanded with carbon dioxide, produced by the water-isocyanate reaction. The CO_2-blown foams are more easily processed above 4-pcf density and are safer to use in a sealed system subject to radiation, where Freon 11 may give rise to corrosive outgassing. Foam density of prepolymer-based foams blown with CO_2 is changed by varying the amount of water in the catalyst component and by adjustment of the mass of the liquid resin to fill a specific void volume.

6-

Table 44.—Miscellaneous Examples of Applications of Foams

Satellite	Agency	Material	Type	Equipment used on	Remarks
NIMBUS	General Electric	GE formulas MP 49 and MP 50[20]	Silica microballoon filled epoxy resins	Vidicon and sequencer timing circuitry	Transparency permits effective inspection for encapsulation voids, thereby correcting arcing problems at >200 volts.
Explorers 18, 21, 28	Goddard	Eccofoam FP-12/6	Foam-in-place polyurethane		
Syncom	Hughes Aircraft	CPR 23-4A (4 pfc.)	Foam-in-place polyurethane	Travelling wave tube	No corona at room temp. Traces of corona, but no breakdown after 6 weeks at 160° F.
Surveyor	Hughes Aircraft	CPR 23-8 (8 pfc.)	Foam-in-place polyurethane	Travelling wave tube	Flight qualified.
Telstar	Bell Telephone Labs.	Eccofoam FPH (4.3 pfc.)	Foam-in-place polyurethane	Broadband transponder (400 mg band)	Communication equipment meet operational radiation requirements.
LETS	Hughes Aircraft	Nopcofoam P506 (6 pfc.)	Foam-in-place polyurethane	Low voltage digital	Acetone soluble when cured - for repairable modules.
ATS	Hughes Aircraft	CPR-302 (2 pcf.)	Foamed slab stock	Low voltage digital	Used for P.C. board assemblies - stable 350°F at 10^{-10} torr and 400° at 760 mm.
Sounding Rockets	Goddard	Eccofoam FPH (6-10 pcf.)	Foam-in-place polyurethane	MOFSETS* circuitry	Specially processed to avoid damage due to electrostatically charged surfaces.
Pegasus[21]		Nopco G-304 (4 pcf)	Semi-rigid polyurethane	Capacitor for micrometeoroid detecting surface	For 8- and 16-mil thick detector panel.
Pegasus[21]		Dela-Trigid	Rigid polyurethane	Capacitor for micrometeoroid detecting surface	For 1.5-mil thick detector panel.

*Metal-Oxide Field Effect Transistor

Table 45. —Properties of Irradiated Eccofoam FPH (4.3 lbs/ft^3)

	Irradiated	Control
Dielectric constant*		
1 kc	1.29	1.28
1000 kc	1.34	1.29
Dissipation factor*		
1 kc	.0015	.0014
1000 kc	.0032	.0033

* Per ASTM D 150-59 T

Syntactic Foams

The syntactic foams primarily consist of epoxy or silicone resins filled with glass, silica, or phenolic microballoons. Glass or silica microspheres are preferred as fillers since they result in a more rigid foam after curing the resin. In electrical applications, the specific gravity of these syntactics usually ranges from 0.6 to 0.8. They represent a compromise in terms of weight and structural strength. This type of filled system usually requires special handling in processing due to the increased viscosity or thixotropic effect.

Syntactic foams have especially good resistance to thermal and mechanical shock, thermal aging and exposure to vacuum and nuclear radiation. Stycast 1090 (Emerson & Cuming) is a typical syntactic foam and was used to encapsulate electronic circuits and welded modules in the Ranger and Mariner spacecrafts.

Other advantages favor the syntactic system. In filled systems generally, weight losses are reduced during heat aging and there is a reduction in the exothermic heat of the system during curing. Reduced shrinkage and reduced thermal expansion diminish the tendency for resin cracking, compared to the unfilled resin.

FOAM DIELECTRICS FOR HIGH VOLTAGE NETWORKS

In high-voltage networks, corona and dielectric breakdown can cause problems. Corona is caused by ionization of gas in pockets or layers adjoining or within insulated structures. It can be a luminous discharge around a conductor when the existing voltage gradient exceeds a critical value, termed the "corona starting voltage."

During the ascent of space vehicles, electrical assemblies can be subject to corona and flash-over at relatively low voltages. The problem range, in terms of earth altitude, is about 60 000 to 310 000 feet (50 mm. to 5 × 10^{-4} mm Hg.), and usually at voltage levels above 270 volts peak. For power-supply equipment in communication satellites, the intermediate voltage range of 700-6000 volts has been of prime interest. The travelling-wave tube transmitter-receiver is typical of equipment in which such voltages are generated. Diffusion of gases and outgassing of organic materials may produce corona problems not encountered at atmospheric pressure.

Space electronic equipment must be insulated because of outgassing products from spacecraft materials, especially in confined areas. These volatile materials may ionize, reducing corona threshold levels and encouraging early electrical breakdown.

Corona Starting Voltage

The corona starting voltage in air is a function of the product of air pressure and electrode spacing.[20,21] At one atmosphere and a peak voltage sparkover of 350 volts, the required spacing is in the range of 5 to 8 × 10^{-3} mm. At low pressures (altitudes of 50 000 to 100 000 feet), the spacings for minimum breakdown voltage are increased to fractions of an inch. When the insulation is only a small fraction of the spacing, it has relatively little effect on the corona starting voltage, since it bears even less than its geometrically proportionate share of the applied voltage because of its high dielectric constant compared to air.

In the case of foams, whether open or closed cell, corona starting voltages may be greatly increased at low pressures because the foam structure breaks up a large air gap into many small gaps. The voltage across each gap or cell may have to exceed 270 peak volts for corona to occur within it.

These features of low pressure phenomena have resulted in two considerations for designing laboratory tests for materials:[20]

(1) Specimens for testing corona suppressing encapsulants must be designed so that the entire evacuated volume around the test electrodes is uniformly filled. As voltages are raised over 1[illegible] volts and pressures are lowered, the region of ionized gas may extend several inc[illegible].

(2) The range of applied pressures is based on a critical pressure region (CPR), considered to correspond to 60 000 to 310 000 feet altitude. In this range the dielectric strength of air is less than 20 percent of the value at sea level.

An ionization voltage curve for the SERT-I system is depicted in Figure 74.

Corona Suppression

A combination of techniques is generally used to increase corona and flash-over voltages. Some of them are: (1) to encapsulate in a void-free, solid dielectric material; (2) to submerge in a liquid dielectric fluid; or (3) to use a hermetically sealed gas-filled container. They are used infrequently for space equipment since [illegible] cause weight problems or difficulties in providing hermetic seals and shock and [illegible]ion protection.[2]

Lightweight dielectrics in the form of CO_2-blown, rigid, foam-in-place, polyurethane compounds were investigated by Hughes Aircraft for moderately high voltage applications and successfully used in communication satellite equipment. One such material was CPR 23-8 (8 lbs/ft^3 density) a two-component, heat-cured, polyester-polyurethane foam. This foam has a closed-cell structure and is cured around the

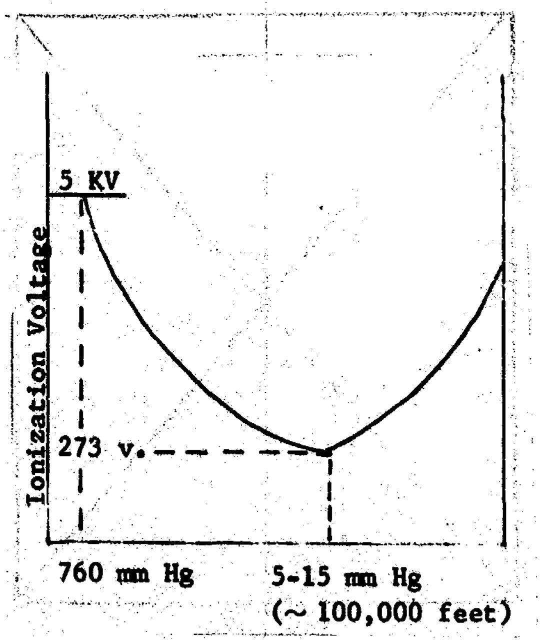

Figure 74.—Ionization voltage curve.

circuitry inside of vented metal cans which are shielded and protected. A foam density of 8 lbs/ft^3 was preferred because of maximum strength, low density, and easy removability of foam sections for repair purposes.

Examples of High Voltage Applications

A list of spacecraft built by Hughes Aircraft[17] and the voltage and life requirements for their power supplies is given in Table 46.

Evaluation of Rigid Foam Materials

Corona starting voltages have been determined as a function of pressure in the approximate range of 0.01 to 10 mm Hg. pressure for foam-in-place and syntactic foam embedding materials manufactured by the 3M Company,[20] using two types of high voltage electrodes as listed in Table 47. Reference data for air-spaced electrodes were determined for several electrode geometries. Corona starting voltages fell to values in the range of 250 to 350 volts (RMS) at pressures between 0.2 mm and 2 mm Hg., depending on the electrode shape and spacing.

Closed-cell materials markedly raised corona starting levels at low ambient pressures. The materials were effective in eliminating corona in the range of 2 kilo-volts, provided that the foam composition and processing resulted in complete void filling. The dry, pourable, syntactic foams, such as XR-5068 and especially XPT (which expands slightly during cure and thereby shows less tendency to trap air), are particularly effective corona suppressors, in spite of the fact that these materials are porous. These foam compositions have negligible change in volume during cure or temperature cycling.

Table 46.—Voltages [illegible] Power Supplies for Satellite Equipment

Satellite or vehicle	Organization	Type	Operational life	Voltage RMS
Syncom 2	GSFC	Communication	2 years	700
Early Bird	COMSAT	Communication	1 year	1500
Blue Bird	COMSAT	Communication	(2.5-3 years)	1500
ATS	GSFC	Communication	---	3000
Surveyor I	JPL	Lunar probe spacecraft	24 earth days	1200
SERT-I	GSFC	Interplanetary Ion engine	14-day experiment	5000-7000

Corona Onset Voltages in Foam Materials[5,21]

Corona and associated harmful effects are possible problems when using a foam encapsulating resin for insulation at voltages greater than 270 volts in a hard vacuum. In the critical air pressure region between 60 000 and 310 000 feet, at a voltage above the critical region voltage of 270 volts, high-voltage breakdown can occur. The diffusion of the blowing gas out of the individual foam cells may cause the region between the high-voltage conductors to pass through the critical air pressure range. With foam in the path, arcing will not occur, but a partial breakdown or corona could conceivably result in individual foam cells when the conductor separation is large enough. The result would be to break down cell walls gradually, forming a conductive path between electrodes.

The Jet Propulsion Laboratory has established parameters and techniques for high voltage packaging through the critical pressure region and in the high vacuum region.

(1) A plot was made of the corona onset voltage level between fixed conductors as a function of the pressure. This pressure calibrated corona onset voltage curve was obtained by measuring the corona current. The calibration curve indicated a critical region between 50 and 5×10^{-3} torr.

(2) Corona breakdown tendencies were measured on foam samples exposed to a vacuum of 10^{-5} torr. The pressure calibrated corona onset voltage level was used as measure of the average gas pressure existing in the foam between the electrodes.

(3) The diffusion behavior of blowing gases in rigid, closed-cell foams was determined because the dielectric strength of a foam depends markedly on gas pressure.

(4) Voltage endurance tests on a 2-lb [illegible] closed-cell polyurethane foam (Eccofoam SH) showed the dependence of el[illegible]rength on rate of voltage application.[22] This relationship is linear on a l[illegible] the relationships for correlating failure

Table 47.—Foam-in-Place and Syntactic Foams for Corona Suppressant Tests

Material tested	Type of Resin System	Cure cycle	Cured density (lbs. /ft. ^{3})	Compressive strength, psi	D_x* at 23°C 100 cycles	K** at 23°C 100 cycles
Scotchcast 603	one part, powdered epoxy resin	1 hr. at 95°C 2 hrs. at 115°C	6.5	75	0.04	1.6
Scotchcast XR-5017	two-part, liquid silicone	24 hrs. at 23°C	25	>30	0.05	2.8
XR-5068	one-part, syntactic powdered epoxy resin	16 hrs. at 95°C 1 hr. at 150°C	15	550	0.03	2.0
XR-5090	two-part, syntactic liquid epoxy resin	24 hrs. at 30°C	44	4000	0.01	2.8
XPT (experimental)	one-part, syntactic low melting solid epoxy	16 hrs. at 95°C	15	80	--	---

* D_x = dissipation factor

**K = dielectric constant

148 NCK
6-26

times to the rate of voltage application and the parameters characterizing foams were evaluated as a means of predicting long-time high-voltage endurance.

For direct current, breakdown is also dependent on the duration of the applied field and the geometry, including inter-electrode distance. Generally, breakdown strength decreases with increasing temperature. The corona currents, measured in the corona-detection network, were of the order of 10^{-6} to 10^{-7} ampere. An objective of the corona breakdown study was to determine the ultimate d-c electric strength of insulating materials. The standard test for electric strength (ASTM-D149) using a-c potentials and electrodes with rounded edges did not appear to supply sufficiently meaningful design information for d-c applications.

Corona Tests

Tests were performed on foam samples, with embedded electrodes and exposed to a continuous vacuum of 10^{-5} torr. The applied voltage was either 11.8 KV or the corona onset voltage, whichever was lower. After several months, work on this program was inconclusive although Samples 2 and 3 (see below) showed a decreasing corona onset voltage from the value measured originally at ambient pressure.

Test samples of CPR 23-8 (8 lbs/ft^3 density) used in this program are shown in Figure 75. Sample descriptions for the experiments follow:

Sample 1 - 4" x 4" x 2" block with 3/32" diameter, stainless-steel electrodes inserted in a planar "T" configuration in drilled holes and spaced 1 inch apart at the closest points.

Sample 2 - Split in half through the four-inch sides, with a triangular cavity and electrodes positioned similar to samples 3 and 4. The two halves are bonded together with Epon 828/Versamid to make an airtight seal.

Sample 3 - Constructed in a similar manner to Sample 2, except that a Plexiglas window was bonded to the foam to enable visual observation of the electrical breakdown.

Sample 4 - Construction same as Samples 1, 2, 3, except that the cavity was exposed to the ambient pressure. Sample 4 was used to obtain the corona onset voltage calibration curve.

In the tests performed, voltage was applied continuously to Samples 1, 2 and 3 while passing through the critical region.

The effect of corona occurring in the vicinity of an insulation material is to shorten insulation life (by partial breakdown). The laws governing corona effects appear to be complex. For a given test setup and method of evaluation, insulation life is shortened rapidly as the applied voltage is increased over the corona onset voltage. The three basic manifestations of damage due to corona effects are:

(1) Electrical—reduction of original V_c and relative dielectric strength.

(2) Physical—surface eruption, erosion, and pitting of the insulator, and eventual charring of organic insulations from the heat liberated by the recombination of electrical charges. The erosion depends on frequency and applied voltage. Cumulative heating increases at higher frequencies, especially in the megacycle range.

(3) Chemical—These are long-term, volume effects, generally measured by changes in the power factor.

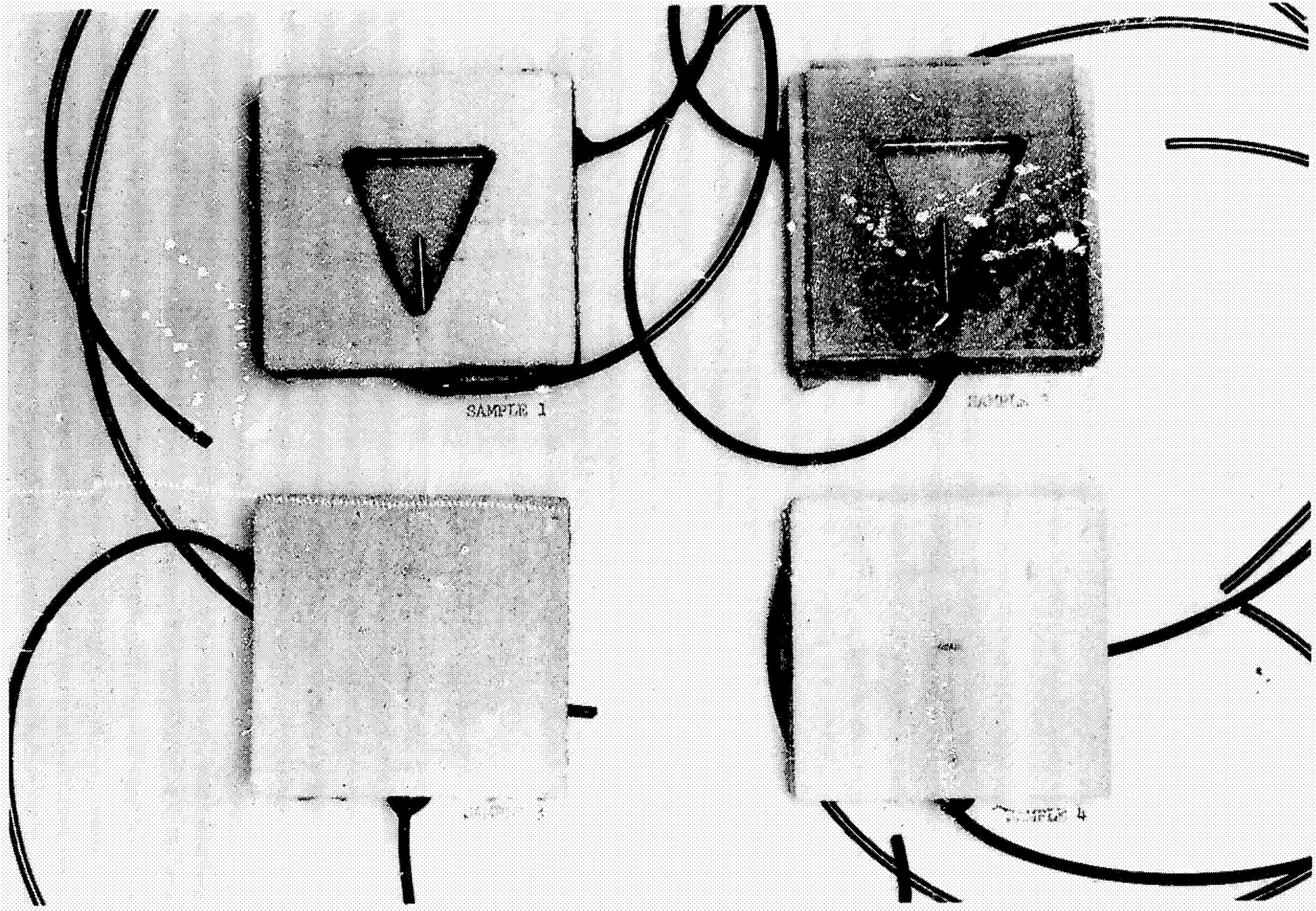

Figure 75.—Geometrical configuration of polyurethane foam samples.

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Corona damage or "tracking" on the surfaces directly between conductors is due to contaminants on exposed surfaces. As the surface resistance of an insulator is reduced, the leakage current tends to heat up the surface. Visible short arcs can occur which carbonize organic insulators and leave conducting tracks on the surface.

DIFFUSION OF GASES IN POLYMERIC FOAMS

JPL has investigated the diffusion rates of CO_2 from rigid, closed-cell foams in a vacuum.[24, 25, 26, 27] When foams are used as high-voltage encapsulants, their dielectric strengths depend markedly on the gas pressures within the foam cells. JPL showed that the diffusion behavior of a foam could be described in terms of a single diffusion coefficient, D. Diffusion rates for carbon dioxide were determined for closed-cell polyurethane foams of various densities by monitoring, for several weeks, the weight loss from specimens suspended in a vacuum of 10^{-7} torr. The experimental data were used to calculate coefficients for the foam materials, which were found to be of the order of 10^{-6} to 10^{-5} cm²/sec, between 22 and 81°C.

From theoretical considerations the following equation was derived:

$$D = 3 \frac{RT}{M} \frac{\rho_0}{\rho} P_e$$

where P_e is the permeation constant for the polymeric material; ρ and ρ_0, the foam and polymer densities, respectively; R is the gas constant; T, the temperature; and M the molecular weight of the gas. Coefficients are calculated from P_e data by the above equation. Good agreement was obtained between calculated and experimentally determined D values.

One of the relationships derived from the mathematical analysis of the diffusion equations for polymeric foams was that the diffusion constant (D) is inversely proportional to the foam density and can be represented simply as $D = K/\rho$. Using the diffusion coefficients for 4.5 and 6.4 lb/ft³ Eccofoam FPH foams, this equation becomes, for Eccofoam FPH polyurethane foam:

$$D\ (\text{cm}^2/\text{sec}) = \frac{7.9 \times 10^{-6}}{\rho\ (\text{lb/ft}^3)}$$

The polymer foams investigated are listed in Table 48. Weight-loss curves for polymer foams 4, 5 and 6 are shown in Figure 76.

Figure 76 is a normalized plot of Q/Q_∞ versus time at 10^{-7} torr for all three Eccofoam FPH foams, where Q = weight loss in mgm for a 3-inch diameter x 1 inch-thick specimen, and Q_∞ is the calculated total CO_2 content of the foam.

Temperature Dependence

Outgassing rates for an Eccofoam FPH/12/6H foam of 4.5 lb/ft³ density were determined at 22, 41, 61 and 81°C. Temperature dependence of the outgassing rate is presented in Figure 77, which shows weight loss both in air and in vacuum with zero time taken as the point when vacuum was applied. Above 61°C, the changes in rate of

Table 48.—Polymer Foams for Diffusion Rate Studies

Material	Type	Density lb/ft^3
1. Eccosil 5000	Syntactic silicone	30
2. Eccofoam SH	CO_2-blown polyurethane slab stock	7.6
3. Stycast 1090	Syntactic epoxy	48.8
4. Eccofoam FPH/12/2H	CO_2-blown polyurethane foam-in-place	2.1
5. Eccofoam FPH/12/6H	CO_2-blown polyurethane foam-in-place	4.5
6. Eccofoam FPH/12/6H	CO_2-blown polyurethane foam-in-place	6.4

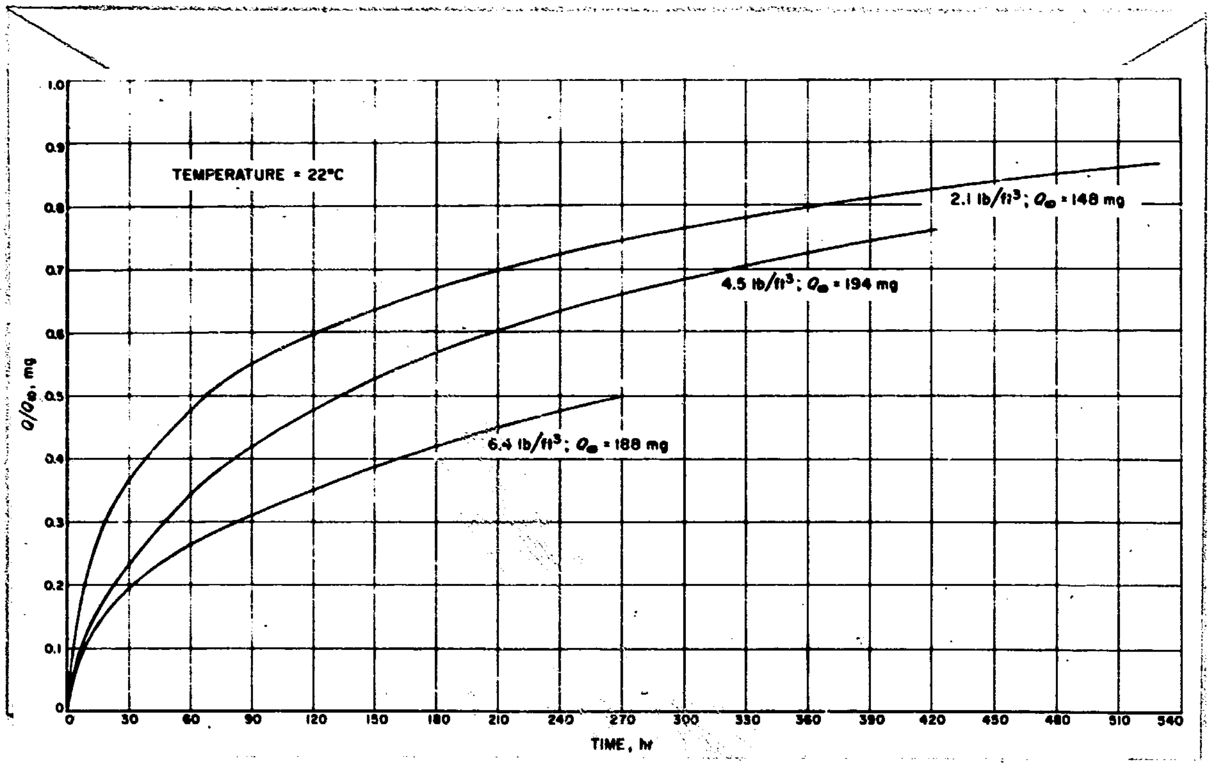

Figure 76.—Q/Q_∞ vs time for eccofoam FPH foams at 22°C.

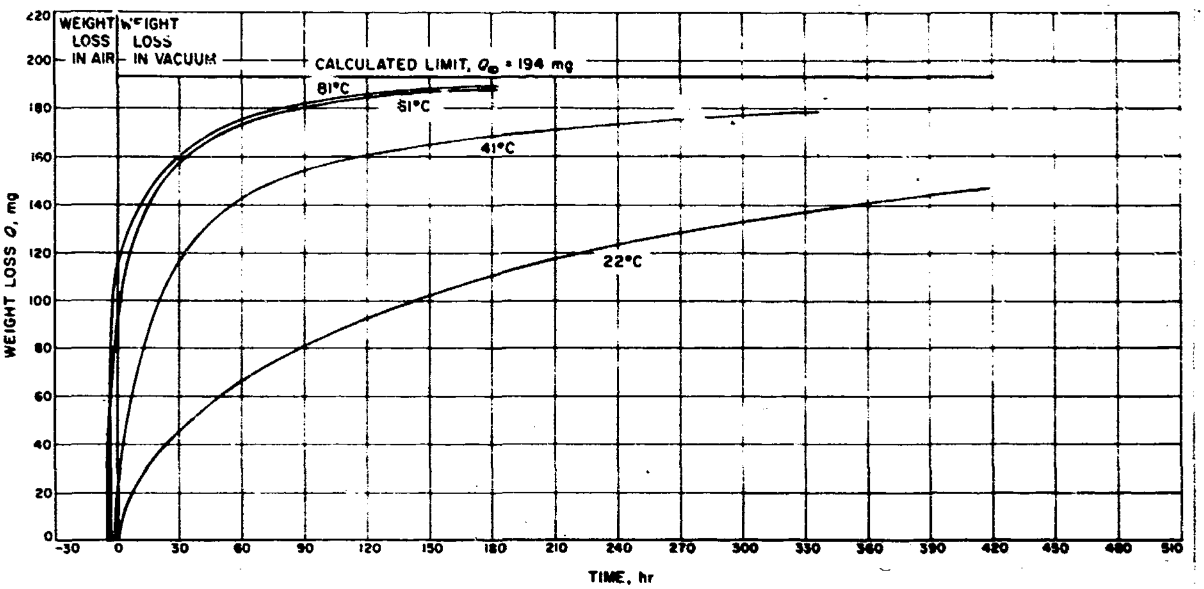

Figure 77.—Temperature dependence of the outgassing rate for an eccofoam FPH/12/6H foam of density 4.5 lb/ft^3

gas removal are small. Using the value Q_∞ = 194 mg. (which appears to be also the weight loss asymptote), it is seen that the Eccofoam has lost approximately 97.5 percent of its gas content in 180 hours at 61°C and higher, whereas only 57 percent of the gas content was lost in 180 hours at 22°C.

REFERENCES

1. Shennum, R. H.: Design of the Telstar Communication Satellite. Fifth Annual AIAA Structural and Materials Conf. Palm Springs, Calif., 1964.
2. Dunaetz, R. A.; and Bahun, C. I.: Foam-In-Place Dielectric Materials for Embedment of Aircraft and Space Vehicle Electronic Networks Operating at 3000 Volts. New York, N. Y., Sept. 1965.
3. Thielman, Russell: Foamed Plastics for Structural Functions in Electronic Equipment. Electrical Manufacturing, Jan. 1958, pp. 67-72.
4. Saunders, J. H.; and Frisch, K. C.: Polyurethanes: Chemistry and Technology: II Technology. Interscience Publishers, pp. 241-245; 261-268, New York, N. Y., 1964.
5. Bunker, Jr., E. R.: High Voltage Insulation Using Foams in Vacuum. JPL Space Programs Summary 37-37, vol. IV, V, Feb. 1966, pp. 89-90.
6. Anderson, B. H.: Rigid Foam Structures for Shock Protection of Electronic Sub-Assemblies. Electro-Technology, Sept. 1963, pp. 90-94.
7. Packaging, JPL Tech. Report No. 32-844, Section III, pp. 8-9.

8. Dunaetz, R. A.: Welded Module Packaging for Outer Space Applications, presented at National Electronic Packaging and Production Conf. New York, N. Y., June 4, 1963.

9. Lampe, J. W.; and O'Reilly, I. L.: Lightweight Embedment of Heat Sensitive Assemblies for Installation in the Manned Section of the Gemini Spacecraft. Presented at National Electronic Packaging Convention, Long Beach, Calif., June, 1965. Sponsored by NASA Contract NAS 9-170. Paper also appeared in SAMPE Journal, Oct. 1965, pp. 26-34.

10. Skochdopole, Richard E.: Thermal Conductivity of Foamed Plastics. Chemical Engineering Progress, vol. 57, no. 10, pp. 55-59, Oct. 1961.

11. Ledoux, Francis N.: Encapsulation, Electronics, Eccofoam. Process Procedure X-723-65-450, NASA Goddard Space Flight Center, Nov. 1965.

12. Ledoux, Francis N.: Handling, Cleaning, Decontamination, and Encapsulation of Mofsets Circuitry. NASA Goddard Space Flight Center, Oct. 1965.

13. Reference 4, pp. 261-268.

14. Ellern, William B.: Development of Sterilizable Electronic Equipment Processes. NASA-JPL Contract No. 951214, Northrop Corp., Sept. 1966.

15. Harper, Charles A.: Electronic Package Design. Electro-Technology, Nov. 1964, pp. 89-92.

16. Clauss, F. J.: Materials in the Space Environment. Presented at the Sixth Annual Symposium on Space Environment Simulation, St. Louis, Missouri, May 17-18, 1965.

17. Private communication, R. A. Dunaetz, Hughes Aircraft Co.

18. Space Materials Handbook, NASA SP-3025, 1966, pp. S-42 and S-57.

19. Detector Panel Development - Fairchild Document. Fairchild-Hiller Corp. NASA Contract NAS 8-5015.

20. Olyphant, Jr., M.; and Meyer, C. L.: Light Weight and Corona Suppressant Encapsulants for Aerospace Industries. Presented at NEPCON Convention, Long Beach, Calif., June 1965.

21. Proceedings of the Workshop on Voltage Breakdown in Electronic Equipment at Low Air Pressures. Technical Memorandum 33-280, Jet Propulsion Laboratory, Dec. 15, 1966. Edited by Earle R. Bunker, Jr.

22. Moacanin, J.; and Farrar, J.: Voltage Endurance Tests for Closed-Cell Foams. JPL Space Programs Summary No. 37-41, vol. IV, Oct. 31, 1966, pp. 109-111.

23. Liao, T. W.: Corona and Its Effect on Insulation. Insulation, pp. 18-21, March 1957, and pp. 22-24, Apr. 1957.

24. Cuddihy, E. F.; and Moacanin, J.: Outgassing Rates in Polymeric Foams. JPL Technical Report No. 32-840, Dec. 15, 1965.

25. Cuddihy, E. F.; and Moacanin, J.: Outgassing Rates in Polymeric Foams. JPL Space Programs Summary No. 37-34, vol. IV, pp. 137-142.

26. Cuddihy, E. F.; and Moacanin, J.: Temperature Dependence of Outgassing Rates in Polymeric Foams. JPL Space Programs Summary No. 37-35, vol. IV, pp. 125-129.

27. Cuddihy, E. F.; and Moacanin, J.: Polymer Permeation Constants from Diffusion Data on Polymeric Foams. JPL Space Programs Summary No. 37-36, vol. IV, pp. 153-154.

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Chapter VII

FOAM MATERIALS FOR HUMAN PROTECTION

PERSPECTIVE

Aerospace technology has posed vibration-isolation and impact-protection problems. One is the protection of crew members during normal and emergency environments without interfering with crew performance. The application of foam materials for crew comfort and safety required new concepts in mechanical design, fabrication techniques to produce intricate shapes and conformal designs, and performance testing with human subjects and anthropomorphic dummies.

Two types of mechanical loading action can affect personnel in space missions: (1) inertial loading (acceleration) and (2) surface loading (or stress) due to equilibrium with the inertial effects. Protection from acceleration involves high loading rates such as those occurring in landing impacts. Surface and inertial loading pertain to personnel comfort and survival.

Polyurethane foams are used for impact attenuation protection and comfort in astronaut helmet liners.[1] Plastic foams have been developed for prototype conformal couches and restraint pads in a support and restraint system. The design, fabrication and testing of a prototype Pilot Universal Couch for acceleration, vibration and shock has been reported.[2] This prototype was a soft-cushioned, contoured couch with a highly damped system in shock deceleration.

In a space-suit helmet, a rigid nonresilient foam would be desirable to attenuate high impact energy. To provide comfort as a cushion, a flexible foam is preferred since it undergoes gradual and continuous compression and deflection. Under severe loading or shock conditions, a resilient foam tends to "bottom," limiting its usefulness.

Required shapes are produced by molding of preforms or foaming-in-place techniques. Pads or stop forms are ordinarily made by cutting and trimming stock sizes. An individually sized helmet liner for the Mercury and Gemini programs was constructed in two principal steps: (1) preparing a silicone cast of the liner, and (2) transposing the cast to a mold in which a polyurethane foam liner is formed in the required head shape.

PROTECTION APPLICATIONS

Design with foam materials requires the resolution of conflicting material requirements for the man-environment interface.[3] The soft, flexible materials that reduce fatigue are inadequate for high-stress conditions, whereas high-strength rigid structural materials do not deflect sufficiently to provide comfort or relief from fatigue. So a soft, pliable foam is combined with more rigid contour materials. For some seat restraint systems the contours for each individual have been adjusted by means of stretchable materials, such as nylon Raschel net.

The principle of the contoured, rigid, protective foam and soft foam comfort liner, developed for the Mercury space-suit helmet, has been generally accepted. The Apollo "Bubble" type helmet developed by the Crew System Division of NASA Manned Space Center has three foam protection pads molded to fit on the inside and outside of the back of the helmet. The foam protects the head against buffeting, vibration, and impact during launch and re-entry. An exterior and interior foam pad are removable during flight, leaving one permanent liner on the inside of the helmet.

Foam materials meet vibration and acceleration (G)* loading requirements, but appear to be limited in handling landing impact shock. Crew couch-restraint systems have been designed without foam materials. The couch cushioning for the Mercury capsule was made of fiberglass enclosed in a continuous plastic covering. During development work on the restraint system for Project Mercury, a NOPCO urethane foam was used in the couch, which was precisely molded to the body contour. The foam maintained original body contours, even under high G loads. The subject of restraint systems is beyond the scope of this text.

Some materials have other disadvantages due to their modes of energy absorption. Thus, excessive rebound increases the strain on personnel while "bottoming" limits the energy absorption.

MATERIAL PROPERTIES FOR IMPACT AND VIBRATION ISOLATION

A fundamental group of properties governing the classification of foam materials in cushioning applications is the manner in which energy is stored, transmitted, absorbed, and dissipated.

Foam materials for cushioning applications may be classified as either of two types: (1) elastic (flexible or resilient) and (2) nonelastic (rigid or crushable). Elastic cushions withstand repeated shock and vibration; crushable cushions are also used. Typical static and dynamic properties of polyurethane foam cushioning materials are illustrated in Figures 78 to 87.[5]

Exclusive of thermal characteristics, the properties of greatest significance for shock isolation are: (1) compression stress versus strain, (2) maximum acceleration versus static stress, and (3) creep or strain versus time.

The characteristics of different foam materials for comfort cushioning applications can be illustrated by the compressive resilience for 2 lb/ft^3 flexible polyether and polyester foams in Figures 88 and 89.[6] Resilience is a measure of the rate at which load and thickness are recovered after deflection, under slow loading and unloading

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*G is the unit used for physiological acceleration defined as the total reactive force divided by the body mass.

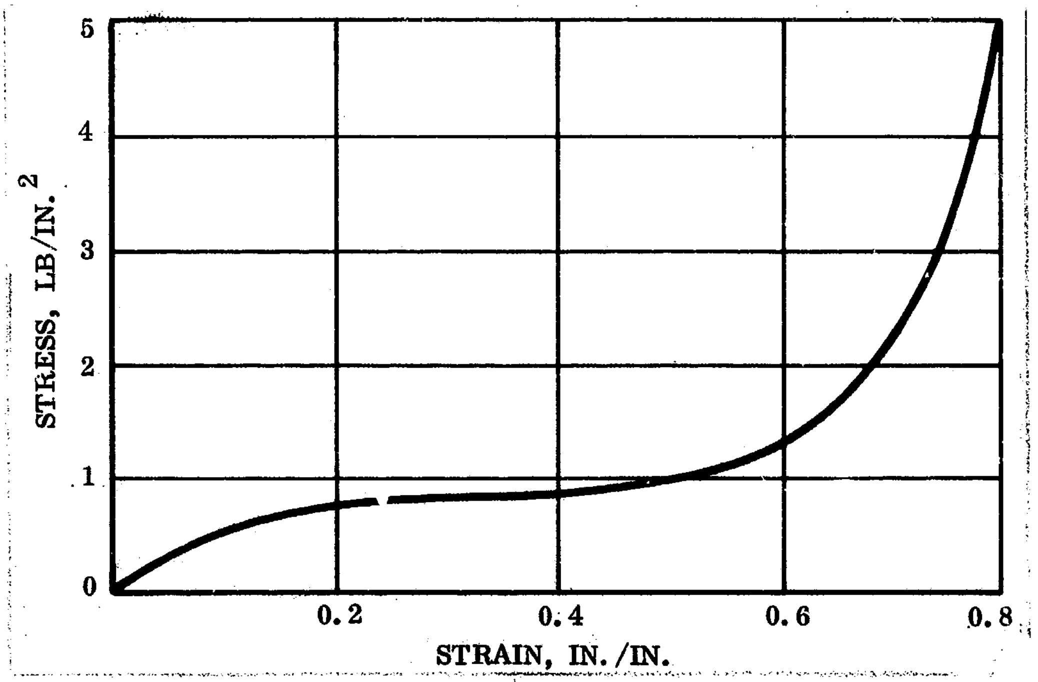

Figure 78.—Compression stress vs. strain for polyester urethane foam (2.2 lb/ft^3).

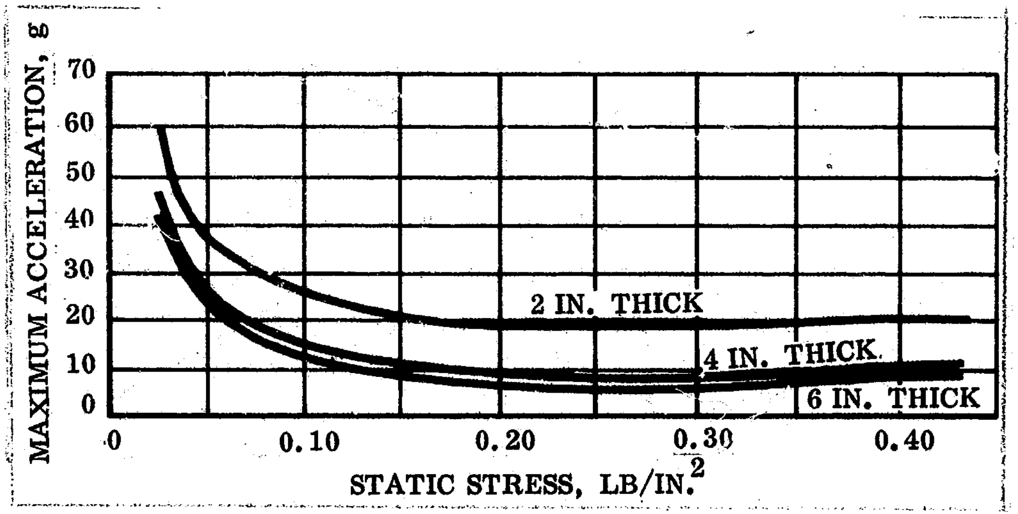

Figure 79.—Maximum acceleration vs. static stress for polyester urethane (2.2 lb/ft^3)—12-in. drop.

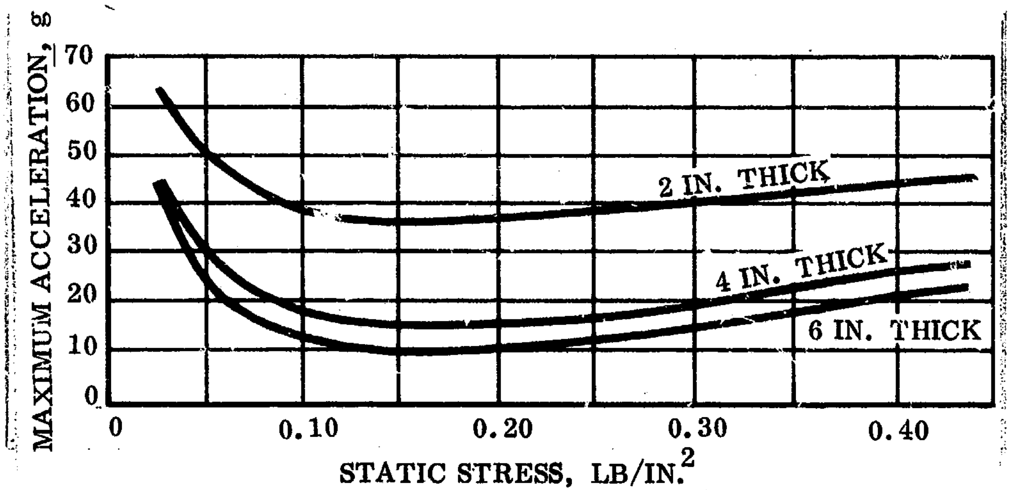

Figure 80.—Maximum acceleration vs. static stress for polyester urethane (2.2 lb/ft^3)—24-in. drop.

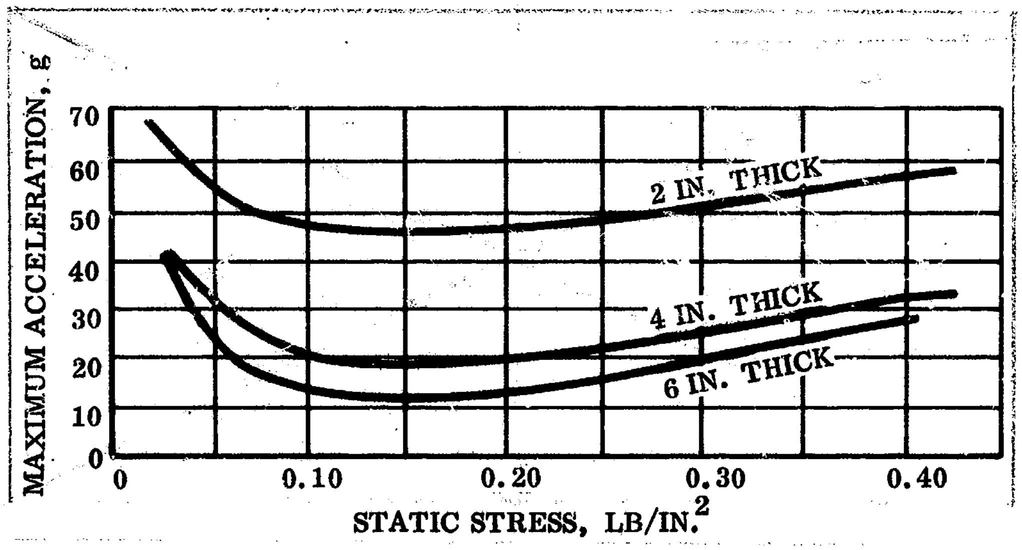

Figure 81.—Maximum acceleration vs. static stress for polyester urethane (2.2 lb/ft^3)—30-in. drop.

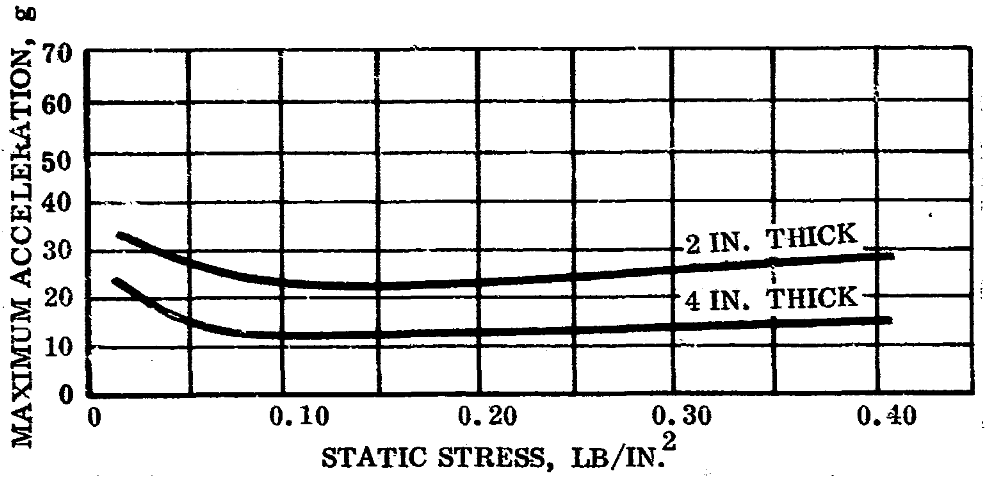

Figure 82.—Maximum acceleration vs. static stress for polyether urethane (2.2 lb/ft^3)—12-in. drop.

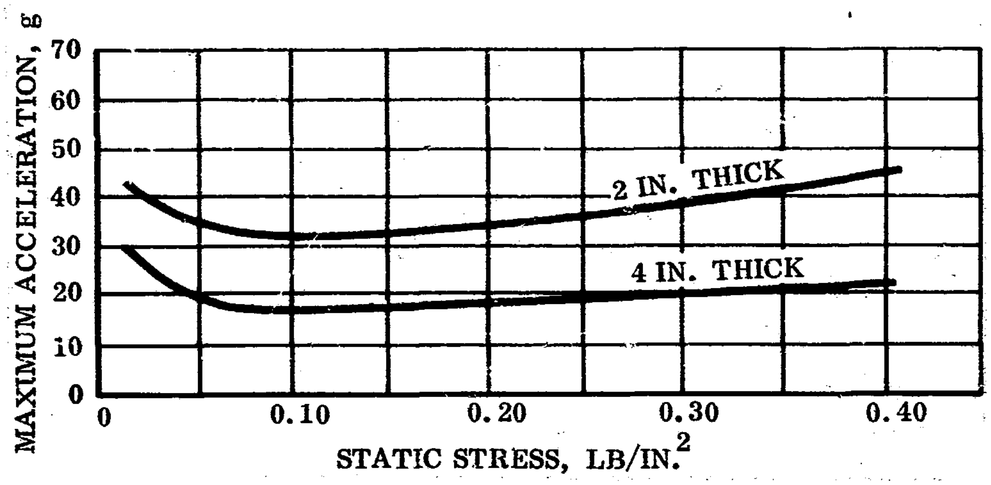

Figure 83.—Maximum acceleration vs. static stress for polyether urethane (2.2 lb/ft^3)—18-in. drop.

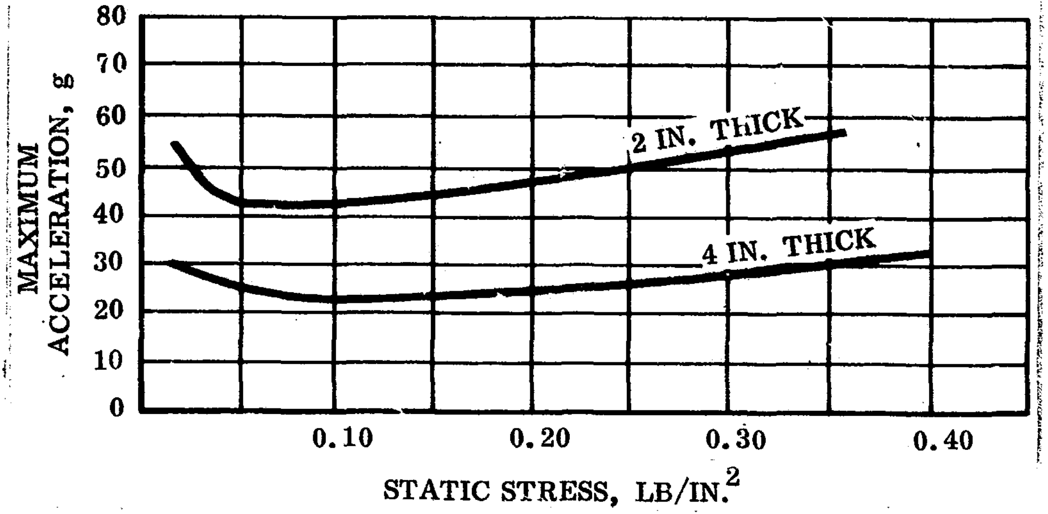

Figure 84.—Maximum acceleration vs. static stress for polyether urethane (2.2 lb/ft^3)—24-in. drop.

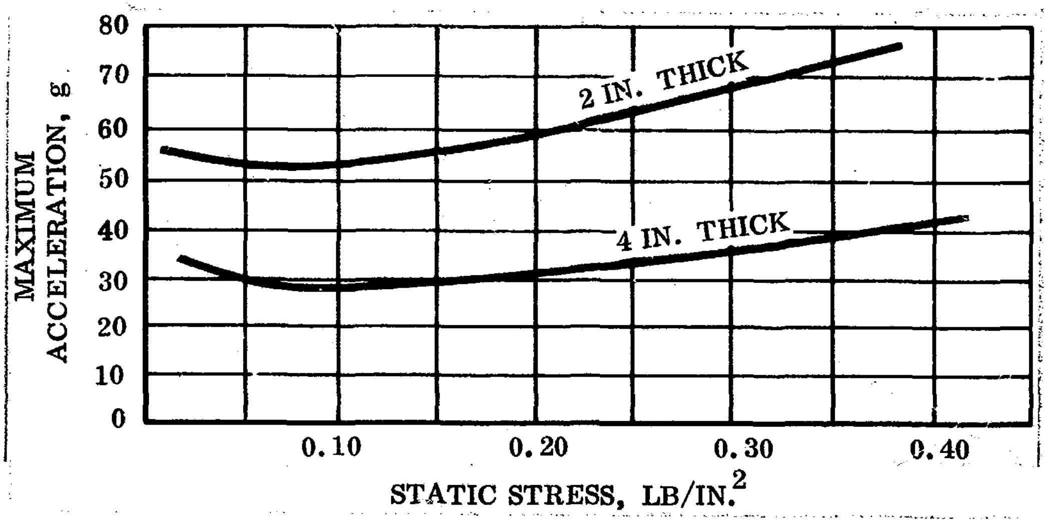

Figure 85.—Maximum acceleration vs. static stress for polyether urethane (2.2 lb/ft^3)—30-in. drop.

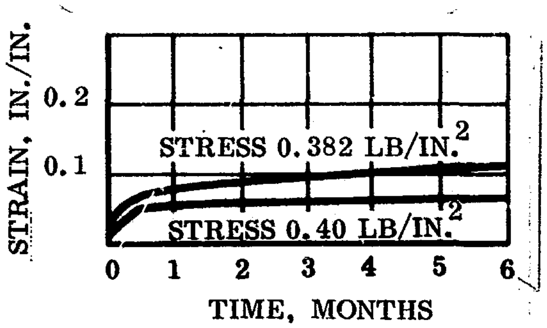

Figure 86.—Creep characteristics for polyester and polyether urethanes (2.2 lb/ft^3).

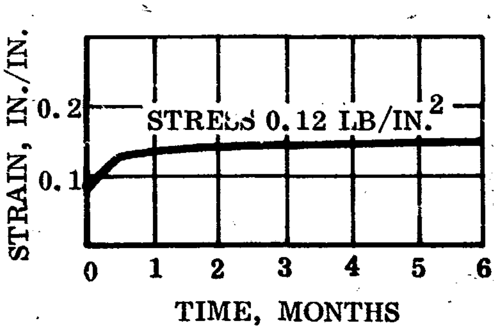

Figure 87.—Creep characteristics for polyester and polyether urethanes (2.2 lb/ft^3).

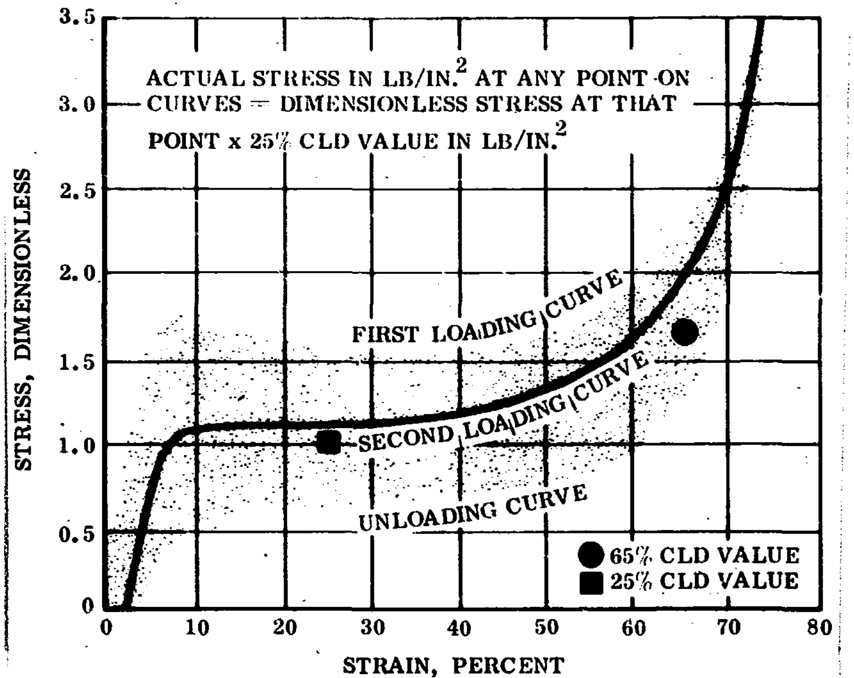

Figure 88.—Typical dimensionless stress—strain plots for polyester Nopcofoam S-5502-C.

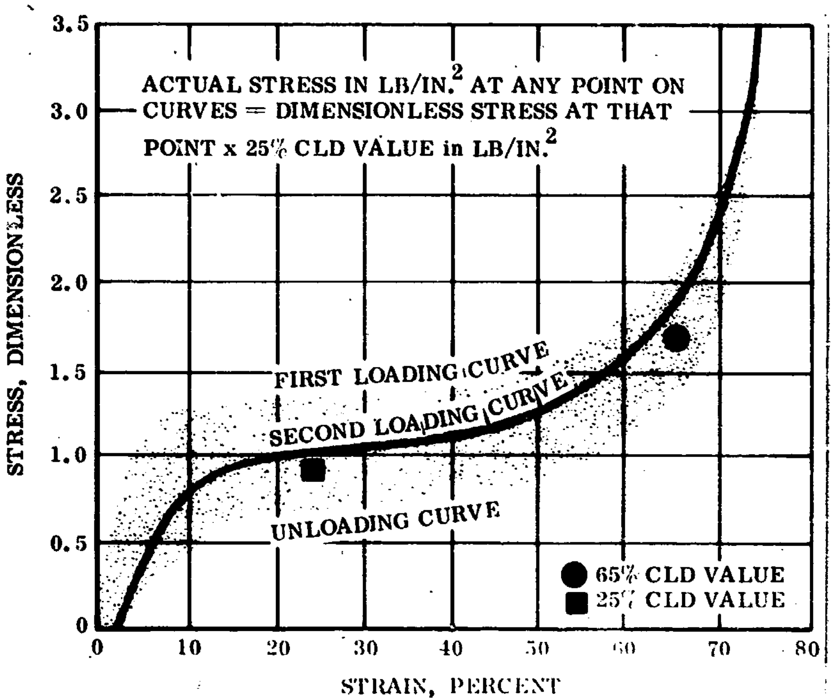

Figure 89.—Typical dimensionless stress—strain plots for polyether Nopcofoam.

conditions. Compressive resilience is a dimensionless energy term and is defined as the percent ratio, (area under the unloading curve/area under loading curve) x 100. The hysteresis loop also shows relative behavior; the smaller hysteresis loop of a polyether foam characterizes it as more resilient.

The curves for static stress versus strain or compression versus deflection in Figures 88 and 89 show a non-linear behavior with three distinct loading regions. These are: (1) the initial steep rise or linear loading, (2) the plateau region where relatively uniform loading distribution prevails, and (3) the final steep rise where the stress or loading increases rapidly with change in deflection. In region (1), kinetic energy is stored as potential energy by resilient deformation, providing comfort. Region (3), which represents a rapid rate of rise of force input into the material, may mean an excessive accelerational force area to be protected. This effect limits the use of currently known flexible foams for shock attenuation, as compared to a rigid crushable foam.

Rationale for Maximum Force Attenuation

An idealized representation of the behavior of resilient (energy-storing) versus nonresilient (energy-dissipating) materials under compression is shown in Figure 90.[7] In resilient compression, the restoring force varies linearly with displacement as in line AB, and the stored energy is measured by the area of triangle ABG. For equal

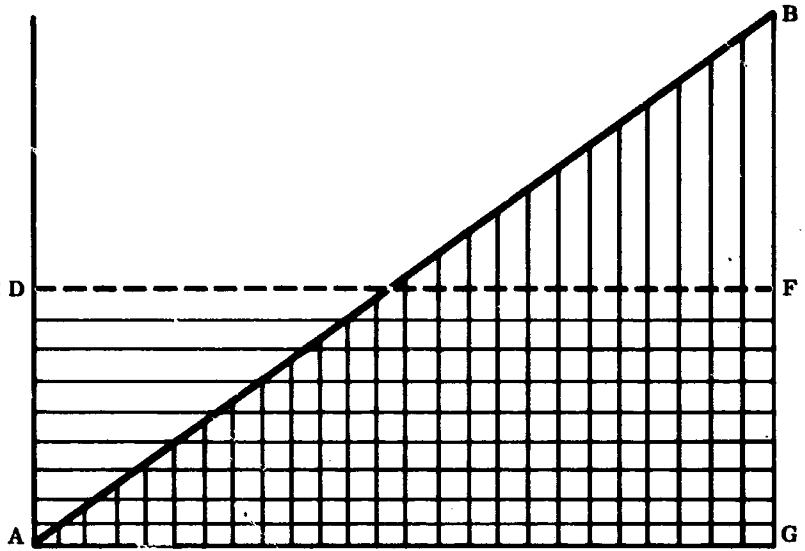

Figure 90.—Idealized representation of energy—storing vs. energy dissipating behavior of foams under compression.

kinetic energy, if a material could be compressed at a constant force expressed by line DF, with conversion of the kinetic energy into non-recoverable work (measured by rectangle ADFG), the maximum force would be only half that developed during resilient compression and there would be negligible rebound. This principle has been applied in development protective headgear.

A desirable material would exhibit, under compression loading, a stress-strain diagram similar to Figure 91. This curve, for a rigid, crushable foam, is characterized by: (1) a maximum permissible strain of approximately 80 percent and (2) conversion of input energy into nonrecoverable work due to permanent deformation.

An ideal material for shock protection would exhibit a similar stress-strain diagram but would undergo an even greater range of percentage compression and would not be permanently deformed. Such a material recovers its shape after deformation (without fracture) in a moderate period of time. Such damping would minimize rebound. However, the time between impacts may be brief enough to limit the use of a material with slow recovery.

"Bottoming" which occurs in nonrigid foams, refers to a compression for which no further material displacement occurs.

Rigid foams have excellent impact and shock absorption characteristics, but appear to have limits for high impact loading (high G) when measured against allowable human response. Orientation of loads on landing is approximately 20 G in the Z direction (longest axis) and 100 G in the X and Y directions (lateral or transverse axes).[8] G is defined as the ratio of acceleration force/gravitational force. Desirably, values $\pm G_X$, $\pm G_Y$, $\pm G_Z$ greater than 100 G, or associated impact forces, would be accommodated by energy attenuation in a properly restrained system.

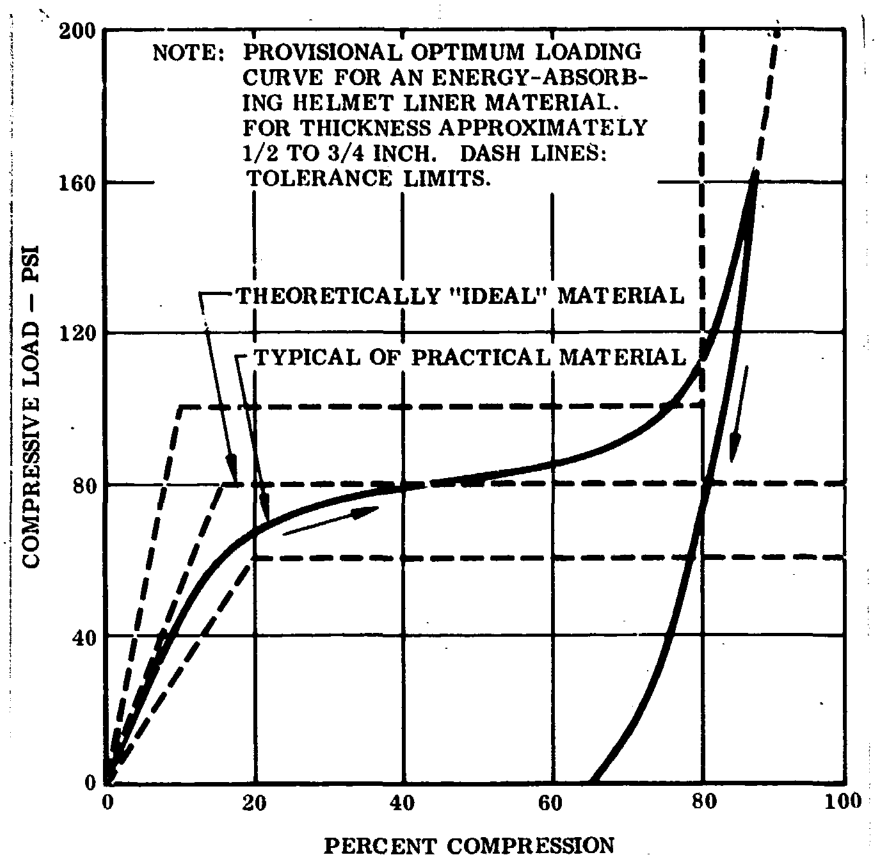

Figure 91.—Compression loading curve for a rigid, crushable foam.

PROTECTIVE HELMET TECHNOLOGY

Effects of Shock and Vibration

A statistical survey of mishaps related to high velocity impacts on the body indicates the importance of head protection. Actually, the head can withstand a relatively high, long duration impact acceleration, compared to the body. But since its natural frequency is higher than the rest of the body, it cannot tolerate as high a velocity change. The response of the head to a blow is a function of the velocity change and the duration and area of impact. Based on pendulum tests, head velocity change should be kept at less than 10 feet per second.

The ability of a helmet to absorb kinetic energy has been determined in a test program by International Latex Corporation. The helmet was made to collide with an immovable object and the incident and rebound velocities were determined.[9]

Behavioral abnormality such as disturbance of visual acuity, arising from body vibrations, is dependent on both the frequency and amplitude of vibration. The head's natural frequency is approximately 30 cps, whereas the body's natural frequency is in the range of 4 to 8 cps. When vibrated in a longitudinal direction, for example, the head exhibits a mechanical resonance between 20 and 30 cps. In this vibration range, the head displacement amplitude can exceed the shoulder amplitude by an acceleration ratio (transmissibility ratio) of 3.0 to 3.5, with a loss of visual acuity.[5] The above effect would be illustrated in a plot of acceleration ratio versus frequency (cps) of longitudinal vertical vibration applied to a seated human. Above a frequency of 10 cps, vibration displacement amplitudes of the head are larger than the amplitudes of the exciting force (in this case an exciting table).

Vibration Protection

In general, vibrations of high amplitudes and low frequencies are dangerous for the entire body system. Vibration protection is normally provided within the initial deflection of the attenuation system. This portion of the attenuation system should be critically damped. The effective natural frequencies for flexible foam liner material are usually in the range of 8 to 12 cps, with initial deflections of 0.25 to 0.38 inch.

Impact Protection

Impact protection is provided the helmet by an acceleration attenuation system such as plastic foam, a deformable strap suspension, or a combination of both. Acceleration protection provided over particular segments is a function of the fragility of that segment and the likelihood of impact.

Impact phenomena are inherently of short duration. As stress pattern changes occur, energy is stored or released as a deformation of the elastic elements. Peak values depend on the ways in which the mechanical protection system transmits or accepts energy.

Principles in Protection Against Head Injury

A fundamental rule in preventing head injury is to minimize the amount of transmitted energy, which can be done in the following ways:

(1) Use a hard, smooth surface for the helmet shell to direct a projectile particle, such as a micrometeorite, away from the head by an elastic collision. This will also help prevent helmet penetration by the sharp points of the impacting particles.

(2) Absorb and attenuate the energy of impact by the use of appropriate materials to reduce the level of acceleration, the rate of acceleration, and the amount of energy transmitted. Storage of energy alone does not materially decrease the energy transmitted.

Studies of materials for controlled impact energy absorption, helmet sizing, and comfort have included cork, nylon webbing, rigid foamed plastic epoxy spheres, flexible foam, and stretch fabrics.

Rationale for Shock-Absorbent Foam Material Design[10]

Design of foams for impact protection is based on their value in an acceleration attenuation system. Such a system is required to provide the optimum dynamic mechanical response as well as protection to the adjacent human segments.

The fragility of an item is defined by the peak acceleration it can withstand. Fragility is expressed as a dimensionless ratio defined as acceleration of force environment/acceleration due to gravity (g - 32.2 ft/sec^2). The term "fragility" is thus a quantitative index of the capability of an item to withstand shock and vibration and connotes a maximum permissible acceleration. Fragility is commonly determined by drop-test machines, hydraulic shock tests, and pendulum impact machines.

The basic system for a crushable (rigid) foam cushion for single impacts can be represented by the schematic shown in Figure 92. When the system is impulsively loaded, the helmet shell experiences a velocity change in a time very small compared to the duration of the response. The dynamic response characteristics of the head depend on the characteristics of the crushable liner, which are expressed by the coefficients which appear in the stress laws for the material, and the following system variables:

m = mass of the head
v = velocity change of the helmet case
A = characteristic area of the head along the direction of the forcing function
t = duration
h = characteristic thickness of the linear

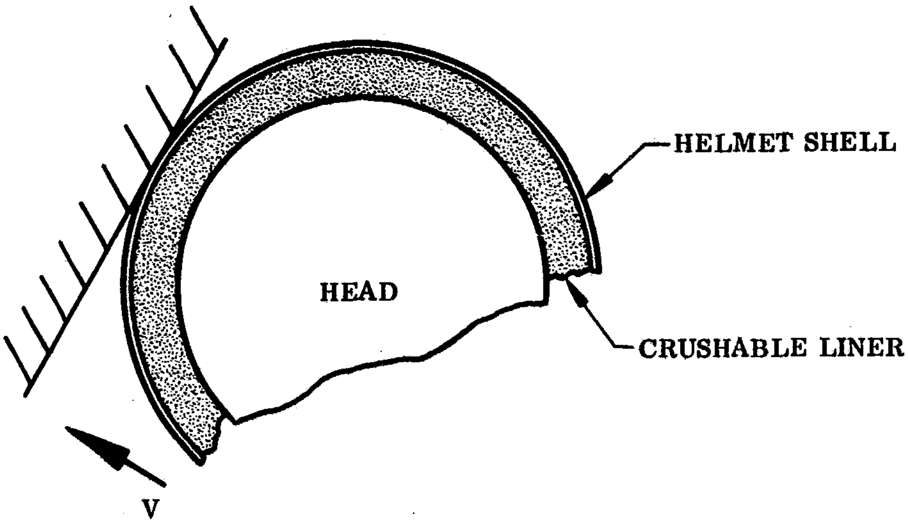

Figure 92.—Head-helmet system.

The design factors applicable to this system model are (a) the shock environment; namely, maximum G loading and rate of change of acceleration or loading pulse; (b) fragility index of the system; (c) maximum acceleration versus static stress for a given material and thickness; (d) static stress versus strain curve for the applicable material to determine the static deflection; (e) creep properties to make allowance for any loss in thickness during storage.

An equation governing the acceleration, (a) of the packaged item with a given cushioning material can be nondimensionally represented by the following relation

$$\frac{a}{v^2/2h} = f\left(\frac{mv^2}{2Ah}, \frac{v}{h}, t\right) \qquad (1)$$

This equation was derived in a study on Package Cushioning. Equation (1) lends itself to optimization of the dynamic response characteristics of the system. It may also be used to establish an index similar to the fragility index employed in package cushioning analysis.

Illustration of the impact attenuation provided by an energy absorber may be presented by typical energy profiles and the stress-strain relation for an energy absorber as shown in Figures 93 and 94, respectively.

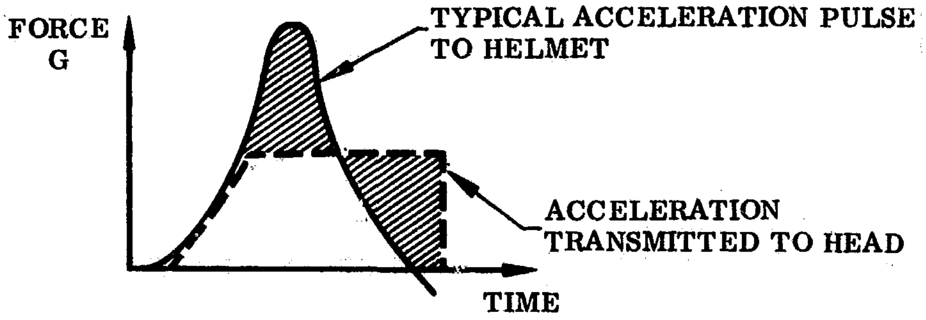

Figure 93.—Energy profile.

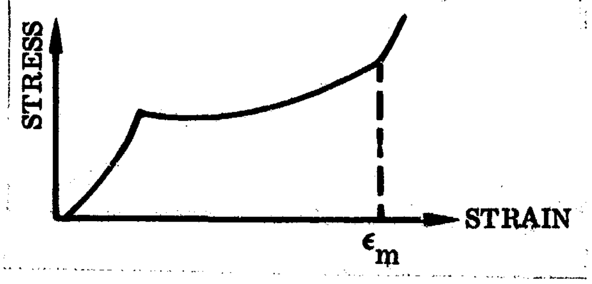

Figure 94.—Stress-strain relation for an energy absorber.

Equations for this system can be written as

$$V^2 = 2G\ S \tag{2}$$

$$S = \epsilon_m H \tag{3}$$

where

V is the impact velocity
G is the acceleration transmitted to the head
S is the stopping distance
ϵ_m is the maximum permissible strain
H is the cushion compression

Eliminating S from equations (2) and (3), one obtains

$$H = \frac{1}{\epsilon_m} \cdot \frac{V^2}{2G} \tag{4}$$

Equation (4) governs the relation between the compression, the impact velocity force, and permissible strain. The mass term (m), which does not appear in Equation (2), can be derived from the energy equation, $1/2\ mV^2 = m\ G\ S$.

In reference to Figure 93, the object of the crushable material is to reduce the maximum G of the acceleration pulse. When inadequate attenuation is provided, the maximum G transmitted can exceed the tolerance limit (indicated by the fragility index). The $G_{maximum}$ can be reduced to an acceptable limit, shown by the horizontal line, by selecting a material and thickness cross-section which absorbs the energy transmitted by extending the pulse time.

Sample Calculation for Crushable Foam Thickness

Assumptions

1) The limiting velocity of head motion is 10 ft/second
2) The head mass is 11.4 lbs.
3) The stopping distance of the head mass is approximately equal to the cushion compression
4) $\epsilon_m = 0.8$ and $G = 100$

From equation (4)

$$H \text{ (inches)} = \frac{1}{\epsilon_m} \cdot \frac{V^2}{2G} = \frac{(10^2)\ \text{ft}^2/\text{sec}^2}{0.8 \times 2 \times 100 \times 32\ \text{ft/sec}^2} \times 12 = 0.234 \text{ inches}$$

to provide a safety factor of 2, approximately a 0.5 inch thickness would be employed.

Vibration Isolation

For vibration isolation of systems having a single degree of freedom, the most effective isolator is the soft cushion. The material frequency of the protected system on the cushioning medium must be low in comparison to the frequency of vibration to be withstood. This is illustrated by a log-log plot of transmissibility as a function of the forcing frequency/material frequency ratio (Figure 95) and by a plot of force transmissibility for various damping ratios, $\xi = c/c_c$ (Figure 96).[5] Where

$$c/c_c = \frac{\text{damping}}{\text{critical damping}} \text{ ratio}$$

In Figure 95 one will note that for the high values of W/W_n the transmissibility is small, where W = forcing frequency and W_n = natural frequency. Transmissibility is the ratio of the transmitted force (F_T) to the exciting force (F_0), or the ratio of transmitted displacement of forcing displacement.

Transmissibility-versus-frequency curves indicate that the transmissibility is less than unity for $W/W_n > \sqrt{2}$, establishing the governing condition for vibration isolation. The curves also indicate that an undamped spring is superior to a damped spring in reducing the transmissibility; damping is necessary when the frequency passes through the resonant region.

In helmet designs, critical damping (c_c) is desirable for completely damped oscillatory motion ($\xi = 1$). Critical damping is attained when the point is reached where oscillatory motion just ceases.

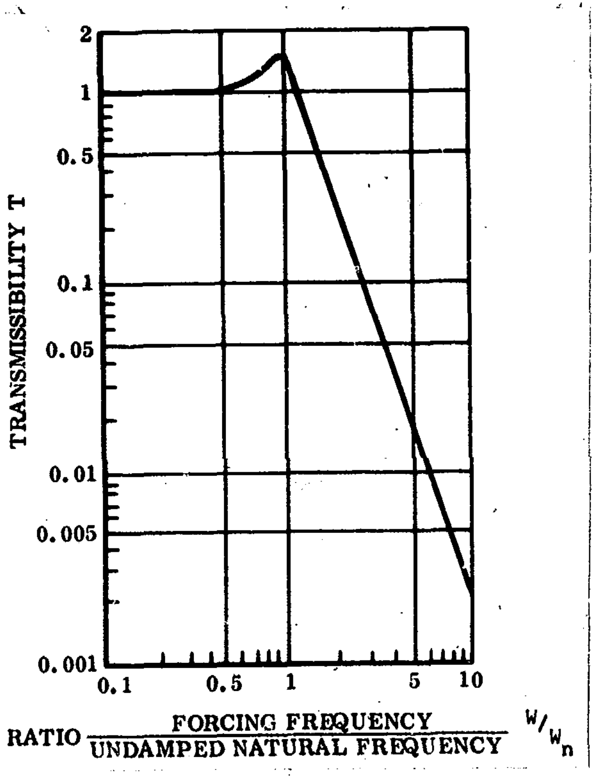

Figure 95.—Transmissibility curve for polyether.

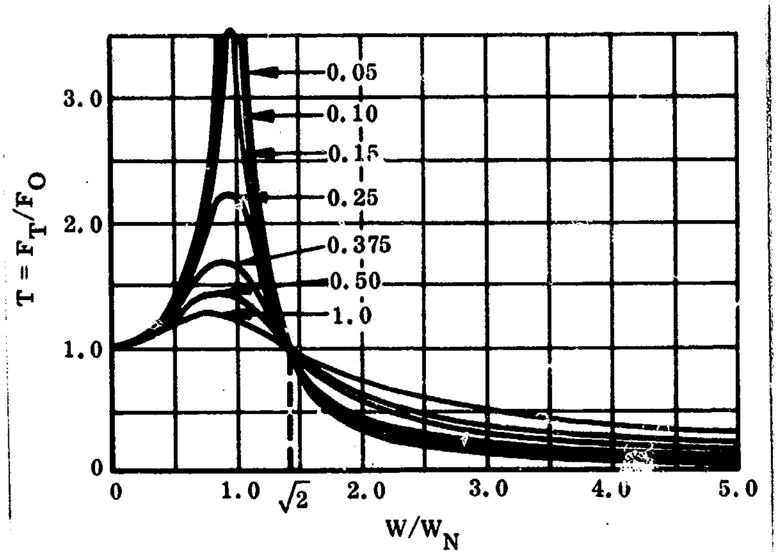

Figure 96.—Transmissibility versus frequency ratio, W/W_n.

APPLICATIONS OF URETHANE FOAMS TO HELMET DESIGN

Urethane foam materials have been evaluated and used for the design of astronaut helmet liners. The object was to produce a custom fit providing both comfort and protection.

For severe impact loading, designs have been based on: (1) load/compression curves adapted to dissipation of high impact energy while crushing under impact forces; (2) high human-head tolerance to applied forces, when these are evenly distributed and stress concentrations are essentially absent.

About 1960, Nopcofoam Type E-304 was applied (by Protection, Inc.) to custom fit an astronaut's head inside of a helmet shell. E-304 foam, a crushable, rigid foam, acted as a force spreading member. An impression of a man's head was converted to a plaster replica, followed by a process to conform to the replica.

Project Mercury Helmet Liners

In the first stage of helmet design, impact protection was limited because an energy-absorbing protective liner was not included. One early concept featured a suspension of nylon webbing anchored to a reinforced fiberglass shell. Nylon was not suitable for side-loading, although it was apparently satisfactory for the top of the head.

In 1962, B. F. Goodrich Aerospace and Defense Products delivered to NASA under contract, ten individually sized helmet liners, six semi-universal helmet liners, and one Mercury helmet.[11] The helmet liners were fabricated from semi-closed-cell, polyurethane foam (Nopco Lockfoam F-506-C). The liners included a one-quarter inch flexible, open-cell polyurethane foam (Nopco Lockfoam Type UU-34) as a comfort liner.

Fabrication of Polyurethane Foam Helmet Liner Head Casts

In making the head cast, an aviator's type inner liner, made from one-quarter-inch neoprene sponge, is placed on the subject's head while making the cast (Figure 97a). The outer casting shell is fabricated from a Mercury helmet with provision for separation at the center line for removal of the cast (Figure 97b). The gap is filled by pouring catalyzed Silastic RTV 502 casting material through the opening at the top center of the shell (Figure 97c). Both sponge liner and shell are tied down under the subject's chin. The Silastic cures in 15 minutes to a hardened elastomer that is flexible and easily removed. The low exotherm heat does not cause discomfort. The silicone cast is then removed from the head and helmet and stripped from the sponge liner (Figures 97d through 98c). Thus a pattern of the foam liner is produced, with allowance for a one-quarter-inch comfort liner.

Liner Mold and Sizing Plugs

The female half of the liner mold starts with a Mercury helmet shell, its lip cut to a predetermined line. This outer shell is placed in a container and enclosed with epoxy-fiberglass mixture (Figure 98d) to form a hard, compact mold half. The silicone cast is then placed in the female mold, held firmly, and trimmed around the outer edge to fit. The mold and cast are encased in a wooden container (Figure 98e), which extends two inches above mold top, then filled with molding plaster. After forming a plaster plug, the cast and plug are dried for 48 hours at 125°F. The plug is sanded and waxed before use.

Five vent holes, drilled at the highest points of the female of the mold, allow the excess urethane foam to escape and vent internally generated gasses. A ridge across the top of the mold forms a recess for communication leads, and patches on the mold form recesses for Velcro tape segments which hold the liner in the shell.

Urethane Liners

Before casting, both mold halves are waxed and allowed to dry. The urethane polymer and catalyst are thoroughly blended (about 1 minute); when a white foam starts to appear, the mixture is poured into the mold. The mold is closed, secured with a steel framework and allowed to foam for one and one-half hours before removing the foamed liner. (Figure 98f.)

Processing Technique

Nopcofoam F-506 is a two-part system, a polyester polyurethane prepolymer component and a catalyst component which also contains water to react with isocyanate groups and thereby provide the CO_2 blowing agent. Nopcofoam F-506 is a "flexible" semi-closed cell foam with approximately 45 percent closed cells.

In foam technology, the term "flexible" may be somewhat misleading. The load bearing characteristics of a foam can vary widely with density, the average density may not be the same as the core density. Mechanical strength properties increase

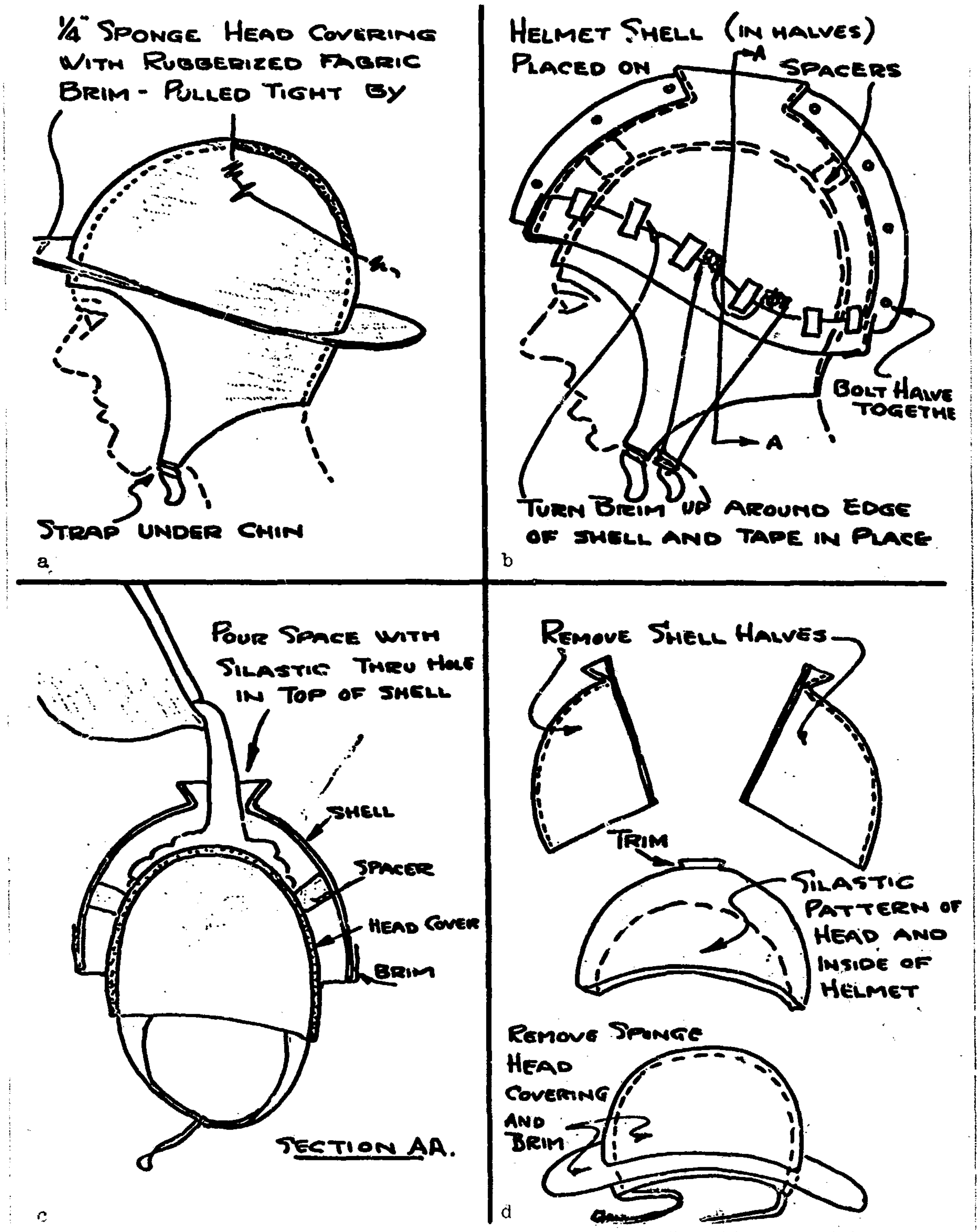

Figure 97. —Foam helmet liner head casts.

with increasing density. A range of overall densities from 4.0 to 1.0 lbs/ft^3 and higher can be produced with Nopcofoam F-506.

The helmet liner may have an overall density of about 10 lbs/ft^3 and a nominal thickness of one inch.[12] Thickness varies with head size. The density of the molded-in-place foam increases from core to outer surfaces.

The stress/strain loading and unloading curves were obtained on 2" x 2" x 1" thick specimens in an Instron Tester at a crosshead speed of 2 inches per minute.[12] Under these conditions the mechanical characteristics are:

(1) About 75 psi static stress at the "knee" of the curve just prior to rapid loading. This point corresponds to approximately 75 percent deflection. The stress far surpasses the value obtainable for a 6-lb/ft^3 density (about 7 psi).

(2) The curve for a first and second loading shows good hysteresis and energy absorption characteristics.

Impact loading measurements with force inputs of one to ten milliseconds duration would be required to evaluate against the expected performance.

(Curing)—The helmet foamed liners, after forming, are cured in an oven for 3 hours at 170°F to remove all odors, and to stabilize the mechanical properties.

(Molding Accuracy)—Accuracy in molding is ±1/16 inch on each dimension. Any shrinkage distortion is related to the shape being made.

(Comfort Layer)—A 1/4 inch Scottfoam open-cell comfort liner is cemented to the helmet liner and trimmed to contour. A preformed, soft leather liner is positioned over the comfort liner and cemented in place around the periphery of the foam liner. The comfort layer compensates for variations in fit.

(Attachment in Helmet)—Velcro tapes are cemented in the recess on the outside of the liner, and matched inside the helmet to secure the liner.

Project Gemini Helmet Liners

Gemini helmet liner work has been performed under NASA Contract 9-1252. The techniques of molding urethane foam shapes were similar to those for Mercury liners. The outer surface of the helmet liner had molded channels as a distributing ductwork for ventilation.

Project Apollo Helmet Liners

New applications of foam helmet liners or protection pads are found in the Apollo "Bubble" type helmet developed by the Crew Systems Division of NASA Manned Space Flight Center. This helmet design has improved comfort and peripheral vision. The polycarbonate plastic shell has excellent impact resistance and transparency.[4]

Three different foam sections provide impact protection. One is permanently mounted inside the helmet and there are two removable foam liner sections (Figure 99). They are used in the following manner:

(Permanent Foam Section)—At the rear of the shell, the shock-resistant foam has channels to distribute gas for breathing and defogging. It provides protection against slight impacts.

(Removable Interior Section)—This is a preformed, slightly resilient bump cap which can be inserted to hold the wearer's head in a relatively stationary position with respect to the shell during periods of potential severe impact.

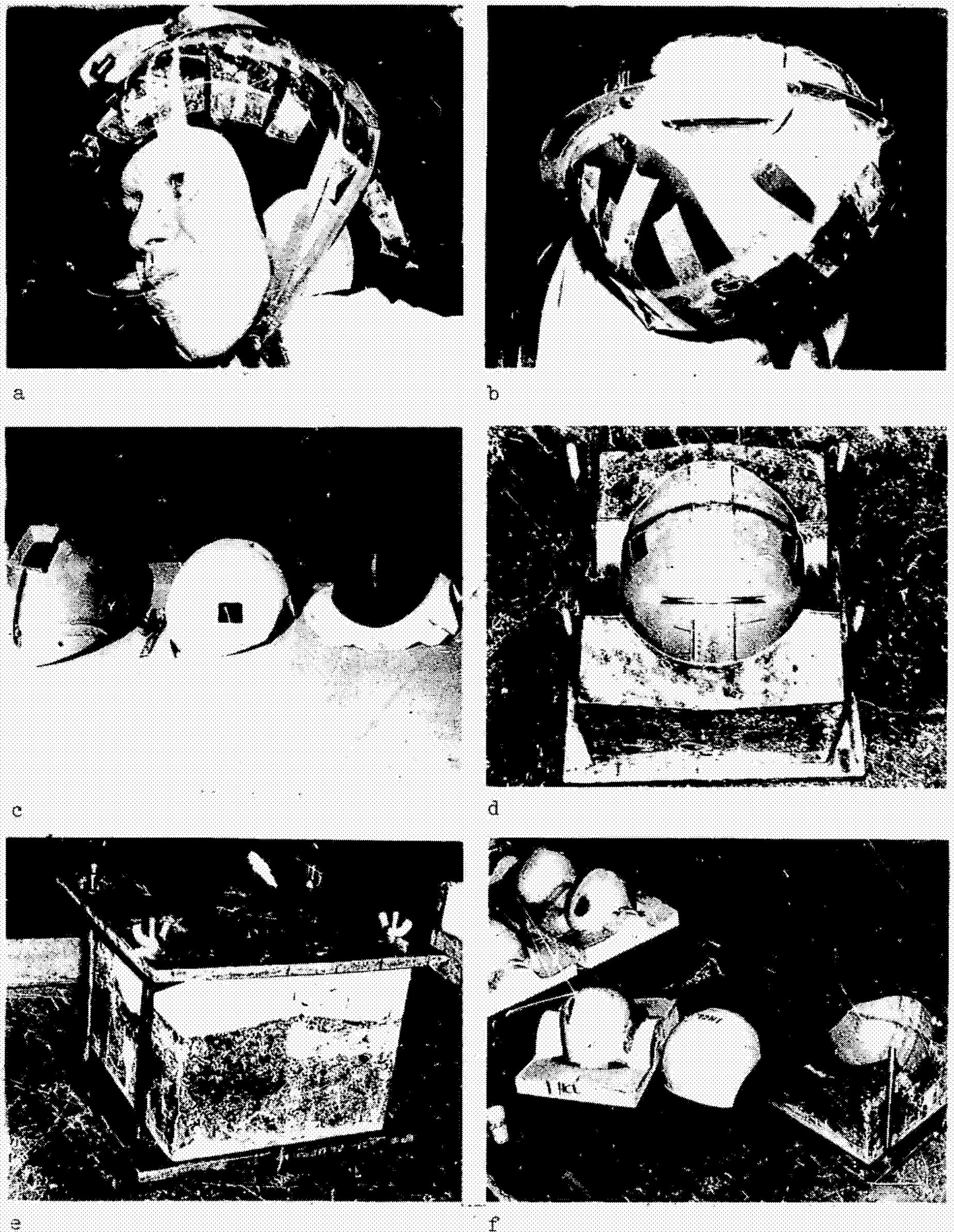

Figure 98.—Sponge liners.

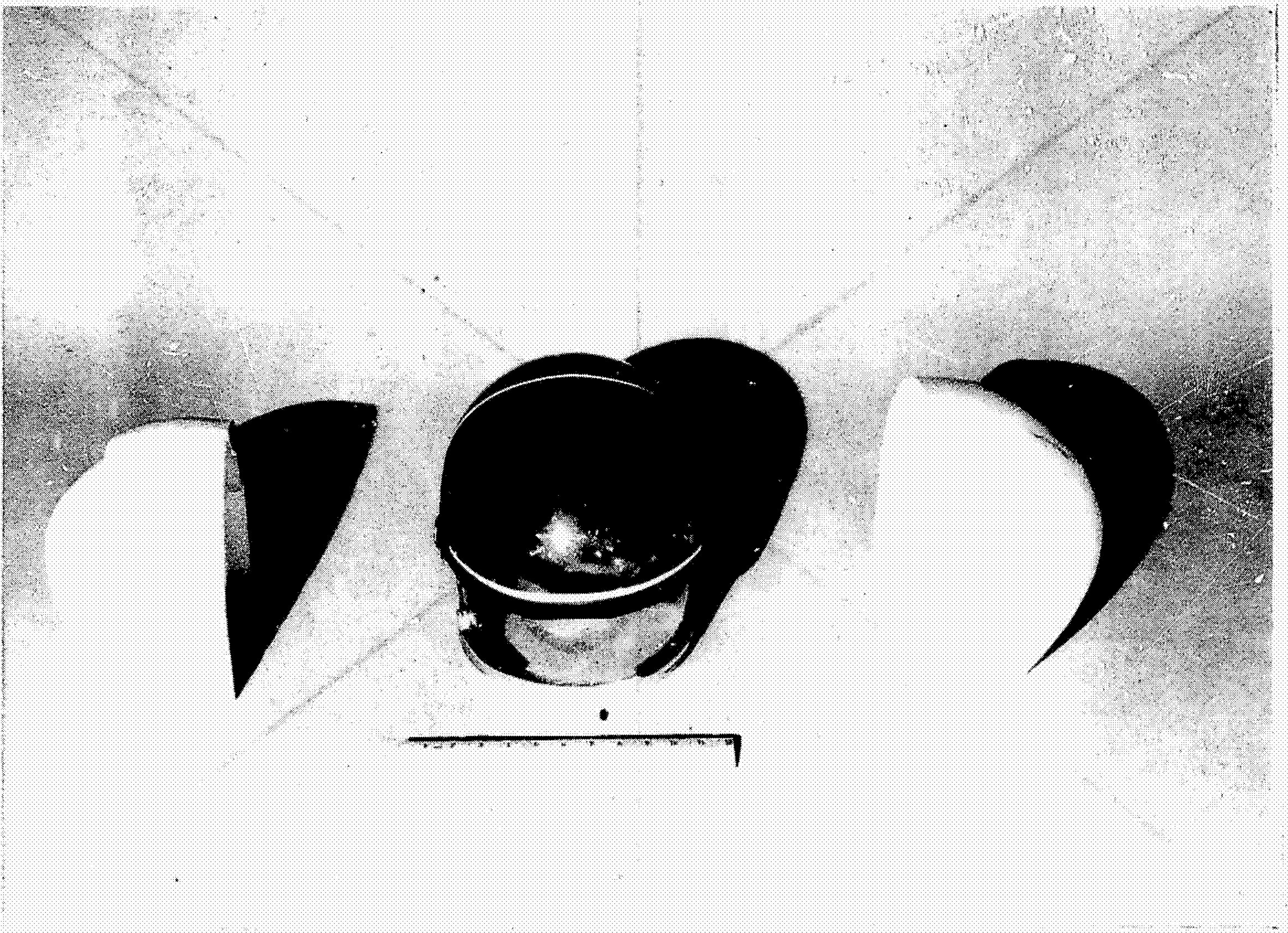

Figure 99. —Apollo helmet foam liners.

(Removable Exterior Section)—This consists of an external impact pad which can be removably secured on the rear exterior of the shell during severe impact periods. This increases protection without requiring a larger helmet shell.

SUPPORT RESTRAINT MATERIALS

Support-restraint systems must offer:

(1) comfort during extended periods of occupancy
(2) optimum fit for a wide range of crew sizes
(3) maximum protection against impact and vibration
(4) minimum restriction on movement

Researchers have investigated dilatant materials, paramagnetic particles in viscous solutions, fluids, nylon Raschel nets, wire screens, plastic foams, microballoons, foam-in-place materials, three-dimensional fabrics, and wire-reinforced nylon webbing.

Principles for Support-Restraint Design

If resilient or elastic support and restraints cause excessive rebound they can be replaced by rigid, nonresilient materials. Distribution of pressure uniformly over the entire body by suitable contouring tends to reduce the applied pressure and therefore minimize the tendency to damage the human tissue under impact on high acceleration loading.

An elastic foam liner (comfort layer) is of a thickness and compressive strength to attenuate vibration without any appreciable elastic rebound during impact accelerations. Polyurethane foam with reduced resiliency and a 3-lb/ft^3 density in 1/4 inch to 1/2 inch thickness has been evaluated for this purpose. The foam is precision molded to the body contours.

Restraint pads are used for restraining parts which are difficult to handle by other methods; e.g., the hips and knees. Pads are usually made of polyurethane foam or microballoons and are used in connection with restraint, particularly from lateral loads.

In the universal integrated couch-restraint system,[13] the back pan and seat pan are covered with a comfort cushion of foam rubber. Shoulder restraint is lined with foam rubber.

In the design and fabrication of a microballoon body,[14] the head is supported within a contoured shell by a layer of polyurethane foam one inch thick. The arms are restrained by fiberglass lined with 1/2-inch polyurethane foam. The lower legs are restrained by fiberglass molded to approximate the leg contour and lined with 1/2-inch polyurethane foam.

In the personnel restraint system for advanced manned flight vehicles, the seat pan is a flat surface covered with Liquifoam. This is made by encasing open-cell polyurethane foam in a liquid-tight liner which is, in turn, encased in a structural liner. The assembly is completely saturated with water. The Liquifoam surface is comfortable for normal operations but presents a hard contoured surface at impact.

REFERENCES

1. Johnston, Richard S.; Correale, James V.; and Radnofsky, Matthew I.: Space Suit Development Status, NASA TND-3291, 1966.

2. McClernan, T. M.; and Thayer, W. S.: Development of a Pilot Universal Couch for Acceleration, Vibration and Shock. Institute of Environmental Sciences, 1965 Annual Technical Meeting Proceedings, pp. 225-240.

3. Bennett, Edward, et al: Human Factors in Technology. McGraw-Hill Book Co., New York, N. Y. 1963, Chapter 4, author Carl Clark.

4. Helmet Assembly. NASA Case No. 4935, 1965-66, Dr. Robert T. Jones and James H. O'Kane, Inventors, and David Faulkner, Patent Attorney, NASA.

5. Shock and Vibration Handbook, vol. 3, C. M. Harris and C. E. Crede, Editors, McGraw-Hill Book Company, N. Y. (1961).

6. Chemical and Physical Properties of Nopcofoam. US 6-36, Nopco Chemical Co., Newark, N. J. (1963).

7. Roth, Herman P.: Impact and Dynamic Response of the Body. Proceedings of a Symposium on Frontiers of Man-Controlled Flight, Los Angeles, Calif., Apr. 3, 1953.

8. Investigation of a Personnel Restraint System for Advanced Manned Flight Vehicles. Contract No. AF 33(600)-41418, Sept. 1962.

9. Reihm, Jr., Homer D.: Helmet Impact Tests. AF Contract No. AF 33(600)-39536, Report MRL-TDR-62-19, Apr. 1962, International Latex Corp., Aerospace Medical Division, WPAFB.

10. Investigation of Vibration and Impact Protection of the Head and Neck. Contract No. AF 33(615)-5199, Northrop Space Labs. 1966.

11. Bright, Sr., Charles W., and Wohlgemuth, D. W.: Mercury Helmet and Molded Helmet Liners. NASA Contract NAS 9-249, Final Report. B. F. Goodrich Aerospace and Defense Products.

12. Private communication, Nopco Chemical Company, North Arlington, N. J., Aug. 3, 1966.

13. Universal Integrated Couch-Restraint System Concept Development, NASA Contract NAS 9-274, Report No. 332.5, Sept. 1963.

14. Design and Fabrication of Microballoon Body Support Restraint System Contract. Contract No. AF 33(616)-8429, Dec. 1961.

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