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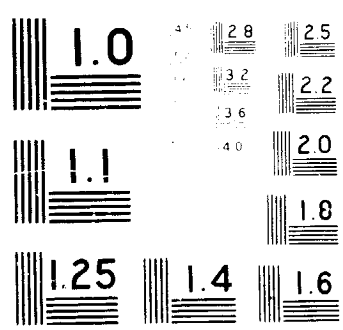

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PREPRINT MANUSCRIPT

NASA TECHNOLOGY UTILIZATION SURVEY ON COMPOSITE MATERIALS

Prepared for National Aeronautics and Space Administration
Technology Utilization Division
Washington, D.C.

MAY 1972

COMPONENTS AND MATERIALS LABORATORIES
AEROSPACE GROUP

HUGHES

HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

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NEWS RELEASE

A variety of civilian uses for new composite plastic materials developed by the National Aeronautics and Space Administration and its contractors has been described in a recently completed survey by the Hughes Aircraft Company.

Funded by a NASA contract, the survey emphasizes the potential uses of these new materials in such industries as agriculture, chemical and petro-chemical, construction, consumer goods, machinery, power generation and distribution, transportation, biomedicine, and safety.

The survey points out that selection of one of the new composite materials for any application depends on its savings in weight, advantages in performance, longer service life, and reduced maintenance. In addition to describing the new materials, the survey briefly covers the methods by which they can be manufactured.

Over 500 books, technical reports, magazines, and papers were examined in preparation of the survey. Nearly a hundred personal interviews were also conducted with NASA scientists and NASA-funded contractors in search of new materials and their possible non-aerospace applications. The survey should be of considerable interest to workers in many industries who seek better materials for their products.

PREPRINT MANUSCRIPT

NASA TECHNOLOGY UTILIZATION

SURVEY ON COMPOSITE MATERIALS

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ABSTRACT

NASA and NASA-funded contractor contributions to the field of composite materials are surveyed. Existing and potential non-aerospace applications of the newer composite materials are emphasized. Economic factors for selection of a composite for a particular application are weight savings, performance (high strength, high elastic modulus, low coefficient of expansion, heat resistance, corrosion resistance, etc.), longer service life, and reduced maintenance. Applications for composites in agriculture, chemical and petrochemical industries, construction, consumer goods, machinery, power generation and distribution, transportation, biomedicine, and safety are presented. With the continuing trend toward further cost reductions, composites warrant consideration in a wide range of non-aerospace applications. Composite materials discussed include filamentary reinforced materials, laminates, multiphase alloys, solid multiphase lubricants, and multiphase ceramics. New processes developed to aid in fabrication of composites are given.

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General Composite Materials Technology

INTRODUCTION

The limiting element on many advanced design concepts for supersonic aircraft, rockets, and spacecraft has often been the development of a suitable materials system. This limitation was particularly evident in applications in which the materials would be subjected to stresses and environments near their capacities. Materials were required that were lighter, stronger, stiffer, and more heat resistant than materials available at the beginnings of the new designs. Further, most of the new demands placed on materials were for combinations of properties not available from one-element or simple alloy materials: for example, thermal dimensional stability combined with high strength, and stiffness and light weight combined with high strength and inherent corrosion resistance. Consequently, developments aimed at the improvement of existing materials were accelerated, and new approaches were sought.

The requirements for "designed" materials were realized by combinations of two or more components to obtain composites that had properties superior to those of the constituents when the latter were used individually. This composite concept is as old as man's technology; e.g., the use of straw in clay bricks by the ancient Babylonians and the use of wood, horn, gut, and silk to produce improved laminated bows by the Mongols (ref. 1).

This publication was prepared to present a survey of the field of the newer composite materials and to report the contributions of the NASA facilities and NASA-funded contractors in this field. A major consideration in preparation of the report was to emphasize the existing and potential non-aerospace applications of composite materials rather than to detail their present aeronautical and aerospace usage. Although it is impossible to list all the potential commercial usages of the NASA developments in a report of this nature, it is intended that the report will act as a catalyst in stimulating further thought on the use of particular materials or processes for existing and future applications.

A number of definitions of composites exist in the literature (refs. 2, 3, 4); however, for the purposes of this survey the following definition was established.

> A composite is a material made up of several identifiable phases, combined in an ordered fashion to provide specific properties different from or superior to those of the individual materials.

The composite materials considered here include filamentary reinforced materials, laminates, multiphase alloys, solid multiphase lubricants, multiphase ceramics, etc. In addition, information is included on new monolithic materials such as polymers, fibers, etc., that might be used as components in composites. Liquid coatings, greases, and similar semisolids and solid-state electronic materials are excluded. New processes developed to aid in fabrication of composite materials are also listed. Data on conventional, widely used composites, such as epoxy-fiberglass laminates, filled thermoset plastics, reinforced thermoplastics, etc., are given in limited form only, since such information is already widely disseminated and would be superfluous.

TYPES OF COMPOSITES

The form and nature of the composite constituents influence the composite configuration. Most composites contain a structural or reinforcing component and a matrix. The reinforcing component may be in the form of fibers, flakes, particles, and laminae. These reinforcing components, shown in figure 1, determine to a large extent the physical properties of the composite (ref. 1).

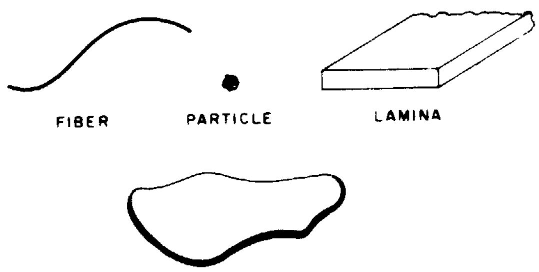

Figure 1.- Types of structural constituents.

The reinforcing constituents are held or embedded in the matrix. Matrices may be organic such as resinous polymers, inorganic such as cement binder in concrete, or metallic such as copper infiltrating tungsten fibers. The matrix holds the reinforcement in its original configuration, protects it from the environment, transfers the load from fiber to fiber or from particle to particle, etc., and, in general, is the constituent that determines the shape and form of the composite. There are, of course, composites that do not have distinct reinforcement and matrix components such as honeycomb sandwiches and bimetallic laminates. Further, not all types of reinforcements are used in all matrices.

Basic Classification

Composites are usually classified by the type of reinforcement used. The matrix, however, is an important consideration in a complete description of the composite and is usually given at the end of a composite's name. For example, boron fiber-aluminum is a composite with an aluminum matrix reinforced by boron fiber, graphite fiber-epoxy is a composite with an epoxy matrix reinforced by graphite fiber, elastomer-coated fiberglass fabric is a composite with a fiberglass fabric matrix reinforced by elastomers, etc. The five basic types of composites are illustrated in figure 2 and are discussed below.

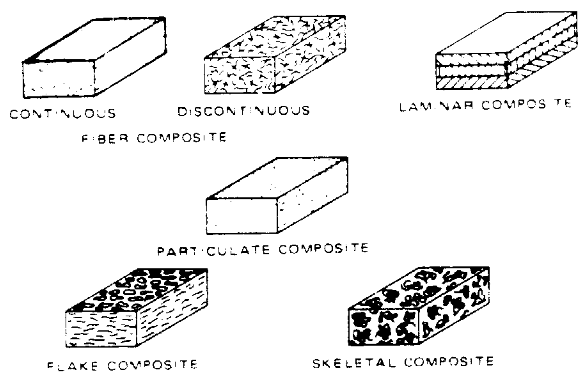

Figure 2.- Classification of structural constituents.

Fiber composites. – Fiber or fibrous composites utilize continuous or discontinuous fibers dispersed in a matrix. Composites formed of two fibers also fall into this type. These fiber-fiber composites, used in production of special fabrics, have no matrix material, although if one fiber is used in large preponderance, it functions as the matrix. An example would be a cotton-polyester blend.

Laminar composites. – Laminar composites may be formed of two or more layers of material bonded together. Copper-silver laminated coins, such as a quarter, are a familiar example.

Skeletal composites. – Skeletal composites are composed mainly of a three-dimensional continuous network constituent into which is introduced a second constituent. An open-celled foam filled with resin and a filled honeycomb would be examples of this type of composite.

Particulate composites. – Particulate composites are so designated because of the use of many minute or larger particles of regular or irregular shape, embedded in a matrix. The most familiar example of such a composite is concrete. Another is a wood flour or other powder-filled plastic materials. Short, discrete single-crystal fibers are termed whiskers and are included in this category.

Flake composites. – Flake composites are similar to particulate composites except that the filler or reinforcing materials are flakes or flat particles. The flakes may be held together by a simple interface binder, or the materials may be completely dispersed in a continuous matrix. An example of a flake composite would be aluminized paint.

Materials Used

Many of the materials commonly or experimentally used in composites are shown in tables I and II. Most of these are discussed in this report. It should be noted that fiber-reinforced composites are by far the largest class of composites used. In this case, glass reinforcement is used in considerably greater quantities than all the others combined. The reasons for the use of glass include its good strength properties, good heat resistance, corrosion resistance, low cost, and a large variety of forms, e. g., yarns, rovings (continuous fibers), woven fabrics, mats. All the other fibers listed have properties that make them desirable for specific applications, particularly those in which high strength or high modulus properties must be emphasized. Table III presents a summary of the more important properties of the commercially available fibers.

TABLE I.- REINFORCING MATERIALS

Class	Specific Types
Fiber	Glass fibers, organic fibers (nylon, polyester, PRD-49*), boron, graphite, metal fibers, ceramic fibers (aluminum oxide, silicon carbide, etc.), asbestos.
Laminar	Fabrics, metal sheets and foils, plastic films, papers, sandwich core constructions.
Skeletal	Organic and inorganic foams or sponges, cellular core stocks (honeycomb, corrugated and waffle).
Particulate	Oxides, whiskers, short fibers, metallic powders and ceramic particles, graphite, molybdenum di-sulfide, polytetrafluoroethylene (TFE Teflon).
Flake	Aluminum, silver, mica, glass.

*A new organic fiber, made by the Dupont Company, on which no constituent information is yet available.

TABLE II.- MATRIX MATERIALS

Class	Specific Types
Organic Polymers	Polyester resins, epoxy resins, polyimides, phenolics, thermoplastic resins.
Metals	Aluminum, magnesium, copper, nickel, columbium (niobium).
Ceramics	Alumina, zirconia, glass.

The properties of short fibers or whiskers are included because these materials are commercially available although at very high prices. The technology of whisker usage is still in the embryonic stage because of the difficulty in aligning whiskers for optimum reinforcement. For these reasons the data shown for whiskers represent a compilation of many whisker properties.

TABLE III. - PROPERTIES OF COMMERCIALLY AVAILABLE FIBERS

Type of Fiber	Tensile Strength (10^3 psi)	Tensile Modulus (10^6 psi)	Specific Gravity	Maximum Temperature of use (°F)	Diameter (10^{-4} in.)	Available Forms	Approximate Price ($/lb)
E-glass	[illegible] - 500	10	2.5[illegible]	800 (42[illegible]°C)	[illegible]	fibers, tapes, fabrics, mats, rovings, yarns	[illegible] to 2.[illegible]
S-glass	[illegible]	12	2.4[illegible]	[illegible] (482°C)	[illegible]	yarns, rovings, fabrics, tapes	[illegible]
Nylon	[illegible] - 12[illegible]	1.4 - 4.[illegible]	1.14	250 (121°C)	[illegible]	fibers, fabrics	[illegible]
Polyester	105-120	1.4 - [illegible].5	1.38	2[illegible] (135°C)	4 - 12	fibers, fabrics	0.55
Polyacrylonitrile	32 - 3[illegible]		1.14	250 (121°C)	[illegible] - 11	fibers, fabrics	[illegible]
PRD-49	400	20	1.45	460 (238°C)	4	yarns, rovings, fabrics	50.00
Cellulosics	[illegible]	2	1.54	225 (107°C)	4 - [illegible]	fibers, yarns, fabrics	0.25 - 1.00
Graphite	250 - 400	35 - 80	1.75 - 1.95		3-1/2 - 5	tows, tapes, fabrics	[illegible]0.00 - 275.00
Boron (tungsten core)	400 - 450	55	2.63	900 (482°C)	0.4 - 0.5	fibers, tapes	250.00
Metallic (steel)	600		7.8		0.4		1.00
Whiskers	1000 to 6000			900 - 1800 (482 - 982°C)	down to 0.8	fibrils	200.00 - 1000.00

Composite Characteristics

The major benefits offered by composites are their superior properties compared with those of monolithic materials. A strong, low density laminate may be made by the use of a lightweight matrix with a high-strength filler. Similarly, oxides introduced into powdered metal aluminum alloys may raise the maximum usable temperature from approximately 600°F to 1000°F (316 to 538°C). Some of the common characteristics of the various types of composites available are shown in table IV. A composite of any given type may exist in a large variety of configurations or compositions. Therefore, the characteristics listed in the table should be used as general guides.

TABLE IV. - CHARACTERISTICS OF AVAILABLE COMPOSITES

Type of Composite	High Strength/ Weight Ratio	High Stiffness/ Weight Ratio	Maximum Temperature Usage ~350°F	Maximum Temperature Usage			Cryogenic Usage - Structural	Thermal Insulation	Chemical Resistance	Low Density
				To ~500°F	From 500-1000°F	Over 1000°F				
Fiber										
Glass-epoxy	X		X						X	
Glass-polyimide	X			X					X	
PRD-49-epoxy	X	X						X		X
PRD-49-polyimide	X	X						X		X
Graphite-epoxy	X	X					X			X
Graphite-polyimide	X	X	X				X			X
Boron-epoxy	X	X								
Boron-polyimide	X	X	X							
Boron-aluminum		X		X						
Tungsten-metal matrix					X					
Laminar										
Polymer coated fabrics			X	X				X	X	
Fiber-reinforced film	X		X				X			X
Honeycomb sandwich	X	X	X	X				X		X
Bi-metallics and inorganic-metallics					X	X			X	
Metalized organic film								X		
Skeletal										
Filled organic foam			X					X		
Filled metal matrix					X	X				
Filled honeycomb	X									
Particulate										
Dispersion-strengthed alloys					X	X				
Short fiber-strengthed alloys					X	X				
Fiber strengthed (ceramics)					X	X		X		X
Cermets						X			X	
Flake										
Mica-epoxy									X	
Aluminum-epoxy									X	
Glass-epoxy									X	

COMPOSITE PRODUCTION TECHNIQUES

Production methods for composites are influenced most by the matrix material. Composites with an organic matrix are laminated, compression molded, and extruded, the particular technique depending on the type of reinforcement, the configuration, the service requirements, and the cost constraints. Composites with a metallic matrix are laminated, cast, rolled, and extruded, with the particular technique again dependent on the above parameters. The differences in production methods between organic and metallic matrices arise largely from the temperatures and pressures used. The similarities involve the requirement to surround the reinforcement fibers or particles with a matrix that transfers the load among the reinforcement elements.

Ceramic matrices are usually cast. Low-strength ceramic matrices involve the use of chemically setting materials that cure at room temperatures, such as gypsum plaster and cements bonded with alkali silicate binders. Phosphate and calcium aluminate binders require moderate heating to promote chemically reactive bonding for medium-strength composites. In high-strength ceramic composites, the ceramic matrix is sintered and the composite heated to conventional ceramic sintering temperatures. If wire reinforcements are utilized in a ceramic composite, they must be protected from oxidation by means of an inert or reducing atmosphere.

Specific production techniques of the basic types of composites are discussed below.

Fiber-Reinforced Composites

Composites formed of organic resin matrices and fibers may be made by impregnating the fibers with the resin and then collimating the fibers into thin sheets or tapes. These are laid up in a unidirectional or multidirectional arrangement until the desired thickness is obtained. The lay-up is cured under the conditions of heat and pressure required for the specific matrix material. Such techniques have been used extensively for fiberglass, graphite, and boron filament composites.

An alternative technique is to lay the unimpregnated fibers in the desired configuration in a mold into which resin can then be injected. This method has been used for both organic resin matrices and for liquid metal infiltration for those fibers compatible with such a matrix.

Another technique used with boron fibers utilizes metal foils diffusion-bonded to fibers by high temperatures and pressures. Such a process has been used to make magnesium-boron and aluminum-boron composites. Electrodeposition or plasma spraying of a metallic matrix, such as aluminum on fiber, has also been used to form tapes and sheets, which are subsequently diffusion-bonded using hot-pressure techniques.

Laminar Composites

Laminar composites are usually made by bonding two or more layers of similar or dissimilar materials together. The bonding material may be a thin organic layer such as an epoxy adhesive or a brazing alloy used to form a bi-metallic laminate. Alternatively, two or more metals may simply be bonded together by a diffusion technique using high temperature and pressure.

Skeletal Composites

The skeletal composites may also be called filled composites, because, in general, the matrix material is the high strength structural component and the second component is a filler material of lower strength, impregnated or infiltrated into the matrix. The matrix is a continuous, three-dimensional cellular material, composed of either an orderly arrangement of honeycomb cells or a more random, spongelike network of open pores. The network can be formed of relatively large pores or fine capillaries. Honeycomb matrices can be made of paper, resin-impregnated fiberglass cloth, or adhesive-bonded, welded, or brazed metal foil. Composites are made by filling the open spaces between the cell walls with a ceramic, slurry, or organic liquid or a paste that is subsequently cured to a solid.

A common form of skeletal composites consists of an impregnated, porous metal matrix. The open network of the matrix is filled with any one of a number of impregnants, including organic resins, lubricants, or lower melting metals. Impregnation techniques include vacuum and pressure filling and the use of capillary forces to insure filling. An example of the latter technique is a tungsten matrix filled with liquid copper or silver to provide better machinability, better resistance to thermal shock, and transpiration cooling of surfaces exposed to very high temperatures.

Syntactic foam is another common form of skeletal composite. The matrix is usually an epoxy resin, filled with small, hollow, gas-filled spheres of glass or plastics. The spheres reduce the weight of the structural matrix and form the cellular configuration.

Particulate Composites

Production of particulate reinforced composites consists of uniformly dispersing a particulate reinforcement throughout a matrix material. The particulate reinforcement may be discrete particles such as oxides, carbides, metallic whiskers, etc., or it may be composed of particles formed in the matrix or precipitated out of solution. Particulate reinforced composites have been made using organic, ceramic, and metal matrix materials. The most widely used class of particulates are plastic molding materials that utilize various types of fillers or reinforcements such as clay powders, glass or cellulose fibers, etc. Since these are very commonly used, they will not be discussed in this report. Metal matrices are currently the materials that are receiving the most emphasis as precursors for the production of particulate-reinforced composites. This emphasis exists because metal matrix materials are best suited for combining with the high strength, high heat resistant particulates such as carbides, oxides, etc., usually used in the form of whiskers. The specific techniques that have been used for the production of metal matrix composites are (ref. 3):

1. Aligned eutectics. A second or reinforcing phase is produced in situ by unidirectional solidification of a eutectic mixture. This technique is in the early developmental stages.
2. Reaction of two liquids to form a new phase in the subsequently solidified metal matrix. An example of this technique is the mixing of copper-thorium and copper-boron alloys as liquids in adequate amounts to form a dispersion of thorium boride in the copper. This step is

followed by casting or atomizing and consolidation by powder metallurgical methods (compacting, sintering, extrusion) to control the size of the dispersions.

3. Gas-solid reactions. One of these reactions involves internal oxidation, in which one metallic component is selectively oxidized in situ by diffusion of oxygen into the alloy at elevated temperatures. Examples of composites made by this technique include sintered aluminum powder, copper-silicon, copper-aluminum, and nickel-thorium.

4. Mechanical mixing of component powders. This technique is essentially a powder metallurgical operation that permits many combinations of components. A major difficulty of the technique is the achievement of uniform dispersion without excessive agglomeration of dispersed phases. Two examples of commercially available dispersion-strengthened composites are TD nickel, a thorium-oxide strengthened nickel, and dispersion-hardened copper in which a small percentage of beryllium oxide is used to upgrade the elevated temperature strength, crystallization resistance, and electrical stability of the copper.

Flake Composites

Flake composites are perhaps the least known of the composites (ref. 1), possibly because the reinforcing fillers are seldom identified by the term flake. Flake materials such as glass, aluminum, and mica are generally combined with an organic binder, usually an epoxy, which is used in quantities just sufficient to coat the flakes at the interface. In general, the flake particles are used as fillers in the matrix and are worked as coatings or as molding materials so as to align the flakes in a laminar configuration. The best known, and probably most widely used, flake composite is a glass-mica composite available as molded parts, shapes, or sheet stock. The production process, details of which are proprietary, consists of a mixture of glass and mica, pressed under heat and pressure to the desired shape. The use of aluminum flakes in coatings is also well known; in this composite advantage is taken of the high reflectivity of the aluminum flakes and the moisture and liquid barrier properties obtained by the tightly laminated structure.

ECONOMIC CONSIDERATIONS

The economic considerations in the selection of a material for a particular application are complex. While parts made of composites are usually, but not necessarily, more expensive than similar parts made of monolithic materials, they often weigh less or perform better. To justify the additional cost, comparisons on the basis of lifetime cost are necessary. The following factors must be taken into account.

- Weight savings
- Performance advantages (higher strength, modulus, low coefficient of expansion, heat resistance, corrosion resistance, etc.)
- Longer service life
- Less maintenance

It is necessary to consider composites at the earliest stage of design to achieve maximum weight saving and performance. Benefits accumulate through the "cascade effect"; e.g., weight savings in one part of a structure lead to additional weight savings in associated structures. Lower weight reduces shipping costs. A material with a low coefficient of expansion would not require thermal environmental control. Longer service life and less maintenance reduce product warranty costs (ref. 5).

The importance of weight saving is readily recognized in a number of industries. In automobiles, for example, the reduction of body weight by one pound saves the manufacturer 6¢ to 10¢ in the powerplant. In mass transit trains and trucks, a pound saved has been valued at up to $2 annually in operating costs. It has been estimated that each pound saved in a subsonic aircraft will result in a savings of $70 to $500 during the life of the aircraft. The savings of 1160 pounds in the floor of a cargo plane would amount to a lifetime savings of $580,000. The use of composites with high specific strength in large commercial aircraft could increase their life-time ton-mile capacities by at least 25 percent (ref. 6).

With the exception of fiber-reinforced composites, most other structural composite materials are still in the developmental stage, and, because of the rapid pace of development, today's estimates could easily change a year from now. It is, therefore, extremely difficult to make an accurate economic analysis of the newer, non-fiber-reinforced composite materials. The cost data given in the following section relate principally to fiber-reinforced composites of high strength or high stiffness and represent only a best current estimate.

Cost of Materials

Because the matrices of the newer, more highly priced composite materials are nearly always conventional resins or metals, it is the cost of fibers that governs the cost of the composite. These costs today are high, but with increasing volume, they are expected to decrease. For example, the decreasing cost of boron and graphite prepregs has been projected as shown in figure 3 (ref. 7). The 1972 price ot boron fibers is $250 per pound with an expected decrease to $75 per pound by 1975 and to $50 per pound by 1980. Similarily, the price of graphite fiber is expected to drop from the current level of $350 to $275 per pound to $65 per pound in 1975 and to $36 per pound in 1980 (ref. 8). Other high modulus fibers such as PRD-49 at $50 per pound and boron nitride filaments at $175 per pound, as well as graphite and boron, may compete in some applications with low-cost glass-reinforced composites at $0.50 to $10 per pound.

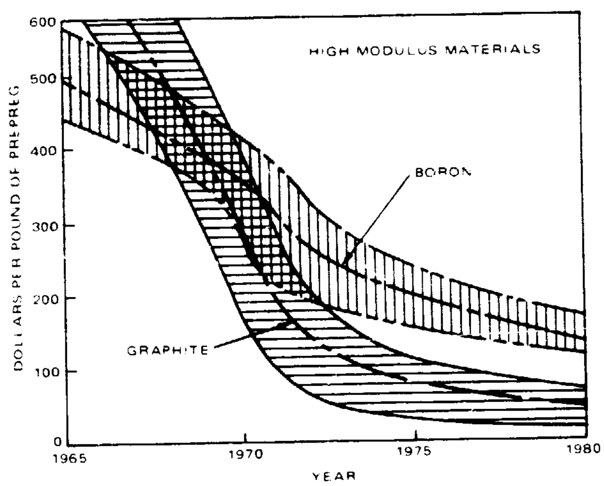

Figure 3. – Projected costs of boron and graphite prepregs. (from ref. 7)

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One apprcach for minimizing the cost of advanced composite structures has been selective enhancement of the properties of low-cost fiberglass-epoxy by the addition of high-modulus fiber reinforcement. Another cost reduction technique is the incorporation of high modulus fibers in a metallic structure to reinforce the predominantly metallic structure. This hybrid concept of mixing various fibers in a resin-matrix composite or adding fibers to the metal structure has aroused considerable interest among governmental agencies and will have considerable commercial potential (refs. 5, 7). A possibility exists of reducing the price of a fiber material, in this instance, graphite fiber. The price of graphite fiber could be reduced to $10 per pound if high-strength, high-modulus fiber could be mass-produced from pitch instead of from the usual synthetic textile precursor (ref. 9).

In general, then, higher prices must be paid for higher performance until volume and new developments can alter the situation.

Cost of Manufacturing

Processing costs are an important factor in the selection of a composite using a resin matrix versus a metal matrix. One of the goals of current composite research is to convert the raw materials into finished products in single-step processes, using the simplest possible tooling. In this respect, the use of an organic resin as the composite matrix offers promise of considerable savings over the cost of metal matrices because of the greater ease with which the organic materials can be processed.

Resin-matrix composites.– In the manufacture of resin-matrix composites, a shape can be built up from preimpregnated tape on a form, in contrast to grinding, machining, eroding, or forging it out of a block as is done in metal fabrication. This technique provides several major advantages: organic matrix composite parts can be of variable thickness and of practically unlimited size and can be made with integrally molded stiffeners, fittings, and attachments. These advantages may bring the cost of manufacturing parts below that of conventional metal parts and may result in shorter overall fabrication time as well. Improvements in the porosity of finished parts for paint acceptance, in curing time, and in dimensional stability are necessary, however, for low-cost, mass-produced items.

Metal-matrix composites.– Single-layer preforms of boron/aluminum alloy are commercially available at $560 to $660 per pound. These preforms are produced by liquid infiltration, diffusion bonding, or plasma spraying of boron fibers in tape form. With further reductions in the price of boron filaments, the cost of preforms would also decrease.

After preparation of the preform, subsequent fabrication is by hot-pressure bonding, either diffusion or brazing, in various configurations. While the diffusion bonding process offers a small strength advantage, the brazing process appears to be simpler and cheaper. The current and projected costs of fabrication by hot-pressure bonding of single-layer boron/aluminum tapes are as follows.

Year	Cost per pound
1971	$500
1974	200
1979	100 - 125

The cost is based on 5.6-mil boron fiber at $210 per pound in 1971 and $100 per pound in the 1974 to 1979 period (ref. 10).

Rods, tubes, beams, angles, and channels of aluminum or magnesium reinforced with boron fiber and coated with silicon carbide have been produced by a continuous casting process. The economics of this process are sufficiently superior to those of hot-pressure bonding that considerable developmental effort has been exerted in this area. The cost per pound of continuous-cast structural forms at a moderate annual production rate of 2000 pounds has been estimated to be $230 per pound in 1971 and $150 per pound in 1974-1979 (ref. 10).

Composite Applications and Descriptions

Designers and engineers are finding, more often than not, that technologically advanced hardware concepts and lower lifetime costs of components and systems hinge on the availability of the right material. The demand for materials with tailored, multifunction properties is increasing. This demand has accelerated the growth of composites.

Advanced technological fields, such as space exploration, by their very natures reach beyond the state of the art in materials to satisfy performance requirements. Consequently, NASA has sponsored the development and extended the use of many new composites. Many of these materials have made possible the hardware used in aircraft and spacecraft, including their propulsion systems. Some of these composites are now used in industry, and many could be used to help provide the technological advancement and lifetime cost savings that are the lifeblood of industry.

The two-fold purpose of this chapter is to present 1) an overview of applications for composites and 2) a general description of basic composites using each class of reinforcement.

COMPOSITE APPLICATIONS

Existing and potential applications for NASA-developed composites in eight industrial areas are given in table V. These applications are presented as a matrix of application areas and composites, classified by reinforcement as in Chapter 1. The matrix serves as an introduction to a more detailed

TABLE V.– MATRIX OF COMPOSITE MATERIALS BY APPLICATION

Composite Type	Agriculture	Chemical and Petrochemical	Consumer Goods	Construction	Machinery	Medical Sciences, Health, and Safety	Power Generation and Distribution	Transportation.
Fibrous	Portable well digging derricks, cherry picker booms, portable silos, water tanks, ladders.	Pipes, tanks, filter materials, hybrid structural elements, gaskets and seals	Sporting goods, bows, skis, masts, golf clubs, non metallic springs, boats, gliders, etc., hybrids in extension stools and step ladders, molded gear and housings, bicycle frames.	Hybrids in truss construction for roofs, bridges, scaffolding, mobile home chassis and frameworks, water storage, tanks; graphite-epoxy for extreme precision parts such as communication antennas.	Boron/epoxy composites and hybrids for machine tools; graphite fiber composites for zero expansion in precision machines; reinforcement of textile machines; boron and graphite composite torque tube.	Artificial limbs, harnesses, heart valve components, safety helmets.	Filament reinforced boilers and pressure vessels; hybrid construction for transmission towers.	Aircraft components, pure fiber and hybrid motor and rail transport components, marine transport, jet engine compressor blades, pipeline transport, rotor bearings, brakes, floor panels, fiber overwrap on high pressure bottles.
Laminar	Air-supported barns, crop covers, permanently lubricated gears, low-cost cryostats, balloon transporters.	Tanks and tank linings, heat insulation systems for tanks and pipes at cryogenic and elevated temperatures, resin systems, tank covers.	Tents, blankets, portable buildings, upholstery, drapes, inflatable furniture, green houses, insulation for refrigerators and portable coolers, permanently lubricated gears, hot air balloons.	Portable shelters, light diffusers, temporary ceilings, honeycomb sandwich walls, floors and ceilings, insulation systems and air ducting.	Self-lubricated gear for power transmission and ball nuts on lathe feed screw.	Portable insulating blankets, implants, fireproof clothing.	Cryogenic insulation, bimetallic (clad) boilers and tubes, multilayer cryogenic insulation.	Aircraft components, helicopter rotor blades, self-lubricating gears, thermal insulation.
Skeletal	Tree netting for bird protection in orchards	Honeycomb core used in sandwich laminate construction, fire retardant foams.		Foam insulation and fire suppressants, for thermal and acoustical purposes.	Steel matrix-carbide impregnated, used for punches, dyes, gages.	Implants, orthotic cushions and pads.	Solid lubricants. Foam insulation.	Acoustical insulation, fire suppressant foam.
Particulate (includes dispersion-strengthened and aligned eutectic alloys)	Solid lubricants, wear resistant blades, plowshares, etc.	High temperature parts, furnace nozzles, heat exchanger parts, solid lubricants, insulation (heat), corrosion resistant parts, high temperature fasteners (bearing for cryogenic service) valve components.	Solid lubricants, furnace and heater elements, small engine parts.	Furnace insulation.	Solid lubricants, oxidation resistants for gas turbine shaft bearings.	Dental restoratives, surgical implants.	Gas turbine blades and buckets, tungsten reinforced copper transmission lines, solid lubricants, bearings for cryogenic service.	Turbine blades, solid lubricants, bearings.
Flake	Solid lubricants.	Fluid resistant coatings, heat resistant parts used for electrical insulation.	Lubricants.		Solid lubricants.			Solid lubricants.

treatment of composites in the succeeding chapters. Some composites are very new or are incompletely developed; consequently, they are in very limited use. This factor accounts for blanks in the matrix. In the following chapters, then, each application area is discussed in detail with specific references to NASA and other sources of information.

COMPOSITE DESCRIPTIONS

Chapter 1 dealt with the classification of composites by structural constituents. This part of Chapter 2 extends the presentation to specific composites, discussed according to the classification given in Chapter 1. The discussion includes various matrices that are used with the reinforcement (one or more), important typical properties, manufacturing methods, advantages, and deficiencies. In addition, discussion of some very new composites with limited use is presented here because they have good application potential. Extensive references are included so the reader may obtain complete information where desired.

Fiber Composites

The most frequently used fiber composites consist of boron or graphite fibers with polymer or metal matrices, fiberglass in polymer matrices, and metal fibers in metal matrices. Various processing techniques have been found suitable for the different composites, depending on the ultimate properties desired and/or the cost.

Boron Fibers

Boron (tungsten core) fibers. – Boron fiber with a tungsten core falls into the class of advanced structural composites and was the first to find practical application. Boron filaments are prepared by the deposition of boron on a substrate of 0.01 mm (0.005 inch) diameter tungsten wire. Two filament diameters are available – 0.004 inch and 0.0056 inch. Properties and cost figures are presented in table III in Chapter 1.

Boron fibers are produced in continuous lengths. During processing they are collimated at a precisely controlled spacing and introduced into the matrix (metal or resin). The larger diameter of boron fibers compared with graphite fibers permits easy collimation in uniform patterns. The specific processes are dependent on the matrix used.

Some advantages of boron fibers are the combination of high strength, the equivalent of fiberglass, and of high modulus, four times that of fiberglass. Properties are consistent, and reliable design allowables may be determined for composites. Some disadvantages are the stiffness of fibers which prevents their being shaped to small radii or fillets. In addition, the density and cost are high because of the tungsten wire core.

Boron fibers/polymer matrix. – Polymer matrices used with boron fibers include epoxy resins, polyimide resins, and other special purpose resins. Epoxy resins are the most widely used matrix because of their good overall strength and ease of processing. Polyimide resins have been used in very limited quantity. As a matrix, these resins offer structural use at higher temperature, better resistance to moisture than epoxies, and nonflammability. However, polyimides are difficult to process, requiring special equipment to obtain cures at 600°F (316°C) in contrast to the more generally used 350°F (177°C) and lower for epoxies. Another significant drawback is the release of volatiles during cure which causes voids in the matrix that reduce the strength (ref. 11). Improvements in polyimides should eventually eliminate this problem (ref. 12).

Some typical temperature-related properties are presented in figures 4 and 5 (ref. 13). Strength-to-density data are presented because of the weight significance in most structural applications. These data represent maximum typical properties of composites that have all the fibers oriented in one direction. Properties are reduced when combinations of orientations are used in a composite, e.g., attempts to obtain equal planar strength in all directions, such as in sheet metal.

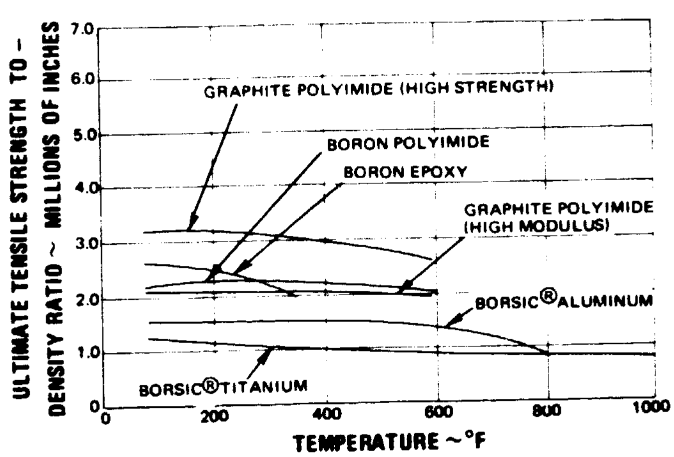

Figure 4.– Ultimate tensile strength-to-density ratio data for typical composite materials. (from ref. 13)

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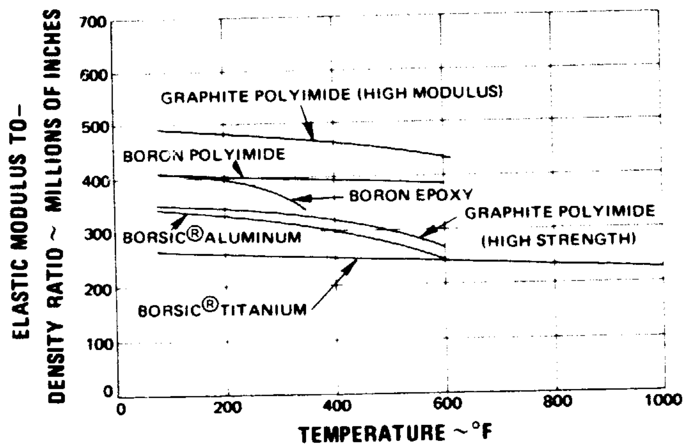

Figure 5.— Elastic modulus-to-density ratio data for typical composite materials. (from ref. 13)

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The directional properties of fibrous composites are advantageous. Structures are manufactured by stacking layers of unidirectional material in selected orientations to efficiently match the applied load direction. Some typical examples are shown in figure 6.

The structural efficiency of boron/epoxy structures can be demonstrated in a lightweight truss application. This truss consists of a series of thin wall tubes attached to each other by a metal joint, a construction typically used in aircraft or bicycles. Compressive structural loads are applied along the axis of each tube and failure is usually by buckling. In a recent investigation by NASA, two types of tubes were compared — all aluminum and all boron/epoxy (ref. 14). Tubes ranged in size from 1/4 to 1 inch in diameter and up to 25 inches long and were designed for equal strength. Including the metal joint, the boron/epoxy tube truss was one-half the weight of the aluminum tube truss. Similar comparisons showing significant weight savings have also been made with titanium and aluminum alloyed beryllium (refs. 15, 16).

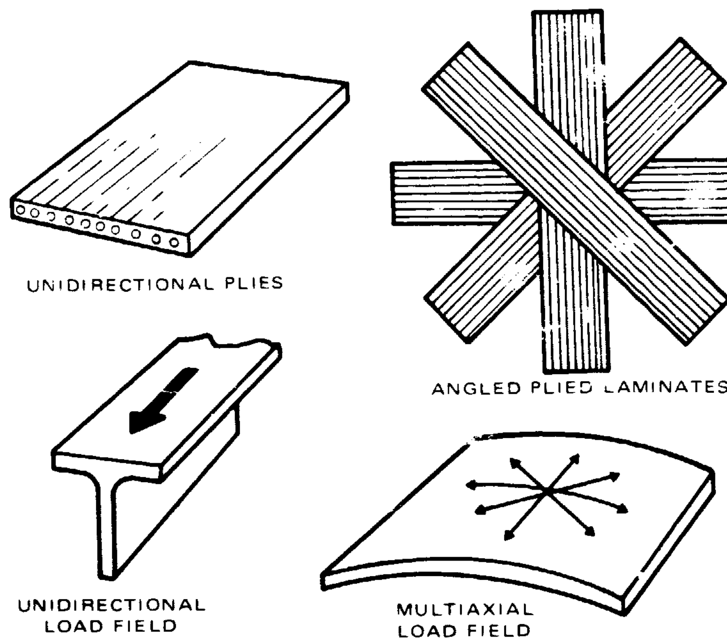
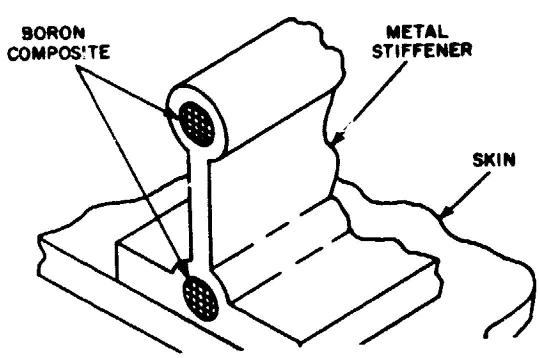


Figure 6.– Fabrication of composite structures. (from ref. 19)

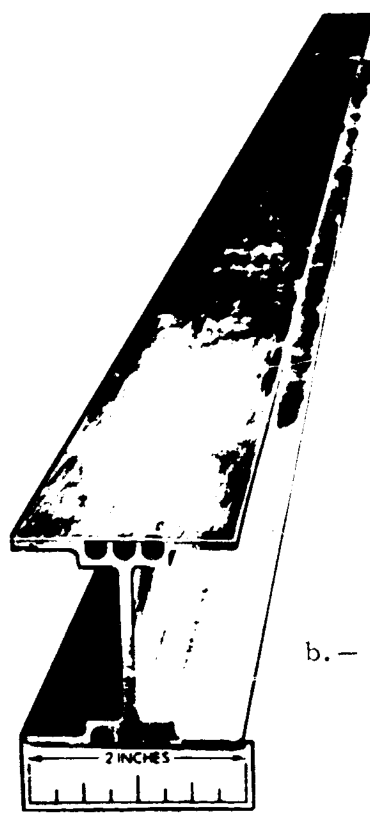
Another application for boron/epoxy is to stiffen metal tubes with a wrap of boron/epoxy (refs. 17, 18). In this concept, joint design is often simplified. Also, existing structures can be strengthened and stiffened, but great care must be exercised where vibration loads exist, because dynamic properties are very different.

Still another approach is to infiltrate epoxy resin into circular or irregularly shaped hollows that have been filled with boron fiber (ref. 20). The process is a relatively simple and inexpensive method for achieving a high strength/high stiffness hybrid structure. A bundle of boron filaments are inserted into a hollow metal section. Subsequently, the hollow is infiltrated with resin and the resin cured. An infiltrated beam section and a hybrid

I-beam with infiltrated hollows (half round areas) are shown in figure 7. In a study of an infiltrated hat section stiffener, a comparison was made of an all-composite construction and a monolithic metal stiffener. Each construction was optimized for equivalent load capacity. The infiltrated stiffener weighed 35 percent less than the monolithic. The all-composite stiffener weighed 50 percent less but required slightly more than twice as much boron/epoxy. Thus, for an extra 15 percent weight savings, substantially more expensive composite material was required. Inclusion of manufacturing costs in these comparisons would produce more savings for the infiltrated stiffener (ref. 20).



a.—Typical infiltrated beam element. (from ref. 21)



b.— Hybrid I-beam stiffened by boron fiber/epoxy infiltration. (from ref. 20)

Figure 7.— Infiltrated boron fiber/epoxy resin structures.
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Boron fiber/metal matrix. – Metal matrices offer the capability of higher service temperature than polymer matrices. In addition, the higher shear strength improves load transfer among the fibers. However, high process and service temperatures degrade room temperature properties. On exposure to air at 932°F (500°C) and above, boron filament strength decreases continually to ultimate degradation. In addition, boron filaments interact with metal matrices at high temperatures to cause fiber degradation. To prevent this degradation, the filaments are coated with silicon carbide or a nitride compound. The silicon carbide coated material is called Borsic.*

Boron filaments are used with several metal matrices, the most common being aluminum. Boron/aluminum composites can be produced in many ways: casting or molten metal infiltration, plasma spraying aluminum over parallel filaments laid down (collimated) over aluminum foil, powder metallurgy, electroplating, vapor deposition, and diffusion bonding. Plasma spraying and diffusion bonding are the most popular. This latter process is performed by interleaving collimated fibers between two layers of aluminum foil and pressing at temperatures between 932 and 1112°F (500 and 600°C) and at pressures near 900 psi. The final thickness and size of a sheet is determined by the number of layers of foil and filaments.

Plasma spraying results in a monolayer, or single ply, intermediate product. These plies are subsequently bonded by diffusion methods (see above) into multilayer composites that may be of varying thicknesses and curvatures. The process has greater versatility than the one-step diffusion bonding and permits the component manufacturer to purchase monolayer tapes

*Patented by Hamilton Standard Div. of United Aircraft.

and fabricate them to a particular configuration (ref. 22). Typical properties of boron/aluminum composites can be seen in figures 4 and 5. These properties are for unidirectional fiber composites only.

The combination of high pressures and temperatures used in diffusion bonding adds considerable cost to the composite. In recent work done for NASA, a process using much lower pressures (200 psi) has been developed that allows fabrication of larger panels (ref. 23).

The structures described above are expensive, mainly because of the batch processes involved. Continuous fabrication is a logical approach to lower costs. NASA is currently developing a method consisting of continuous consolidation of aluminum foil-wrapped boron filaments into tubes, rods, hat sections, and T sections. The fibers are wrapped by a continuous automatic process and fed into tooling that applies pressure in radial and circumferential directions, as well as sufficient heat for fusion bonding. All fibers are aligned unidirectionally (ref. 24).

Another process is performed by continuous casting in two steps. The first step produces a small preform consisting of 15 to 40 filaments in round or flat (tape) cross-sections. This is the general purpose preform. These are then consolidated into the desired shape by the same continuous casting process. This process is also suitable for magnesium matrix composites. A variety of cross sections can be made, such as I-beam, circular, angle, annular, and lenticular. Fibers can be oriented only unidirectionally (ref. 25).

Another advantage of the continuous casting process is the selective concentration of boron filaments where they are most effective. Obviously, this process is a more cost effective use of expensive boron filaments. Composites produced by this process have higher compressive strength in both the crushing and buckling modes of failure because of the higher filament content and stronger interfacial bonding.

A unique technique for fabricating finite lengths of boron/aluminum tubing has also been developed (ref. 26). The composite tubing is built up from a series of concentric, ductile aluminum alloy tubes that have longitudinal slots along their outer peripheries in which boron fibers are imbedded. The fibers are placed in the slots of the tube of the smallest diameter, and the subassembly is then encased in a slotted aluminum alloy tube of larger diameter (see figure 8). This assembly is passed through a die which brings the two tubes with the imbedded fibers into intimate contact (with possibly a slight reduction in diameter). The process is repeated by superimposing tubes of successively

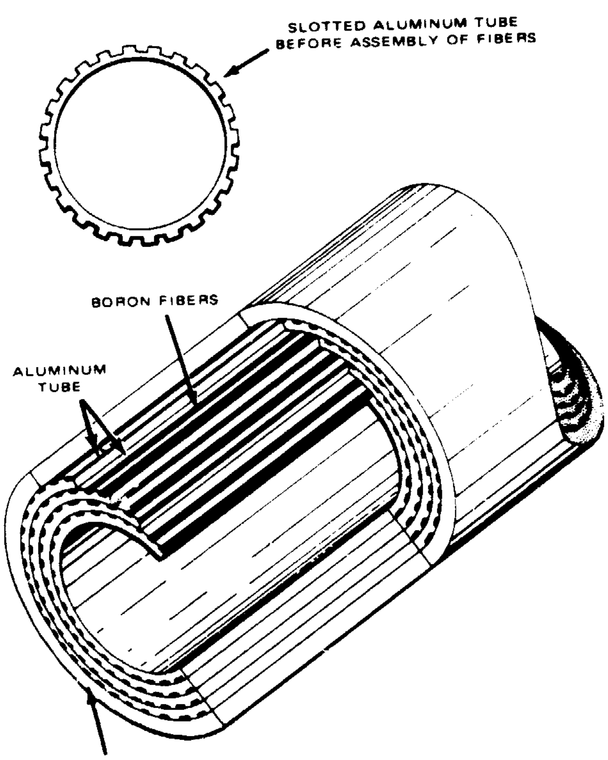

Figure 8.– Experimental boron fiber-reinforced aluminum alloy tubing. (from ref. 26)

larger diameter over the preceding assembly until the desired outer diameter of the fiber-reinforced aluminum alloy tubing is attained. A sleeve of high-strength steel is then fitted over the composite aluminum alloy tubing and the two are drawn into intimate contact. The entire assembly is heated to diffusion bond the aluminum tubes and age harden the steel sleeve. Pressure is applied by the difference in thermal expansion of the metals; the aluminum expands toward the steel sleeve.

Titanium is being explored as a matrix for boron filaments because of its overall high strength. A major problem exists in the high reactivity of boron with titanium: a thick reactive zone results around each filament (ref. 27). This zone has a critical thickness beyond which the mechanical properties are degraded, especially at elevated temperatures [1202 to 1400°F (650 to 760°C)]. Property improvement is obtained by protecting the filaments with silicon carbide (Borsic) and nitride coatings. Specific strength and modulus data for boron/titanium composites are shown in figures 4 and 5.

Magnesium is a very good matrix for boron filaments. No fiber protective coating is necessary. Composites are nearly 20 percent lower in specific gravity than with an aluminum matrix. Tensile strength of unidirectional aluminum and magnesium composites fabricated by the same process are presented in table VI (ref. 28).

Graphite Fibers

Types of graphite fibers. – High strength, high modulus graphite fibers are produced by the controlled heating at high temperature of organic fibers. Two types of precursor organic fibers are commonly used – rayon and polyacrylonitrile (PAN). Graphite filaments are approximately 0.0003 inch in diameter, although the fiber cross-sectional shape varies from round to irregular to

TABLE VI. – PROPERTIES OF CONTINUOUS CAST 20-MIL-DIAMETER ROD

Matrix	0° Tensile Strength (10^3 psi)	0° Tensile Modulus (10^6 psi)
AZ92 Magnesium EZ33 Magnesium	300	42
2024 Aluminum	150	42

dog bone. Fiber density increases with tensile modulus and ranges from 0.054 to 0.070 lb/in^3, nominally 78 percent the weight of fiberglass.

Fiber properties can be tailored by the production process. Modulus values are available from 30 to 75 x 10^6 psi and tensile strength varies from 250 to 400 x 10^3 psi. However, any combination of strength and modulus is not available because, generally, fiber strength varies inversely with modulus. Other important graphite fiber properties include:

- Good lubricity.
- Near zero thermal expansion coefficient. Some fibers have a negative coefficient; that is, they shrink on heating and expand on cooling.
- Resistance to thermal shock.
- Electrical conductivity. Fibers can dissipate electrostatic charges.
- Ready conformance to corners of small radius (0.030 inch) and fillets.

Graphite fibers are very stable and retain most of their strength and stiffness at high temperatures. These are important properties when high-strength, high-temperature, metal matrix composites are considered. With polymer matrices, fiber wetting to obtain good interlaminar shear strength is a problem; consequently, the fiber manufacturers are devoting considerable attention to fiber surface treatment. This treatment generally consists of a chemical oxidation, sometimes followed by a polymer compatible sizing. Actual treatments are proprietary and confidential.

Graphite fibers are available in various forms. The fibers made from rayon precursor are supplied as 720 filament twisted yarns; the fibers made from PAN precursor are available in bundles of 10,000 collimated filaments, called tows. Also available are 1, 2, and 3 thousand filament tows, twisted or untwisted. The availability of many forms provides a versatility in composite manufacturing that is similar to that of fiberglass. Indeed, the fiberglass handling and composite manufacturing methods (using polymer matrix) are applicable to graphite fibers. Recently, these high-performance fibers have become available as woven cloth in a few patterns similar to those used for fiberglass. It should be noted that composites reinforced with cloth will have lower structural properties than when tows or yarns are used in a cross-plied pattern.

Fabrics woven from high-strength graphite yarns have been tested (not as a composite) at temperatures up to 2500°F (1371°C). These fabrics had a higher strength-to-weight ratio than any other fabric at temperatures above 600°F (316°C). Graphite fibers oxidize rapidly in air temperatures above 1400°F (760°C) and require a protective coating. At lower temperatures, a flexible coating of electroless nickel, silicon dioxide, silicon carbide, or silicone is required to prevent strength loss from abrasion (ref. 29).

Omniweave ® is another woven form in which graphite fibers may be obtained. This novel process results in multidirectionally reinforced, thick fabrics composed of interlocking fiber elements that travel in depth so that discrete fiber layers are not formed (ref. 30). The system is very suitable for fiberglass, as well as for graphite fiber composites, and will be discussed later in this chapter in the section on fiberglass.

Graphite fibers/polymer matrix. — Epoxy resins have been used more than any other to make graphite fiber composites because of their generally good overall strength, resistance to chemicals, ease of processing, and availability in wide variety. Some limited work has been done with polyesters and several thermoplastics but with little promise of results. At service temperatures in excess of the limitations of epoxies (greater than 190°C), polyimides are mostly used (ref. 31). Other, more exotic resins, e.g., polybenzimidazole, pyrrones, etc., are being evaluated experimentally (ref. 235).

Polymer matrix composites are generally made from prepregs consisting of collimated yarns or tows impregnated with the liquid resin. These unidirectional fiber tapes are made in any width, usually from 1/4 inch to 10 inches, and in lengths limited only by packaging considerations. The prepregs are flexible, tacky, and capable of conforming to complex tooling contours. Tapes are laid side by side and in layers, with fibers oriented in predetermined directions, or orientations, related to structural load application or thermal expansion characteristic.

Epoxy resin matrix provides the highest specific strength/and modulus available in graphite fiber composites. The properties depend greatly on the type of fiber and resin. In general, this type of graphite fiber composite has an ultimate tensile strength-to-density ratio of 1.5 to 4 x 10^6 inches and an elastic modulus-to-density ratio of 400 to 800 x 10^6 inches. Comparisons with other fiber composites are shown in figures 4 and 5. Properties at 350°F (177°C) are 50 to 100 percent of those at room temperature, depending on the epoxy resin. Properties degrade rapidly above 450°F (232°C). In the 300 to 400°F (149 to 204°C) range, properties degrade substantially after exposure for several weeks to a normal humid atmosphere at room temperature. Research is being conducted by NASA to study the humid atmosphere degradation phenomenon so that the problem can be corrected (ref. 32). Additional data on epoxy resin composites may be obtained in ref. 33.

Polyimide resin matrix provides the highest temperature performance of the commercially available polymers that can be processed by reasonably practical means. Typical properties are shown in figures 4 and 5 for composites with high strength and high modulus fibers. The strength and modulus retention at elevated temperatures far exceeds that of epoxy resin systems. The long term retention of strength at elevated temperature is shown in table VII (ref. 33). These properties are highly influenced by the quality of the composites. Because, during cure, most polyimide resins produce volatiles which tend to create voids, the quality depends on reducing the trapped gases. This tendency to create voids depends on resin chemistry and processing techniques. NASA is developing new resins (ref. 12) and improved processing techniques capable of producing low-void complicated parts with little more difficulty than graphite/epoxy parts (ref. 33). Polyimide resin composites have also been tested for high-temperature strength retention after lengthy exposure to normal moist atmosphere at room temperature; they showed no significant change (ref. 34).

TABLE VII.– FLEXURAL STRENGTH OF GRAPHITE/POLYIMIDE (HT-S/RS6234) COMPOSITE SYSTEM AS FUNCTION OF HEAT AGING TIME AT 600°F (316°C)

Time at 600°F (hours)	Room Temperature Flexural Strength (10^3 psi)	Flexural Strength at 600°F (10^3 psi)
0	207.9	146.6
140	185.1	187.6
250	196.2	150.6
325	224.3	133.4
408	149.9	107.2

Graphite fiber processing techniques.– Graphite fiber/polymer composites are usually manufactured as discrete components one at a time. Unidirectional fiber prepreg tapes of required width and length are placed on or in tooling. The fibers are oriented in each ply as required. Pressure and heat are applied according to specific schedules. Application methods used are vacuum and oven, autoclave, or hydraulic press. Molding compounds have been made by impregnating fibers and cutting them to lengths of 1/4 to 1 inch. These are then compression- or transfer-molded with matched metal tools in a hydraulic press. The latter processes are lowest in cost but the mechanical properties are poorest because of the random fiber distribution. Costs are high in the former methods because the process is discontinuous.

In recent work done for NASA, a continuous process, called Pultrusion, has been applied to fabricating structural hat sections using graphite fibers and epoxy resin (ref. 35). Unidirectional fiber tapes with fibers oriented in the machine direction and ±45 degrees are used. The hat-shaped section comes out of the machine at 90 degrees to the normal position of a hat when worn; to make circular parts, the section is curved in a horizontal plane with the wide base on the outside of a 30-foot diameter circle. These structures are ring frames for potential use on the space shuttle. Other profiles can also be made, such as bars, angles, and channels. These and the hat-shaped profiles are usually straight extrusions; the curved ring frames are a special application demonstrating the versatility of the system.

Graphite fibers/metal matrix. - Graphite fibers are chemically quite stable and retain most of their strength and stiffness at high temperatures. These are important properties when inclusion of graphites in high-strength, high-temperature, metal-matrix composites is considered. Limited solubility in metal matrices can provide a mechanism for achieving good filament-matrix (interfacial) bonds. Because solubility can result in fiber degradation, where it is extensive, the graphite fibers can be protected by special coatings such as nickel and nitrides (ref. 36).

Nickel matrix composites have been prepared by uniformly electrocladding the fibers with nickel and consolidating the aligned coated filaments by hot pressing. Composite properties are influenced by pressure and fiber volume. With optimum conditions, specific tensile strength is as shown in figure 9 (ref. 36). It is clear that specific composite strength is superior to that of nickel, TD nickel, and nickel alloys (Hastelloy) up to 660°F (350°C). Improvements in processes should result in composites having superior strength over the entire temperature range to 1100°C.

Aluminum matrix/graphite fiber composites offer several advantages. These include higher specific strength in the intermediate temperature range, the extension of structural use of aluminum to 800°F (430°C), and good

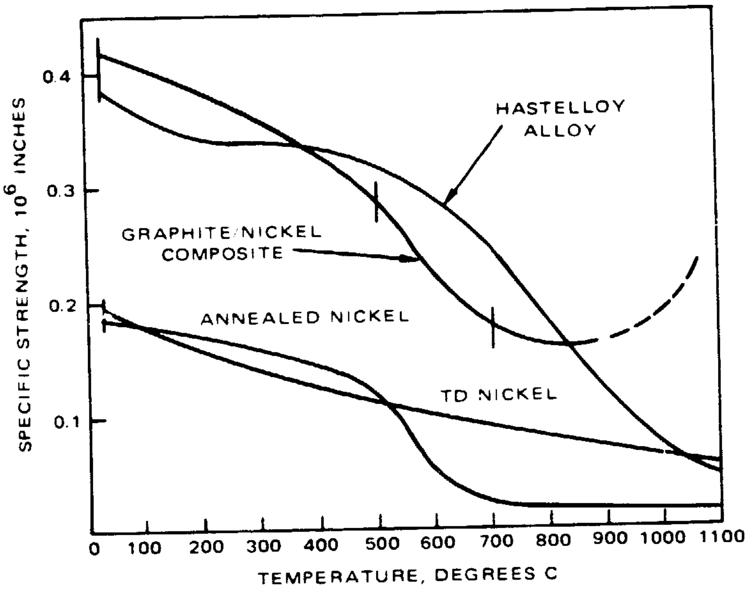

Figure 9.— Strength comparison of graphite/nickel composite with other high-temperature materials.(from ref. 36)

thermal conductivity equivalent to that of reinforced aluminum. Other advantages are easier machining and forming over smaller radii than with boron fiber composites.

Because of these advantages, NASA sponsored an investigation of metal matrix composites including graphite/aluminum for space shuttle heat radiators operating at up to 806°F (430°C) (ref. 23). During this investigation, a nickel coating was used on the fiber to prevent fiber reaction with the aluminum at elevated temperatures and to prevent subsequent degradation at high temperatures. Also, good bare fiber wetting by aluminum was demonstrated, which indicates a potential use of graphite/aluminum composite at moderate temperatures without fiber coatings.

A process for fabrication of graphite/aluminum composite has been developed by NASA using aluminum alloys 1100 and 6061 (ref. 37). The unique feature is that diffusion and consolidation were accomplished without atmospheric controls. However, the samples produced had only 8 volume percent of graphite fiber (50 percent is preferred). Although only in the experimental stage, the process offers lower cost potential. Some properties of composites produced by this process and by still another, liquid infiltration, are presented in table VIII (ref. 38). It should be noted that composite properties are proportional to the fiber volume.

TABLE VIII. – GRAPHITE/ALUMINUM PROPERTIES

Method	Fiber Volume (percent)	UTS (psi)	Density (lb/in^3)	Modulus (10^6 psi)	Specific Modulus (10^6 in.)
Cast Infiltration A-13 alloy	28	106,000	21	0.082	260
Diffusion Bonded 1100A1	8	18,600	9.7	0.094	103
Diffusion Bonded, 6061A1*	8	19,000	10.8	0.094	114

*Not heat treated

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A serious difficulty with graphite fibers in metal matrices is that only 60 to 75 percent of the fiber strength and 75 percent of the modulus is realized. This result is partially attributed to fiber damage during processing. With polymer matrices, greater property translation is common, especially modulus, because of the polymer fluidity and the lower pressures used in manufacturing composites.

Fabrication with small diameter (0.0003 inch) graphite fiber is difficult because molten metal reaction causes fiber damage from solid-state deformation into the bundle of thousands of small fibers. The interfacial reaction during fabrication or during elevated temperature service causes fiber degradation. Protective coatings to reduce the degree of reaction can be applied more easily to larger diameter (0.002 to 0.010 inch) fibers. Also, the volume of coating material is much smaller for the larger fiber because of the smaller surface-to-volume ratio (ref. 39). For these reasons, NASA has sponsored a "fat" carbon fiber program.

High-strength carbon fibers of large diameter have been prepared by deposition of carbon from a vapor phase onto a graphite fiber substrate. The diameters of the new fibers are large enough to permit application of the state-of-the-art fabrication techniques used for boron/metal matrix composites (ref. 40). These include infiltration by polymeric and metal matrices, diffusion bonding, plasma spraying, etc.

Graphite fiber application.— The effectiveness of graphite/fiber composites in optimizing weight critical structures is demonstrated in the following aerospace example (ref. 41). A study was made of the relative weight saving potential of various advanced fibrous composite materials when used in the design of the support structure for the space shuttle orbiter main engine shown in figure 10. The elements analyzed were the tubular compression struts.

Two basic design approaches were used in this study, both of which encompass the hybrid concept. This concept is a combination of monolithic metal (aluminum and titanium) and fibrous composite material. In design A, the preponderance of material was monolithic metal; in design B the primary structural material was fibrous composite. Designs were optimized to minimum weight for identical load support. Table IX shows the weight advantage offered by a high-strength graphite fiber/epoxy resin composite.

Cost effectiveness in this design depends on the material and manufacturing processes, which were not studied. No doubt, the hybrid is more costly, but system analysis would indicate that the strut weight reduction would have a cascading effect on other sub-systems creating a significant cost and

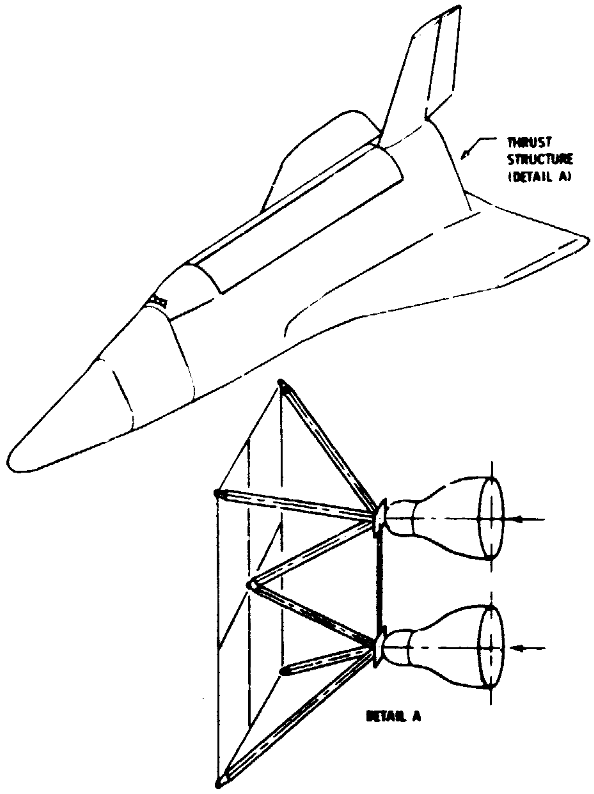

Figure 10.– Orbiter main engine support structure.
(from ref. 41)*

TABLE IX.– TOTAL WEIGHT OF COMPRESSION STRUT *

Material	Weight (pounds)
Aluminum (Al)	111.6
Titanium (Ti)	71.1
Design A	
Al + Graphite/Epoxy	64.9
Ti + Graphite/Epoxy	53.3
Design B	
Graphite/Epoxy + Al	56.6
Graphite/Epoxy + Ti	46.1

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weight reduction for the entire vehicle. Decreasing composite material costs, not expected for metals, would increase this saving during the production cycle.

Fiberglass

Glass fibers are the most fully developed filaments for reinforced composites. They can be considered the grandfather of composite materials and are certainly among those with the lowest cost (see table III in Chapter 1). For these reasons they enjoy the largest volume of structural usage and the greatest variety of applications. Filament properties are presented in table III also. A newer filament material developed by the Air Force, 970-S, has a tensile strength of 800,000 psi and a modulus slightly higher than 15×10^6 psi. Newer fibers with higher properties are discussed below. Glass fibers have a fairly low thermal expansion coefficient, from 1.6×10^{-6} to 2.8×10^{-6} inch/inch $^{\circ}$F.

The fibers are produced commercially in diameters ranging from 0.000375 to 0.000525 inch for structural uses. Several formulations are available having special properties such as low dielectric constants and loss tangent, acid resistance, radiation protection, etc. Fiberglass is available in many forms and is amenable to many processes as shown in table X (ref. 42). Some typical applications are also listed.

Two special types of glass fiber are high silica and quartz. High silica has a silicon dioxide (SiO_2) content of 95 percent minimum, and quartz fiber is produced from 99.95 percent SiO_2 natural quartz crystal. These compare with the SiO_2 content of E glass of 54 percent and of S glass of 65 percent. High silica and quartz are used in composites as consumable thermal insulations

TABLE X. – COMMERCIAL FORMS OF GLASS FIBER REINFORCEMENTS

Nominal Form	General Description	Process	Nominal Glass Content of Typical Laminates (weight %)	Typical Application
Rovings	Continuous strands of glass fibers	Filament winding, continuous panel, preforming (matched die molding), spray-up, pultrusion	25-80	Pipe, automobile bodies, rod stock, rocket motor cases, ordnance
Chopped strands	Strands cut to lengths of 1/8 to 2 inches	Premix molding, wet slurry preforming, injection molding	15-40	Electrical and appliance parts, ordnance components
Reinforcing mats	Continuous or chopped strands in random matting	Matched die molding, hand lay-up, centrifugal casting	20-45	Translucent sheets, truck and auto body panels
Surfacing and overlaying mats	Nonreinforcing random mat	Matched die molding, hand lay-up, and filament winding	5-15	Where smooth surfaces are required – automobile bodies, some housings
Yarns	Twisted strands	Weaving, filament winding	60-80	Aircraft, marine, electrical laminates
Woven fabrics	Woven cloths from glass fiber yarns	Hand lay-up, vacuum bag, autoclave, high-pressure laminating	45-65	Aircraft structures, marine, ordnance hardware, electrical flat sheet and tubing
Woven roving	Woven glass fiber strands – coarser and heavier than fabrics	Hand lay-up	40-70	Marine, large containers
Non-woven fabrics	Unidirectional and parallel rovings in sheet form	Hand lay-up, filament winding	60-80	Aircraft structures

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for reentry heat shields and rocket motor nozzles. Quartz fiber is also used in composites for antennas and radomes because of its special electrical properties. Compared with S glass, high silica is slightly more expensive, while quartz fiber is four to eight times more expensive.

Glass fibers are subject to degradation by abrasion. In addition, they are not easily wet by polymers and, thus, the interface is subject to moisture attack, resulting in degradation of composite properties. Because of these problems, sizings are applied to the fibers to improve fiber wetting and inhibit degradation by moisture. A large variety of sizings is available to suit the polymer and service conditions.

Fiberglass/polymer matrix. – The vast majority of research, development, and use of fiberglass has centered around thermosetting polymer matrices. Little effort has been expended on metal or ceramic matrices because of the low melting point of the glass fibers and/or attack by the matrix on the fibers. Polymer matrices have included almost all available resins. Many thermoplastics such as nylon, acetate, styrene, and polycarbonate are reinforced with short glass fibers. The most commonly used thermosetting resins are polyesters, phenolics, epoxies, and polyimides in descending order of usage. Polyesters are used where moderate strength is adequate and low cost required. The highest strengths are produced with epoxy resins, and polyimides are used where strength at high temperatures is required. Phenolics are used in consumable heat shield applications and in applications in which high-temperature structural properties are required.

A large variety of processes are used to produce composites with glass fibers. Each has certain important features that determine its use, such as obtaining high-strength properties, producing specific configurations, using specific material forms, obtaining low cost of high quality surface finish, producing small or large quantity, etc. Many of these processes are listed in table X and more details are available in ref. 42. Another low-cost process in which fiberglass composites were first used is the Pultrusion method, which is discussed earlier in this chapter under Graphite Fibers.

The strength of glass-fiber-reinforced composites can be varied over a wide range by adjustment of certain parameters. Among the more significant are percentage of glass fiber in the composite, composition or type of the glass fiber, fiber orientation, fiber surface treatment of sizing, composite processing, and type of matrix material used. Some typical strength property data are presented in table XI (ref. 33).

TABLE XI. – STRENGTH-TO-DENSITY PROPERTIES OF FIBERGLASS/EPOXY COMPOSITES

Property	Unidirectional Rovings	Woven Fabric
Fiberglass content, weight %	60 - 90	50 - 65
Density, lbs/in^3	0.016 - 0.079	0.056 - 0.065
Specific Tensile Strength, in x 10^6	1.3 - 3.2	0.43 - 0.93
Specific Tensile Modulus, in x 10^6	65 - 114	54

Comparison of these properties can be made with those of other advanced composites by examination of figures 4 and 5.

New high-performance fibers such as graphite and boron have been welcomed for their many advantages but have not always been cost effective because of the initial high price. Fiberglass composites have been popular because very respectable properties are available at reasonable cost. This is possible because high-strength fiberglass is available at \$5 to \$10 per pound versus \$100 to \$300 per pound for graphite and boron filaments. Fiberglass has the highest specific strength but is not competitive in many structural applications because of its low stiffness.

Consequently, NASA set about to develop a new fiberglass with a high modulus – 30 x 10^6 psi. Although the goal was not achieved, a significant improvement was made with a new glass, UARL 344, as shown in figure 11. The fiber properties are translated into epoxy resin composites as presented in table XII (ref. 43).

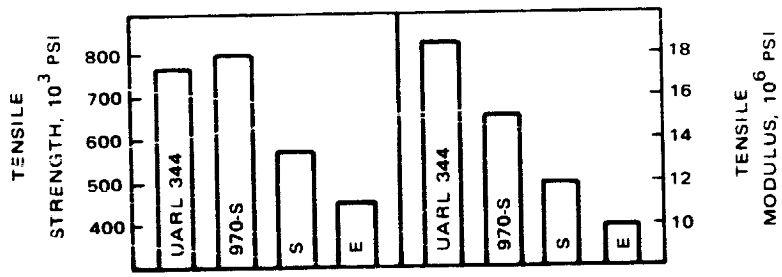

Figure 11.– Comparison of new NASA fiberglass (UARL 344) with other available glass fibers.

TABLE XII.– EPOXY MATRIX COMPOSITES WITH VARIOUS GLASS FIBERS

Fiber	Composite Density (lbs/in^3)	Flexural Modulus (10^6 psi)	Specific Modulus (10^6 psi)
E	0.0776	3.27	42.1
S	0.0762	4.12	54.1
UARL 344	0.0951	6.08	63.9

During this program, many glass compositions were developed, some that had modulus values in excess of 20 x 10^6 psi. However, only UARL 344 had satisfactory commercial production capability.

Three-dimensional woven fabrics.– A novel weaving technique using fiberglass and other high strength/modulus fibers has been developed to help resolve a structural deficiency of collimated fiber/polymer composites. Many of these composites are produced from unidirectional prepreg sheets or tapes that are laid up at specific fiber orientations relative to application requirements and cured by heat and pressure. The in-plane properties of these composites are very good, but the low interlaminar shear strengths limit their overall usefulness.

The composite interlaminar shear strength is essentially that of the matrix because there are no fibers to strengthen the interlayer area. This deficiency of fibers in the cross-plane axis is overcome by a three-dimensional weaving process called Omniweave® (ref. 30). In this process fabrics are produced with multidirectional fibers. The interlocking fibers travel in depth so that discrete layers are not formed. The presence of fibers in the cross-plane axis should enhance the composite shear strength and improve fatigue characteristics. However, a decrease in in-plane strength and modulus occurs. Extensive composite property data on a variety of weaving patterns using several different fibers are available in ref. 30.

Weaving techniques have been devised to produce many fabric shapes including tubes and struts, I-, T- and channel beams, tapered shapes, and integrally ribbed cylinders. A demonstration, free-standing I-beam, woven from quartz fiber roving, was made for NASA to demonstrate the Omniweave® technique (ref. 44). The 12-inch-long beam had a depth of 2 inches and flange widths of 2 inches and 1 inch, respectively. The rib and flanges were 1/8 inch thick. Half the length of the beam was impregnated with epoxy resin and pressure-molded to produce a structural composite.

PRD-49 Fiber

PRD-49 is a new organic fiber that features high strength and modulus and low density. Manufactured by the E.I. Dupont Company, it is very similar to fiberglass (primarily S-glass) in physical characteristics and properties except that it has higher modulus and lower density, as shown in table III of Chapter 1. Another difference from epoxy resin composites is in the thermal expansion coefficient; fiberglass composites expand approximately four times as much as PRD-49 composites. In fact, PRD-49 composites have a negative coefficient; that is, they shrink when heated and expand when cooled (ref. 45). The thermal conductivity of PRD-49 composites is about one-fourth that of fiberglass composites. In addition, the dielectric strength of PRD-49 epoxy composites is substantially lower than that of fiberglass composites (ref. 46).

PRD-49 yarns can be processed on standard textile equipment into fabrics and tapes for coating with resin. Yarns and roving can be impregnated with resin for filament winding and other composite manufacturing processes. Filament winding is a process in which strands or rovings impregnated with resin are wound tightly on a mandrel in a prescribed pattern to form a shape of revolution. Typical shapes are cylinders (pipe), cones and parabaloids (nose cones and radomes), and spheres and closed end cylinders (pressure vessels and rocket motors). Where possible, parts are removed from mandrels; however, closed end vessels are made on meltable or water soluble mandrels which are removed through end fittings (figure 12), or the winding form, e.g., a thin metal shell, may be retained to act as the inner, impervious liner of a high pressure container (ref. 47).

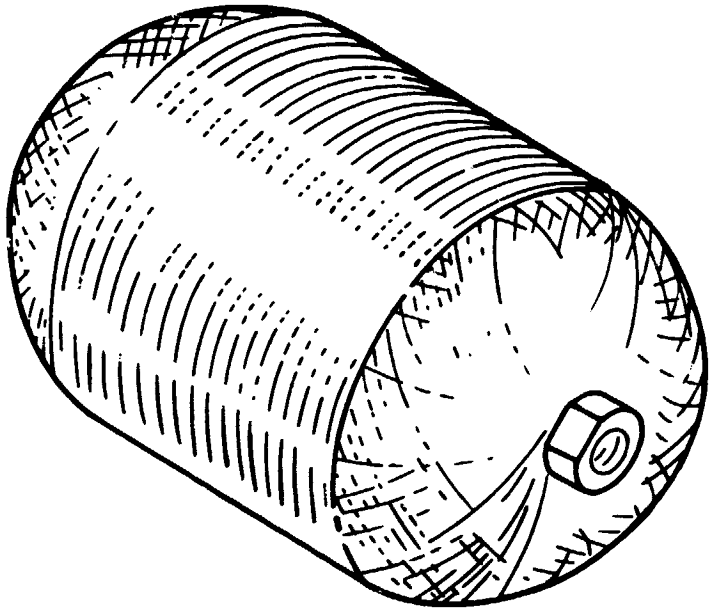

Figure 12. Filament-wound pressure vessel.

PRD-49 fibers in epoxy resin matrix composite have been evaluated by NASA in filament-wound constructions (ref. 45). Basic properties were determined on cylinders four inches in diameter before they were fabricated as small pressure vessels. Results showed that PRD-49 composites had specific strengths slightly higher than those of S-glass composites and a specific modulus value 2.6 times that of S-glass composites. Comparison is made in figure 13 with other composites evaluated in the NASA program and with aluminum and steel bulk materials. Other fiber-reinforced composites can be compared by reference to figures 4 and 5 in this chapter.

Metal Fibers

Metal fibers/metal matrices. – The advantage of metal fibers is that they usually are stronger and stiffer than the same material in bulk form. One

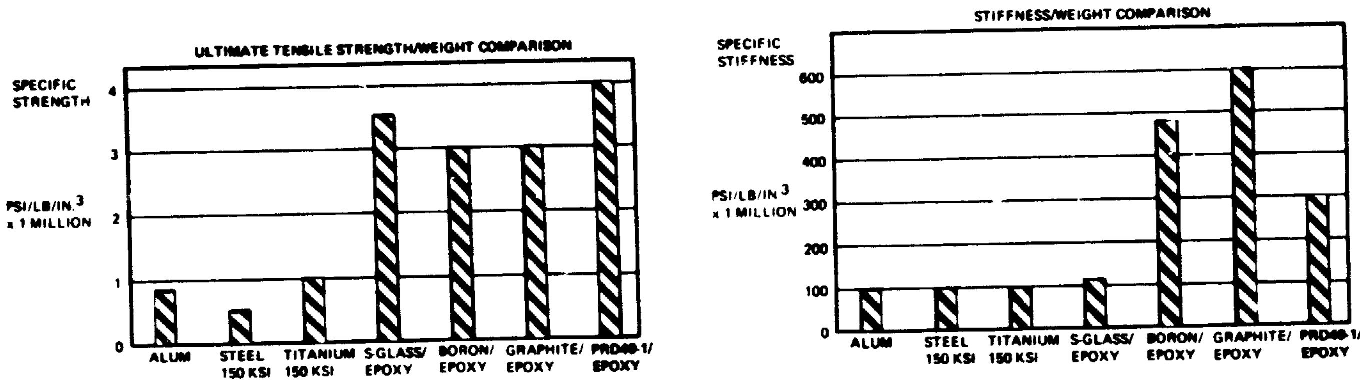

Figure 13. – Comparison of strength, stiffness, and weight of PRD-49-1 with other materials. (from ref. 47)

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advantage of fiber composites is that the component materials can be selected to meet specific service requirements (ref. 48). Metal fibers or wires* are available with good strength and stiffness at very high temperatures, upwards of 2000°F (1093°C) for refractory materials such as tungsten.

Techniques that have been used to produce fine metal filament or fiber include wire drawing, stretching, pin drawing, broaching, foil slitting, electrochemical, liquid metal, vapor-deposition, and proprietary processes. As an example of metal filaments, type 304 stainless steel filament is available over a size range of 4 to 50 microns with an ultimate tensile strength of 100, 000 to 300, 000 psi (ref. 49). The preparation of metal wire for reinforcement is covered in a subsequent section of this chapter.

Metal matrices are available with high temperature capability, in fact, to temperatures above 2000°F (1093°C) for nickel and cobalt superalloys and refractory materials such as columbium** and tantalum. Metals also provide

*Fibers are considered as being of smaller diameter than wire.

**Columbium and niobium are accepted words for the same element.

ductility and toughness. In addition, they protect fibers from damage by abrasion and from oxidation at elevated temperatures.

The potential of metal fiber/metal matrix composites in very high temperature environments is quite good. Two applications in particular, turbine blades for jet engines and structures for the space shuttle, have fostered a substantial amount of development work by NASA (ref. 48).

Tungsten fiber/metal matrix. – The original system, in which early model studies were made, was tungsten fiber in pure copper and various copper alloys (refs. 50, 51, 52). Tungsten is a refractory metal with good high temperature properties. Copper is ductile, easily worked, and compatible with tungsten; that is, there is very little reaction at the fiber interface. These factors make the composite system ideal for model studies to prove concepts and develop analytical techniques. During these studies it was proved that the strength of both continuous and discontinuous fibers in a composite was realized (ref. 53). From the experimental work has come sophisticated structural mechanics techniques to predict composite fracture behaviors and to design composites for specific applications.

The greatest payoff is in very high temperature applications such as turbine blades for jet engines. Increasing operating temperature above 1800°F (982°C) would improve engine efficiency. Nickel and cobalt superalloys are presently used at 1800°F (982°C) but are weak at 2000°F (1093°C). These alloys are good composite matrix candidates because they have ductility and superior oxidation resistance at high temperatures. However, the fiber-matrix reaction is detrimental and must be controlled in elevated temperature service and processing. Reaction during processing has been controlled by the development of a new process for fabrication of composites (ref. 53).

In the same reference, new nickel matrix alloy compositions are described that have been developed that reduce the activity of nickel and increase the matrix strength.

Improvements in the strength of tungsten fibers have also been explored (refs. 53, 54). A tungsten alloy containing thoria (ThO_2) has been tested in the nickel alloy matrix composite mentioned above. Stress-to-density ratios at 2000°F (1093°C) are compared in figure 14. Also included are projections for a new tungsten fiber alloy material containing hafnium (Hf) and carbon.

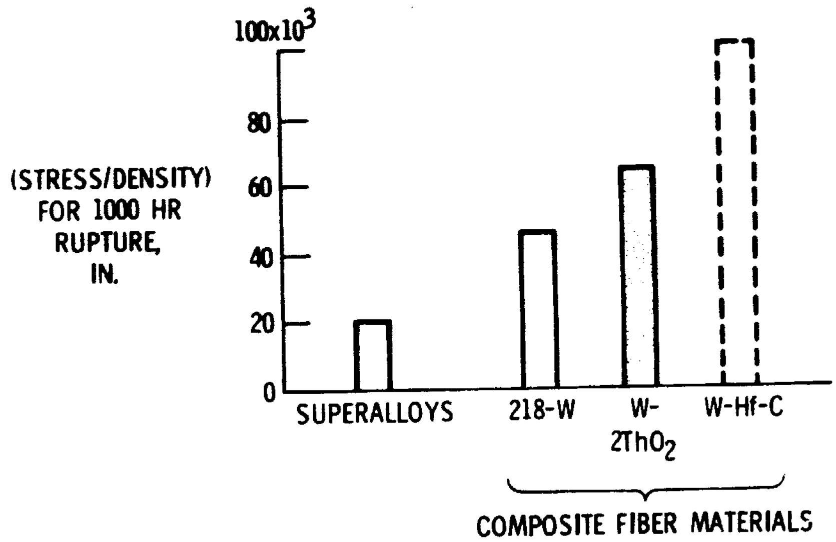

Figure 14.— Stress-rupture strength of superalloy composites. Fiber content, 70 volume percent; temperature, 2000°F (1093°C). (from ref. 53)

Tantalum fiber/tantalum matrix. — Investigation of tantalum fiber/tantalum matrix was an experimental program performed by NASA to determine whether a high strength composite could be produced by hot rolling (ref. 55). The materials used were tantalum fibers (wire, 0.005 inch diameter), tantalum foil (0.002 inch thick), and tantalum power (4×10^{-6} meter size particles). Tantalum was chosen because it can be cold-worked at near normal ambient temperatures and because it possesses good heat transfer, chemical resistance, and strength at elevated temperature.

The composite consisted of a core made of tantalum foil and fibers embedded in a matrix of powder rolled under pressure with the application of heat. Tensile strength at room temperature at various stages of thickness reduction are shown in figure 15. Matrix (from powder) properties were determined separately. For comparative purposes, initial properties of the foil and fibers are given in table XIII.

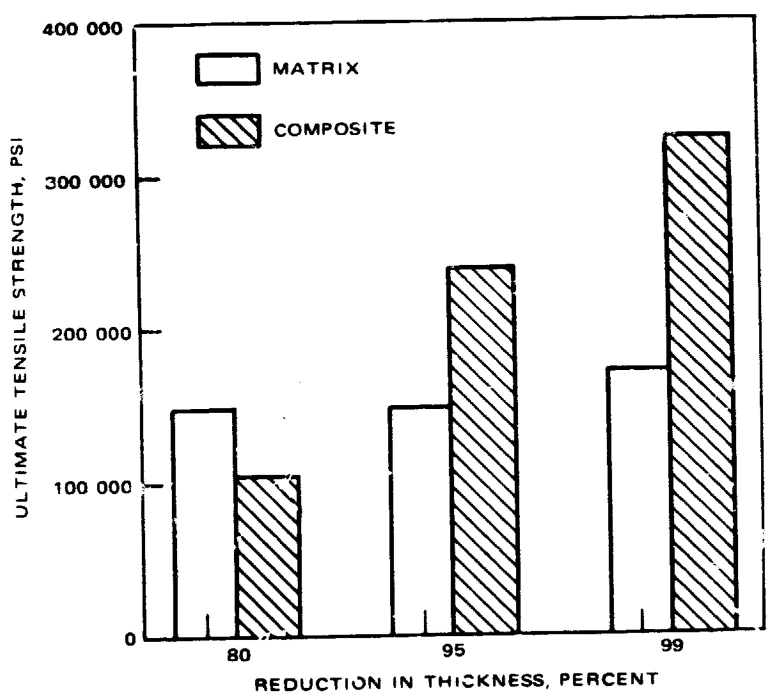

Figure 15. - Effect of rolling on ultimate tensile strength at 77°F (25°C) for matrix and 30 volume percent composite. (from ref. 55)

TABLE XIII. – TANTALUM FIBER AND FOIL PROPERTIES AT ROOM TEMPERATURE

Composition	Ultimate Tensile Strength (psi)	Elongation (percentage)
Fibers, unalloyed	119,000	2
Foil, unalloyed	116,000	1

From figure 15 it is evident that considerable reduction in thickness is required to strengthen the composite substantially in excess of the pure matrix. The strength values in figure 15 are for a composite containing 30-percent reinforcement. The strength is reduced with lower volume fraction of foil and fibers in the composite.

The techniques used here to strengthen tantalum demonstrate a unique composite concept in which the reinforcement and the matrix are the same material. The method may be suitable for other materials.

Stainless steel wire/aluminum matrix. – The reinforcement of aluminum with high strength wire has good potential for commercial products of sheet, plate, bar, and extruded shapes. Wires are of particular interest because of their low cost. They are produced by common manufacturing processes such as cold drawing a rod through dies. The wire is drawn in lengths of thousands of feet and wound on spools. Drawn wires have high strength. As the wire diameter is decreased, mechanical properties increase. The effect of wire drawing on the properties of selected metals is illustrated in figure 16. In general, metal wires are more ductile than fiberglass, boron, and graphite filaments.

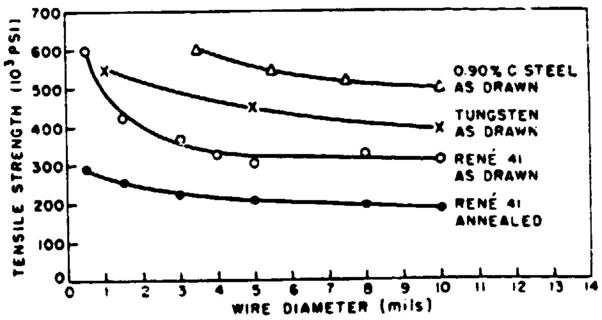

Figure 16. - The effect of diameter size on cold drawn wire. (from ref. 56)

Wire diameters used in composites range from about 0.001 to 0.020 inch. The properties of several wires suitable for reinforcing aluminum are presented in table XIV. Commercial materials are used for the aluminum matrix. The wire-aluminum composite can be fabricated using established processes and skills.

TABLE XIV. - WIRES FOR COMPOSITES

Material	Density lbs/cm/ft	Melting Point ^{o}F	Tensile Strength (10^3 psi)	Elastic Modulus (10^6 psi)
Stainless steel	0.290	2600 (1427°C)	500	29
Rene 41	0.298	2600 (1427°C)	290	24
Beryllium	0.067	2332 (1278°C)	185	35
Molybdenum	0.369	4730 (2620°C)	320	52
Tungsten	0.697	6170 (3400°C)	580	59

Methods for producing wire-reinforced structural aluminum materials have been developed by a NASA contractor (ref. 58). Aluminum alloy 2024 was used for the matrix. Stainless wire, type NS-355, was used for most of the work because of its high strength, ductility, and corrosion resistance. The best fabrication method was found to be hot diffusion bonding followed by hot rolling. The hot rolling reduced the stainless steel by 50 percent without breaking the wire; the development thus demonstrated the feasibility of rolling composite sheet and plate. Typical room temperature properties for the composite are presented in table XV (ref. 59). Preliminary information indicates good composite toughness at -320°F (-196°C) and lower temperatures (ref. 60).

TABLE XV.– TYPICAL ROOM TEMPERATURE PROPERTIES OF UNIDIRECTIONAL WIRE-REINFORCED ALUMINUM COMPOSITE

Property	Composite	Reinforcing Wire	Matrix
Tensile Ultimate	175,000 psi	475,000 psi min.	64,000 psi min.
Tensile Yield	110-145,000 psi		50,000 psi min.
Modulus of Elasticity	15×10^6 psi	29×10^6 psi	10.5×10^6 psi
Density	0.145 lb/in^3	0.282 lb/in^2	0.100 lb/in^2
Material	25 vol. %, 0.009 inch dia., NS 355 steel and 2024-T6 matrix	NS 355 steel	2024-T6 aluminum

Steel aluminum composites are not commercially available today. However, panels for prototype and development hardware are available. It has been estimated that the material price could approach $10 a pound when the steel wire-aluminum composite becomes a production item.

The process appears to be readily adaptable to commercial scale-up. Steel/aluminum composites have been produced in sheet and plate up to 3/4 inch thick and in sizes up to 12 inches wide by 8 feet long. With new tooling the size can be increased to 4-foot widths and 10-foot lengths. The potential exists to produce sheet and plate in thicknesses up to 1 inch and lengths up to 20 feet in 4-foot widths (ref. 61).

TZM fiber/columbium matrix.– TZM (molybdenum alloy) fiber/columbium matrix is an experimental composite being evaluated by NASA for structural applications on the space shuttle skin where service temperatures approach 2500°F (1371°C). The columbium alloy is C129Y.

The interesting feature of this investigation is the use of explosive bonding fabrication of the composites (ref. 62). Layers of TZM wire filaments are unidirectionally positioned between thin columbium sheets and subsequently joined by the energy from an explosive charge. Metallurgical bonds are good, external heat is not required, and the process is relatively inexpensive. Composite strength properties are good, exceeding predictions, as shown in table XVI (ref. 63).

TABLE XVI. – STRENGTH OF EXPLOSIVELY BONDED COMPOSITE

Material	Tensile Strength (psi)	Yield Strength (psi)	Elongation (percentage)
TZM wire (0.010 in. dia	252,000	180,000	4.5
C129Y sheet (0.135 in thickness)	94,000	75,000	22.0
Laminate (no wires)	100,000	92,500	3.0
Composite (14.7 vol. percent wires)	127,000	112,800	3.0
Prediction	106,000	--	--

Explosive bonding of the columbium sheets without wires increased the tensile strength 7 percent and yield strength 23 percent. The wire reinforcement increased the tensile and yield strength of the matrix 35 and 50 percent, respectively.

Other TZM wire-reinforced refractory composites have been formed by this technique. These include refractory matrix materials consisting of Inconnel X, HS-188 cobalt alloy, and FS-85 columbium.

Laminar Composites

In Chapter 1 the definition of laminar composites was given as "composites formed of two or more layers of materials bonded together." The actual scope of the NASA investigations of laminar composites, however, ranges from investigations of simple combinations of two metals to investigations of multilayer insulations, bonding methods, etc. The investigations thus include determinations of the physical, mechanical, and chemical properties of many different types of laminate composites and also include techniques for preparation of the material, i.e., the joining or coating techniques, etc.

The classification of materials used in making laminates is roughly given as those materials that are used in sheet form or are applied to sheets. Thus, films, sheet metals, special coatings, and fabrics are all materials that could serve as laminate components. A honeycomb sandwich structure is considered a laminate; however, the honeycomb core, when used by itself or possibly filled, would be considered a skeletal structure.

The work on composite/laminates that has been done by NASA or NASA-funded contractors is divided in the discussion to follow into the following broad classifications.

1. Films

   a) films used as components in thermal insulating systems

   b) films used with metallic coatings, foils, and/or fiber reinforce-reinforcements.

2. Bimetallic Alloys

3. Fibrous Laminated Composites (woven fabrics combined with other materials — excluding non-woven, unidirectional fiber-reinforced laminates)

4. Special Coatings applied to high-temperature resistant materials for corrosion resistance, oxidation inhibition, etc.

5. Honeycomb Sandwich Structures

6. Ceramic-metal Combinations

Films

Films used as components in thermal insulating systems. — A great deal of work has been done by NASA and NASA-funded contractors on the development of highly efficient, lightweight insulating systems for use on cryogenic tanks. Because the cryogenic liquid storage tanks constitute nearly the entire volume of boosters for spacecraft, it is imperative that the insulation system around the tank be as light and efficient as possible. It was found that multilayer metal-coated film systems, designated MLI, act as excellent thermal radiation shielding and insulation. In general, these films are polymers, Kapton (polyimide), Mylar (polyethylene terephthalate), or Lexan (polycarbonate), coated either with vapor-deposited aluminum or gold on both sides. In addition to the films, the insulation system includes spacers, made of materials such as nylon, polyester Dacron floc, silk scrim cloth, etc. Adhesives with good high and low temperature properties are used to hold the floc to the films at discrete intervals. Thicker gauge face sheets are used on each side of the insulation package to act as structural support for the MLI blanket and to protect the core sheets from rough handling and from degradation of the metallized surface. Materials that have been used for the face sheets include laminates of nylon or Dacron netting sandwiched between metallized polymeric films.

MLI insulation blankets such as that described above are used for temperature ranges from -420 to 300°F (-251 to 149°C). The thermal efficiency that has been obtained from blankets with 30 layers of goldized Kapton and Dacron spacer tufts is 1.37-1.5 x 10^{-5} BTU/hr/ft./°F (ref. 64).

Another type of cryogenic insulation in which laminated structures and films play a major role is designated "The Capillary Internal Gas Layer Insulation System" (ref. 65). In this system, illustrated in figure 17, a capillary opening is placed in a film that is attached to one side of a cellular structure (commonly honeycomb). The other side of the film is in contact with the cryogenic fluid as shown.

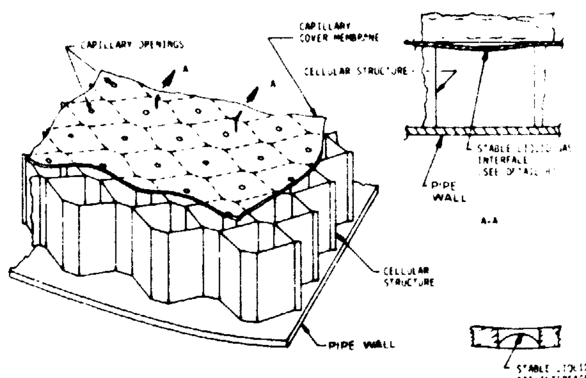

Figure 17.– Capillary internal insulation concept. (from ref. 65)

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Because of the capillary force of the liquid, a stable liquid/gas interface forms at the perforation preventing the liquid from entering the cells.

However, since the opening is large enough to allow some liquid or gas to enter the cell, a small pocket of gas is positioned between the liquid and cell wall. At the same time, because of the opening, the structure is pressure equalized; thus the insulation is essentially free of any stresses due to pressure loads. In the actual installation the cells are also filled with a lightweight, opaque, fibrous batting to control free convection and radiation. The capillary internal gas layer insulation system is lightweight, 0.3 to 0.45 lb/ft^2 for a one inch thickness. A thermal conductivity within 20 percent of the thermal conductivity of hydrogen vapor can be achieved (ref. 138).

Two types of insulating systems are under development. One is a system with a titanium or Inconel tank wall operating at 650°F (343°C); the other has an aluminum wall with a maximum operating temperature of 350°F (177°C). The 650°F (343°C) system uses a polyimide film (Kapton), 0.001-inch thick; a honeycomb structure made of 0.005-inch Kapton; and a polyimide adhesive. The honeycomb has cell sizes varying from 1 to 2 inches, resulting in a core with very low density. For the 350°F (177°C) installation, Kapton core is also used with a polytetrafluoroethylene (TFE Teflon) facesheet. The adhesive used for bonding the facesheet to the core is a methyl-phenyl silicone.

The application of the multilayer insulation system (MLI) previously described was originally intended for operation with space booster external wall temperatures of approximately 70°F (21.1°C). The external wall temperatures of the shuttle vehicle, on the other hand, are expected to be in the 350°F (177°C) range. This increased temperature called for considerable changes in the materials and processes previously developed. One of the systems developed for the higher temperature differential service is known as the "Self Evacuating Multilayer Insulation" or SEMI (ref. 66).

The SEMI system utilizes the same type of highly reflective radiation shields separated by low conductivity spacers, as previously described; however, the entire blanket is made as a number of small panels, each enclosed in an impermeable casing. Each panel is filled with gas having a very low vapor pressure at cryogenic temperature; e. g., carbon dioxide is commonly used. A portion of each panel must contact the cryogenic tankage to provide a cryopumping surface when the tank is filled with a cryogenic fluid. Thus in service the "filler" gas is cryopumped to the cold portion and condensed; because of the low vapor pressure, a near-vacuum results in the insulation package that considerably increases the efficiency of the MLI system used. Figure 18 shows a cross-section of a typical SEMI package, and figure 19 illustrates the assembly of the panels in a three layer "shingle" array, so that a portion of every panel is in contact with a cryogenic tank wall.

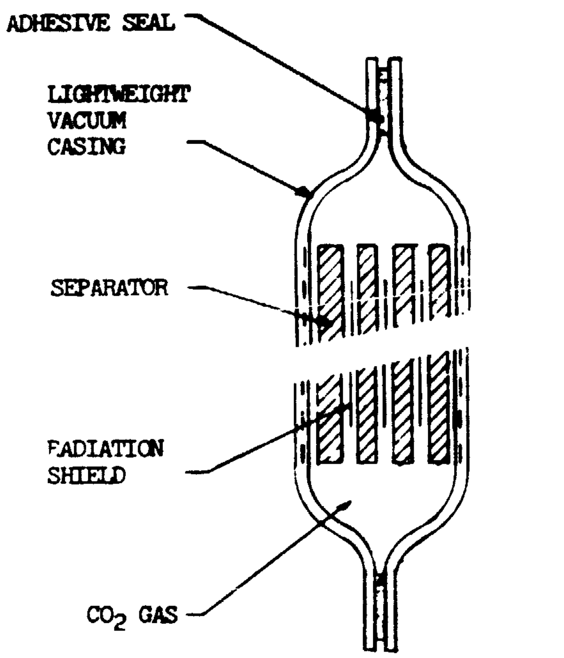

Figure 18.— Schematic of semi panel showing component materials. (from ref. 66)

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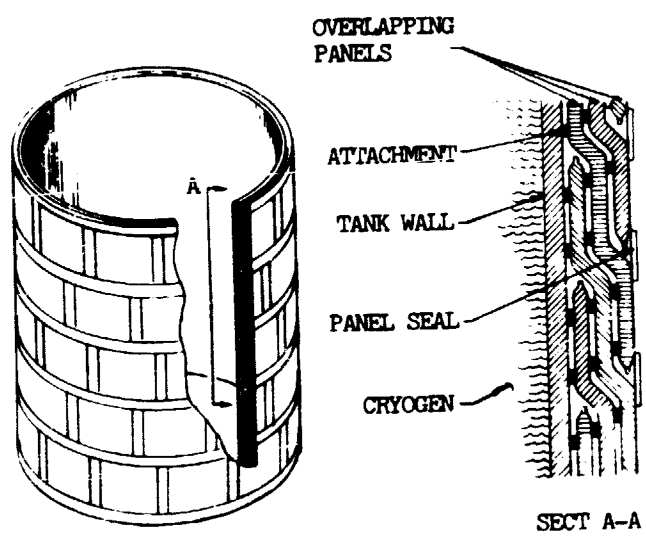

Figure 19.— Semi panel shingle arrangement installation. (from ref. 66)

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The SEMI system for cryogenic tankage has demonstrated a thermal performance of 0.63 BTU/hr/ft^2 in an uncompressed space condition and of 10 BTU/hr/ft^2 during ground conditions with a system weight of 0.39 lb/sq. ft. Several patents, assigned to NASA, have been taken out on similar cryopumping insulation systems (refs. 67, 68).

In addition to the work described above, a number of other programs have been investigated to test the MLI or SEMI systems or variations of these systems, (refs. 69, 70, 71). One report, prepared for the Marshall Space Flight Center, (ref. 72) summarized all the major developments in the field of cryogenic insulation, both film and honeycomb laminate types and foam insulations. A similar, but more complete, compilation of data on all types of insulation systems, including several chapters on cryogenic insulations, is given in ref. 73.

An interesting side development, resulting from the research on cryogenic insulations, is the development of a low-cost cryostat from readily available materials (ref. 74). It should be possible for many small laboratories, small hospitals, industrial firms, etc., to possess an efficient cryostat for storage of liquid gases such as liquid nitrogen, hydrogen, etc. A unit costing approximately $10.00 is said to store liquid nitrogen for one week compared with three weeks storage in a Dewar type of cryostat of the same capacity that costs approximately $150.00.

In contrast with the film and foil laminates for cryogenic applications, multilayer foil and fabric insulation systems have been developed that can be used at temperatures of 2000°F (1093°C) and up to 4000°F (2204°C) (ref. 75). The lower temperature configuration consists of molybdenum foil, 0.001 inch thick, interleaved with silica cloth. The combination is wrapped around the object to be insulated for satisfactory use up to 2000°F (1093°C).

A similar laminated construction using tantalum foil, 0.001 inch thick, combined with carbon cloth is reported to be usable up to 4000°F (2204°C). At temperatures lower than approximately 2000°F (1093°C), the tantalum-carbon combination has higher thermal conductivity than does the molybdenum-silica. The tantalum foil-carbon laminate is therefore recommended for use only at temperatures above 2000°F (1093°C).

A simple insulation system for temperatures up to 600 to 700°F (316 to 371°C), using readily available materials such as aluminized fiberglass tape, cork, and Mylar film, has also been described (ref. 76).

Films used with metallic coatings, metal foils, and/or organic fiber reinforcements. — Metallic-coated film was used in one of the earliest experiments in which NASA worked with large quantities of film. It was the Echo I Balloon Project in 1960, in which literally the whole world was made aware of this composite material. A film of Mylar, 1/2 mil thick, was used to form the 100-foot diameter ballon: the Mylar was coated with brightly shinning aluminum and was seen by millions around the world.

Since the original Echo Project, a number of more sophisticated metallized film laminates have been developed. These included thinner Mylar films, down to 0.15 mil thick; special vinylidene coatings (Saran), applied to decrease the gas permeability; and special adhesives used in fabrication of the laminate. Both single- and double-film laminates have been made, with special equipment being designed to handle the ultrathin Mylar films. The physical properties of some of these laminates are shown in tables XVII and XVIII (ref. 77).

Films combined with metal foils have been used for a number of inflatable structures by NASA, starting with the Echo II project, which was a ballon, 135 feet in diameter, that used Mylar film bonded to aluminum foil. A

TABLE XVII. – METALLIZED FILM LAMINATES

Laminate Designation	Laminate Construction	Thickness (mils)	Weight (lb./ft^2)	Ultimate Tensile Strength (10^3 psi) MD	Ultimate Tensile Strength (10^3 psi) 45°	Ultimate Tensile Strength (10^3 psi) CMD	Elongation (percentage) MD	Elongation (percentage) 45°	Elongation (percentage) CMD	Modulus of Elasticity (10^3 psi) MD	Modulus of Elasticity (10^3 psi) –	Modulus of Elasticity (10^3 psi) CMD
PZ 5508.35	0.25-mil Aluminized Mylar Saran Coating Adhesive 0.15-mil Mylar	0.71	0.00475	14.0	14.[illegible]	17.[illegible]	[illegible]	[illegible]	53	[illegible]	–	[illegible]
PZ 5508.36	0.25-mil Aluminized Mylar Saran Coating Adhesive 0.15-mil Aluminized Mylar	0.73	0.00472	13.2	14.8	17.1	52	[illegible]	51	377	–	[illegible]
PZ 5508.37	0.15-mil Aluminized Mylar Saran Coating Adhesive 0.15-mil Aluminized Mylar	0.60	0.00370	12.4	11.[illegible]	17.1	[illegible]	52	51	388	–	475
PZ 5508.38	0.25-mil Aluminized Mylar Saran Coating Heat Resistant Coating	0.40	0.0016	15.6	19.6	21.2	66	54	48	504	–	640
PZ 5525.05	0.5-mil Mylar Saran Coating Adhesive 0.25-mil Mylar	0.90		19.5	19.2	23.8	89	70	58	530	–	585

MD Machine Direction: 45° = 45° to MD: CMD = Transverse to MD.

TABLE XVIII. – BARRIER DATA OF METALLIZED FILM LAMINATES

Sample	Gas Transmission cc(STP)/(100 sq. in.) (24 hrs)(atm) Oxygen	Nitrogen	Carbon Dioxide	Thickness (mils)
PZ 5508.35	0.037	0.011	0.102	0.75
PZ 5508.36	0.048	0.011	0.083	0.75
PZ 5508.37	0.055	0.011	0.21	0.55
PZ 5508.38	0.021	0.011	0.067	0.45

number of similar projects, such as air density programs, have been or are currently being studied. In general these projects use Mylar-aluminum foil combinations, such as two 1/2-mil Mylar films laminated to two 1/2-mil aluminum foils. Here advantage is taken of the tensile strength and tear resistance imparted by the Mylar film and the work hardening properties of the aluminum foil, which imparts a certain degree of permanent rigidization when used in an inflatable structure. The aluminum foil also, of course, has perfect electromagnetic reflection properties so it may be used very satisfactorily for radar reflection.

Fiber-reinforced Mylar and polyethylene films have been used for a variety of ballon applications by NASA Langley Research Center. In general, these applications involve high-lift, high-altitude balloons that are exposed to high internal pressures and very low temperatures. The combination of lightweight and rip-stop characteristics imparted by the fiber reinforcements, as well as increased tensile strength, make the material ideal for such applications.

By the use of a special device called a flying thread loom (FTL), it is possible to reinforce the polymer film with many geometries in the yarn pattern. Thus it is possible to have diamond pattern reinforcements, square yarn reinforcements, varying distance reinforcements, etc. All these can be produced using Mylar or polyethylene films with 1/4 mil and greater thicknesses, either as single film and yarn composites or as double-film laminates with the reinforcing yarn sandwiched between the films. Typical physical properties of such materials, which were produced for NASA for the Viking project, are shown in table XIX (ref. 78).

Somewhat lower values and lighter weight could be obtained with polyethylene film laminates. The Mylar film laminates are fabricated using special thermosetting tapes. Polyethylene can be easily heat sealed to itself, even with the reinforcing fibers present. The Mylar film materials cost approximately $1.50 per linear yd (5-ft width). The polyethylene material is about 1/3 cheaper for the material and much cheaper to fabricate.

TABLE XIX. – ORGANIC FIBER-REINFORCED MYLAR BALLOON FILM

Characteristic	Type G 101204	Type G 127600
Weight, lb/ft^2	0.0131	0.00817
Ultimate stress, pounds per foot of width (Machine direction)	1450	600
Construction		0.35 mil Mylar 24/ft 1300 denier Dacron warp yarns 41.5/ft 440 denier Dacron fill yarns

In addition to reinforcement of films by fibers and foils, investigations have been funded by NASA to determine the feasibility of rigidizing film structures in space by chemical techniques. Several such methods, using special ultraviolet-activated polyester resin or heat-activated epoxy coatings applied to the films, have been developed (ref. 79).

Bimetallic Composites

Bimetallic composites, as the name implies, are combinations of two metals. As in other composites, the two materials complement each other and produce a final product whose characteristics are superior to those of either of the components. Commonly such materials have been made using a high strength metal combined with a thin laminate of a corrosion resistant stock, or perhaps an oxidation resistant material will be combined with a very strong, tough material.

There have been several NASA investigations into bimetallic sheet composites for corrosion resistance and/or oxidation resistance. Thin

(0.0001 to 0.010 inch) 304 stainless steel cladding is very effective in preventing a titanium-LOX* explosive reaction under a variety of impact situations using various thicknesses of cladding and intentional defect sizes (ref. 80). The laminates were prepared by two methods – explosive welding and physical vapor deposition. Fatigue, tensile, and fracture toughness of products produced from both fabrication methods are given in ref. 80.

Similar work was done on refractory-austenitic combinations (ref. 81). Several types of stainless steel and nickel base alloys were explosively bonded to columbium and tantalum, and columbium and tantalum alloys because of ease of fabrication, rate of interdiffusion, resistance to cyclic thermal exposure, and elevated temperature creep properties. The optimum refractory/austenitic combination was tantalum/321 stainless steel.

Methods of preparing various bimetallic combinations have received attention by a number of workers. A diffusion bonding technique for joining steel and Teflon-infiltrated bronze has been described (ref. 82) and patented (ref. 83). The technique has been used to fabricate high strength, permanently lubricated gears. Thermally stable polyimide adhesives satisfactory for long term use at 600°F (316°C) and for short periods of four to five hours at 1000°F (538°C) are described (ref. 84). Such materials have been used in fabrication of bimetallic laminates using titanium and boron. Spot welding may be done through bonded laminates using these new adhesives. The adhesive acts to give additional strength at the high temperature, better fatigue resistance, and corrosion protection.

*LOX – Liquid Oxygen

A compilation of techniques for joining metals by diffusion bonding, brazing, soldering, etc., has been published (ref. 85). Also included are a number of materials and processes used in adhesive bonding.

Bilaminar Composite

An investigation of polyimide films (Kapton) reinforced with vapor-deposited boron, 0.15 to 0.25 mil thick, has been performed (ref. 86). Since boron constituted only 13 percent by volume of the specimens, the physical properties of the composite films were poor in comparison with boron fiber-reinforced materials. However, they have the distinct advantage of bidirectional properties, whereas single layer fiber-reinforced composites are unidirectional.

Special Coatings for High Temperature Use

Advanced turbine engines, nuclear power plants, etc., have brought about requirements for alloys with higher temperature resistance, better resistance to oxidation, more corrosion resistance, etc. One method for obtaining these improvements with existing materials is by the use of a coating which, in addition to providing resistance to heat degradation, would be thicker or stronger than an ordinary paint coating or might combine with the substrate material to form a resistance surface, etc.

A number of vapor-deposited cobalt chromium aluminum yttrium coating compositions, which were designed to protect nickel base superalloys from excessive oxidation at temperatures up to 2000°F (1093°C) for long periods of time, have been described (ref. 87). Four compositions were found that protected the substrates for at least 1100 hours at 2000°F (1093°C). Three standard aluminide coatings tested failed the 1600-hour burner test.

A phosphate-bonded zirconia coating system was developed to protect rocket engine thrust chamber walls (ref. 88). This heat-barrier coating was applied by a slurry method to thin-walled Hastelloy X tubes. Protection is provided up to 4000°F (1993°C).

A coating has been developed that will protect graphite elements in an induction furnace (ref. 89). Uncoated graphite elements are oxidized at temperatures above 2500°F (1371°C). The new coating, based on tungsten powder dispersed in a phenolic binder, has protected graphite elements for a half hour at 4000°F (2204°C).

Silicide coatings for refractory alloys are known to improve their high temperature capability. One coating, developed by a contractor for NASA Lewis Research Center is particularly effective for tantalum (ref. 90). Tests showed good protection for tantalum for 800 hours at temperatures up to 2400°F (1316°C). Both tantalum and columbium alloys have been protected at 2400°F (1316°C) over four times as long as by conventional silicide coatings at 2400°F (1316°C) and at the critical intermediate temperature range of 1450° to 1800°F in which simple silicide coatings usually tend to fail catastrophically. Additional research conducted at Lewis Research Center has resulted in greatly improved silicide coatings for chromium alloys (ref. 90). Additional work is continuing.

Fibrous Laminated Composites

Efforts by NASA in the field of laminated fabrics have been confined mainly to developments concerned with coatings applied to fabrics to increase fire resistance or resistance to abrasion or both. Along these lines, a great many investigations have been directed by the Crew Systems Division at the Manned Spacecraft Center in Houston, Texas (ref. 91).

One material, originally developed by the Owens-Corning Company, but further developed by NASA for use in the space program is Beta fiberglass (ref. 92). This material, an extremely fine glass fiber woven into soft fabric, shows good abrasion resistance when coated with TFE Teflon and, of course, excellent fire resistance. Beta fiberglass by itself does not provide much effective insulation to high temperatures. Combined with other materials, however, the resulting composite will maintain a high temperature differential. An example is a medical kit, encased in a multilayer assembly of beta fabric, aluminum foil, and asbestos fabric, which survived a three-minute exposure to a 2400°F (1316°C) flame.

Other efforts by the Manned Spacecraft Center have led to development of flame resistant elastomer coated fabrics. The elastomer most frequently used is Fluorel, a 3M Co. copolymer of hexafluoropropene and vinylidene chloride. In tests by Manned Spacecraft Center it was found that Fluorel could be applied to many substrates, all types of fabrics, plastics, etc. In addition to its use as a non-flammable component of laminates, Fluorel can be molded into boot-soles, eye-pieces, headrests, etc. (ref. 93).

On the basis of the work done in developing the elastomer-coated fire resistant materials, two basic types of fire fighters clothing have been fabricated by NASA (ref. 94, 95). One type, designated structural clothing, is normally worn by personnel engaged in firefighting activities. The other is a proximity suit, made to furnish insulative protection to personnel working close to extremely hot fires. In both types of suits, a variety of coated and treated fabrics, such as Fluorel-coated modified polyamides and aluminized polyamides, are used either as separate inner and outer garments, or the fabrics are combined with aluminized asbestos or other insulation materials to work as a true composite material. Very favorable response has been received on these developments from professional fire fighters (see Chapter 8).

The same coating and assembly techniques for production of fire-resistant fabrics and similar materials for spacecraft and fire-fighters suits can be applied to commercial aircraft, in the home, and in institutions such as hospitals, hotels, etc. (refs. 93, 96, 97).

Honeycomb Sandwich Structures

Because honeycomb structures consist of two sheets bonded to a core stock, they are considered to be laminates. This type of construction can possess extremely high strength-to-weight ratios. Consequently, it is natural that NASA would intensively develop sandwich structures.

One of the major problems in exploiting the use of honeycomb structures is the difficulty in fabricating the structures, particularly all metal sandwiches, for high temperatures, at which no organic adhesives can be used. Several NASA projects were specifically concerned with this problem.

Techniques for the fabrication of high-strength, brazed aluminum honeycomb sandwiches have been investigated (ref. 98). It was found that optimum wetting and flow required the brazing alloy to be clad onto the substrate metal. A brazing alloy foil, laid onto the substrate foil, produced less than optimum results. It was also found that the aluminum honeycomb sandwich panels requiring rapid cooling could be produced with minimum distortion if quenched in liquid nitrogen.

Another honeycomb core less common than aluminum is made of beryllium. This material is of interest because it is 35 percent lighter than aluminum and can be used at higher temperatures. Processing, however, is somewhat more difficult than with aluminum. Details are available of processes developed for fabrication of beryllium core in which the nodes are joined by microresistance tack welds (ref. 99). Diffusion bonding was tested and also found feasible. A commercially available brazing alloy, AMS Specification 9773 (silver-30, copper-10, tin), was found suitable for scale-up tests and was used to make a number of laminates using 3- and 6-mil foil for the cores and 0.020-inch face sheets.

Additional efforts by NASA include two patents on the production of honeycomb structures. One relates to a method of producing inflatable honeycomb structures (ref. 100). The other describes several methods of making honeycomb structures using internal heating techniques so that separate curing ovens or furnace brazing facilities are not required (ref. 101).

The use of organic adhesives for fabrication of honeycomb sandwiches is a well established technology and, therefore, is not reported in any detail in this survey. However, an adhesive thermally stable up to 600°F (316°C) for long periods of time could lead to improved titanium and/or aluminum honeycomb core sandwiches. This adhesive is the same one earlier referenced under bimetallic laminates (ref. 84).

Ceramic - Metal Combinations

A review of the theory of ceramic-to-metal joints, the types of materials that can be used, joining configurations, and techniques for making various types of ceramic-to-metal joints is available in ref. 102. Included in the report is a separate section on graphite-to-metal joints. The graphite material discussed in this reference is non-fibrous, massive graphite mainly used for very high-temperature applications as electrodes, anodes, molds for casing, furnace refractories, etc. The section treats the special problems of wettability in joining graphite, the coefficient of expansion differences between graphite and most metals, and other problems. Techniques of joining graphite to metals and to graphite are detailed.

Skeletal Composites

Skeletal composites are those materials in which the matrix is a skeletal material into which a filler is introduced. Such materials would include various types of filled foams and filled honeycomb, and foamant compositions. These latter contain a salt which, during foaming, causes intumescence that smothers the fire.

Foams

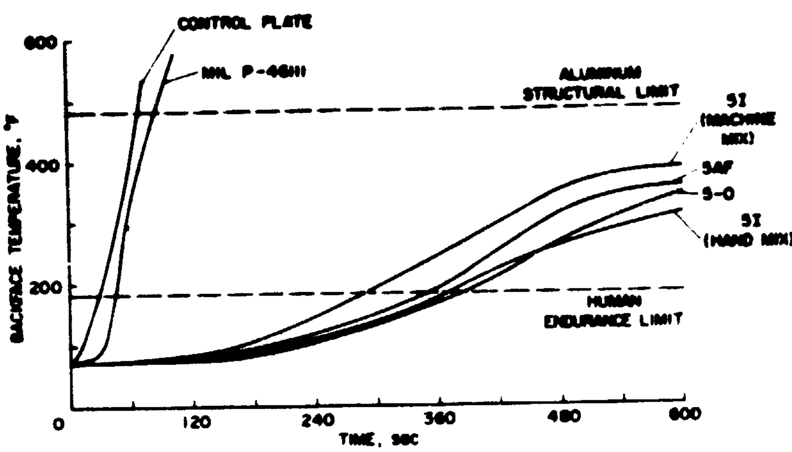
The major effort by NASA in the field of foam composites has been on the development of foam materials that can be used for fire protection of the crew and passengers in aircraft. After the disastrous fires on the Apollo spacecraft and on the aircraft carrier USS Forrestal in 1967, the Thermal Protection Group at Ames Research Center was given the task of producing thermal protection and fire retardant materials applicable to aircraft, boats, cars, houses, and other vulnerable structures. The Ames researchers, up to then involved in development of spacecraft heat shields, decided that the same principles might apply to these new materials. These principles were:

1. The applied material should at all times act as a good thermal insulator.
2. When the outer surface of the material was exposed to high temperatures, it should convert to a stable char and in so doing absorb heat.
3. The char should be a good reradiator of heat (high emissivity).
4. During decomposition, in the char forming process, the gases formed should help quench the flames and also, by the outward flow, cool the char surface.

Using these principles and another which stated that the components in the new materials should be readily available chemicals, two types of materials were developed, foams and intumescent paints.

Polyurethane foams.– One new material was developed by the incorporation of fire suppressant materials into specially formulated polyurethane rigid foams (ref. 103). Thus, in the event of a fire, the area surrounded by the pre-applied foam would have some degree of insulation protection from the heat, and at the same time, while the foam components were forming a char, they would act to suppress or quench the flame propagation. This action was accomplished by the addition to the foam of three types of thermally activated components: (1) halogenated polymers, (2) inorganic salts, and (3) encapsulated volatile or reactive halogen-containing compounds.

Figure 20 indicates the results of the thermal efficiency tests for several foam formulations.



5-0 - Unmodified polyurethane foam-base for 5I and 5AF

5I - Contains potassium fluoborate and polyvinyl chloride acetate

5AF - Same as 5I plus encapsulated Freon 113 microballoons

Figure 20.— Backside temperature history of composite foams from 1-inch foam slab tests. (from ref. 103)

The distinct improvement in thermal gradient protection is shown in figure 20: 180 F is reached in approximately 360 seconds for the specially formulated polyurthanes compared with approximately 50 seconds for the MIL-P 46111 foam. Furthermore, "as can be seen, the foam conforming to the MIL-P-46111 has a very rapid rise to 500°F (260°C) which does not differ appreciably from that of the control plate. The unmodified foam, type 5-0, which is the base polymer system for the fire-retardant foam, performs quite well up to a time of 500 seconds; however, after this time the foam begins to deteriorate, causing a rapid rise in the backside temperature. The fire retardant foams, as illustrated, seem to have reached a plateau at the 500-second level showing an improvement in the thermal-insulation characteristics for long sustained protection" (ref. 103). Complete details of the formulations, methods of application, etc., are given in the cited reference.

Isocyanurate foams.— On the basis of the work done to perfect char-forming heat shields for spacecraft, it was found at Ames that an isocyanurate foam could be formulated that would form a larger char than the best Ames urethane and was considerably superior to a commercial isocyanurate (ref. 104). Figure 21 (ref. 104) shows the results of tests of several of the fire protective foams, including a quartz or glass-fiber-filled isocyanurate. The use of 10 percent by weight of the fibers produces a marked improvement in exposure time, as shown.

Table XX (ref. 104) gives the physical properties of the two types of foams.

It should be pointed out that the effectiveness of these fire suppressant materials lies to a large extent in the generation of a large quantity of smoke and gaseous products. For the most part these are mildly to severely toxic.

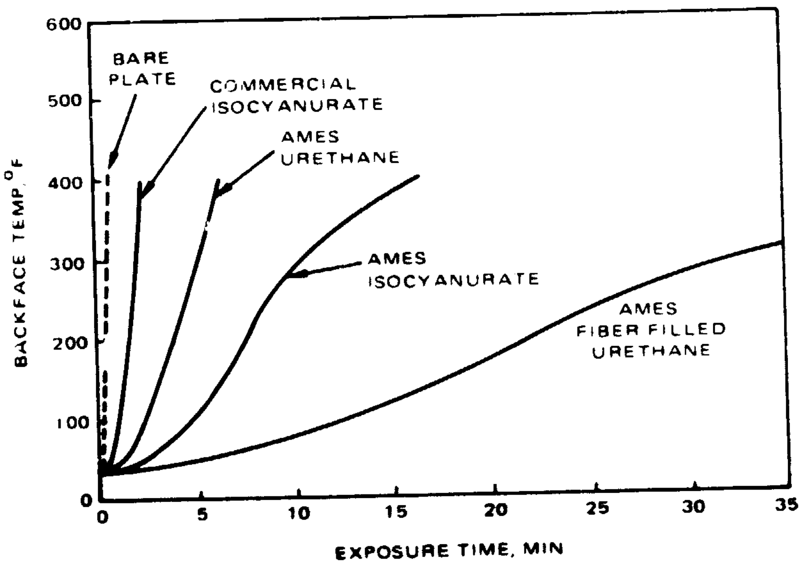


Figure 21.– Performance of various fire-retardant foams in JP-4 fuel fire, heating rate = 10 BTU/ft^2/sec. (from ref. 104)

TABLE XX.– PHYSICAL PROPERTIES OF AMES URETHANE AND ISOCYANURATE FOAMS

Property		ASTM Method	AMES Urethane	AMES ICU
Nominal Density, lb/ft^3		(D 1622)	2.5	2.5-2.7
Thermal Conductivity	BTU in/ft^{3}hr^{o}F W/cm^{o}C	(C 177)	0.175 0.00025	0.150 0.00022
Flame Resistance		(D 1692)	Self Extinguishing	
Compressive Strength	Parallel, psi Perpendicular, psi	(D 1621) (D 1621)	25 15	27 19
Compressive Modulus	Parallel, psi Perpendicular, psi	(D 1621) (D 1621)	600 360	1000 500
Tensile Strength	Parallel, psi	(D 1623)	21	30
Shear Strength	Perpendicular, psi	(C 273)	15	14
Water Absorption, volume, %		(D 2127)	5	3.5
Backface Temperature	Time to 200^{o}F, sec Time to 400^{o}F, sec	AMES T3	210 390	366 786
(Test Conditions; 75±2^{o}F, 50±2% RH)				

Because of the toxicity of the gases generated, adoption of the foam materials for aircraft has not yet taken place These materials can, however, be used for protection of a number of other sensitive, non-personnel items, such as ammunition, outboard wing tanks on aircraft, etc. Figure 22 (ref. 104) shows one such test for protection of ammunition. Figure 23 shows the time-temperature history of protected and unprotected ammunition.

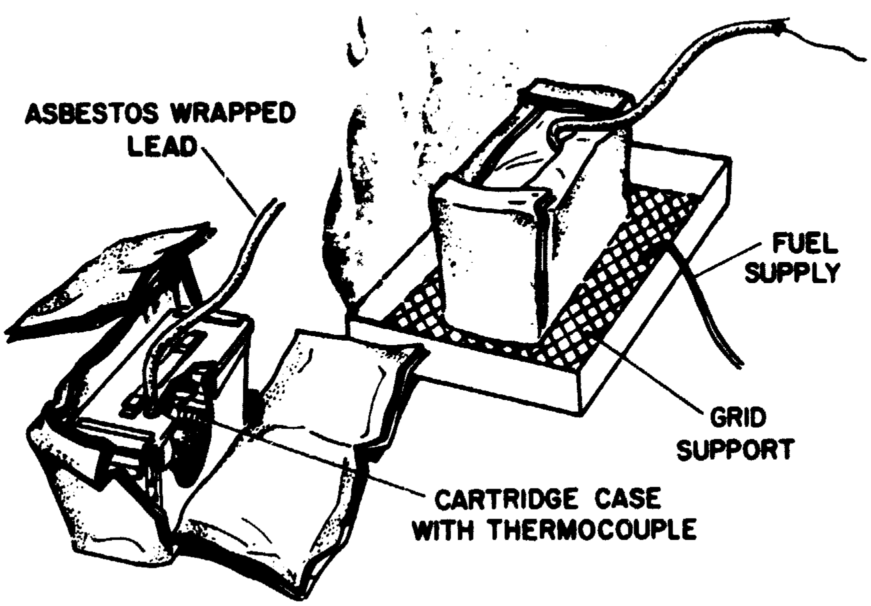


Figure 22.– Test of foam blanket to protect ammunition box. (from ref. 104)

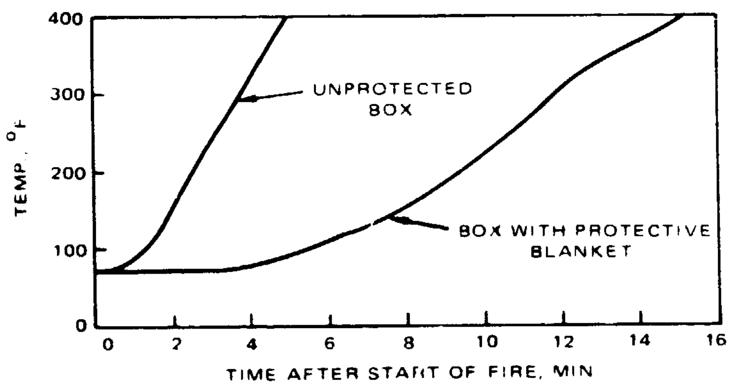


Figure 23.— Time-temperature history of 0.50 cal. cartridge in ammunition box. JP-4 Fuel Fire. (from ref. 104)

Intumescent paints.— The second method of fire protection developed by the Ames Thermal Protection Group consists of the development of intumescent paints. These materials are coatings that are applied in a manner similar to that used with ordinary paints, but when heat is applied, the filler "pigments" (organic salts) swell and form a "fine textured, low density foam, with low thermal conductivity, high emissivity, and good resistance to ignition. The gases evolved during the polymerization reaction and injection into the fire zone further serve as flame quenchers" (ref. 105). Several types of these materials have been developed and are fully detailed in the reference cited and further discussed in ref. 106.

A demonstration of the utility of the isocyanurate foam and the intumescent paint was made in a test conducted on a fuselage section of surplus C-47 airplane (ref. 107). One section of the airplane was unprotected and the other section was fully protected with the foam and the paint. Both sections were immersed in a small puddle of fuel. On ignition the air temperature in the unprotected section rose to 600°F (316°C) in less than 2 minutes and, shortly after, the section was destroyed. In contrast, the temperature in the protected section showed little change for the first 6 minutes and finally reached 300°F (149°C) after 12 minutes when the fire burned itself out. This test is discussed in detail in Chapter 10.

Miscellaneous foam developments.– Other efforts by NASA in the production of heat resistant foams include sponsorship of the development of syntactic and chemically blown pyrrone foams (ref. 108) and polybenzimidizole syntactic foams (ref. 109). Both of these materials could probably be used at considerably higher temperatures than the previously discussed urethane or isocyanurate foams but at a considerable increase in cost and, at present, weight penalties.

An interesting polyurethane formulation with a high-reaction speed is given in a Langley Research Center Brief (ref. 110). This composite formulation was required to produce "instantaneous" foam to provide buoyancy for flotation recovery of instrument packages dropped into the sea from spacecraft. A polyurethane foam composition with opposite properties, i.e., storable after mixing, is described in a patent assigned to NASA (ref. 34). The material is activated and produces foam on exposure to heat at approximately 180°F (82°C).

A somewhat different approach to the problem of foam production for reusable thermal insulation on a shuttle spacecraft was taken by one contractor under the sponsorship of the Manned Spacecraft Center (ref. 111). Instead of using the usual organic matrix foam, the product developed was a syntactic foam based on a ceramic (aluminum phosphate) matrix and silica or carbon microballoons. The material, which is relatively inexpensive, can be produced in a range of densities from 1? to 60 lb/ft^3 and requires relatively low curing temperatures [600°F (316°C)] and pressures from 0 to 500 psi. It is fairly simple to produce in complex shapes and does not show the shrinkage and distortion of some fired ceramics. The final material has heat resistance up to 2200°F (1204°C) with good compressive strength and relatively low thermal conductivity. Areas for further effort include better water resistance, increase in strength, better resistance to rain erosion, and greater impact resistance.

Honeycomb Cores

Techniques for the fabrication of beryllium honeycomb cores are described in ref. 99. These techniques include methods of cutting, corrugating, microresistance tack welding, and brazing of the beryllium foil used to form the core. Modifications of an automatic stainless-steel core-welding machine to form beryllium core are also described. Another technique employed to form the core was diffusion bonding, the results of which are comparable to those obtained with microresistance tack welding. Details of the complete sandwich brazing are described in this chapter under Laminates (page 71).

Particulate Composites

Particulate composites consist of small particles or very short fibers and whiskers uniformly distributed in a matrix. Particles are generally insoluble in the matrix and do not combine chemically with it. Particle sizes range from submicrons to fractions of an inch, as in the case of whiskers. The chemical composition of particles is diversified, consisting partly of metals, oxides, carbides, nitrides, halides, and sulfides. The particle phase of composites usually contributes strongly to the composite properties, sometimes more so than the matrix. Because of the wide range of compositions, particles combined in a matrix can produce composites with many unusual properties.

Particulate composites are made with metal, plastic, and ceramic matrices. Therefore composites fall into classes including metal in metal, metal in plastic, ceramic-metal sulfides, halides, etc., with metal or ceramic. Composites can be formed by blending particles in the liquid matrix such as plastic solutions. Powder metallurgy techniques are used to make cermets and dispersion strengthened alloys. Particles are formed in situ in directionally solidified eutectic alloys.

Metal in Metal Composites

Composites composed of metal particles in a metal matrix occupy an important place as industrial materials. They constitute a means of producing ductile materials by combining an essentially brittle metal with a more ductile one. Free-machining alloys, such as steel and copper base alloys containing lead particles, are included in this group. These materials are made by standard mill practice, e.g., cast into ingots and then worked into final form.

Another type of metal in metal composite is made by the combination of metal fibers, e.g., tungsten fibers and a copper matrix. Such composites result in improvements in strength at high temperatures. These composites are discussed more fully under Metal Fibers.

Metal in Plastic

A number of useful particulate composites consist of metal particles in a plastic matrix. Such filled plastics may contain up to 90 percent by volume of

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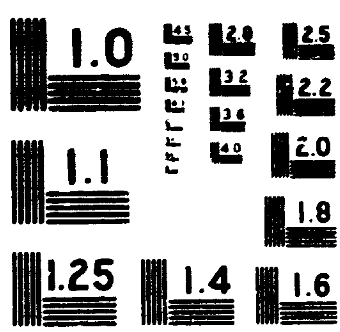


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963

particles. Aluminum as a filler has applications ranging from a decorative finish to the improvement of thermal and electrical conductivity. Steel-particle-filled plastics are used for automotive body solders and hull-smoothing cements for shipbuilding. A significant use for copper in thermoplastic solutions, e.g., cellulose nitrate and vinyl lacquers, is as a coloring material.

Cermets

Cermets are composed of ceramic grains held in a metal matrix or binder. The matrix usually accounts for up to 30 percent of the total volume. Cermet composites are formed by powder metallurgy techniques and can achieve a wide range of properties, depending on the composition and relative volumes of the metal and ceramic constituents. The two most well defined systems are the oxide-base and the carbide-base systems.

The outstanding characteristic of oxide-base cermets is that the metal or ceramic can be either the particle or matrix. A wide range of property values are thus available that make it possible to tailor the composition to service requirements. For example, while the thermal shock resistance of a 28 percent aluminum oxide-72 percent chromium cermet is good, it can be greatly improved by reversing the proportions of the constituents. The same reversal reduces modulus of elasticity at $75^{o}F$ ($23.9^{o}C$) from 5.23×10^{7} psi to 4.7×10^{7} psi. Ref. 112 describes a technique for making a cladding cermet which has the same coefficient of expansion as the matrix material. Such a cladding then is not subject to thermal stresses. Normal powder metallurgy or ceramic techniques can be used to form shapes, but only oxide-base cermets can also be machined or forged. An interesting technique for the

2

production of ceramic fibers consists of extruding oxides of zirconium, hafnium, and thorium. These are fiberized by extrusion in a tungsten matrix. Zirconium oxide produces the best fibers, with an average aspect ratio of 400 (refs. 113, 114). Another technique for the production of oxide fibers is a floating zone fiber drawing method, described in ref. 115.

Tungsten, chromium, and titanium carbide comprise the three major families of carbide-base cermets. Tungsten carbide, widely used as a cutting tool material, has high rigidity, compressive strength, hardness, and abrasion resistance. Chromium carbide, which offers phenomenal resistance to oxidation, excellent corrosion resistance, relatively high thermal expansion, and relatively low density, also has the lowest melting point of the stable carbides. Titanium carbide, principally used for high temperature applications, has good oxidation and thermal shock resistance, retention of strength at elevated temperatures, and a high modulus of elasticity. Ref. 116 describes methods of producing refractory composites from powdered constitutents of tantalum carbide, hafnium carbide, and hafnium boride.

In ref. 117 composites are described that consist of graphite combined with carbides of titanium, zirconium, hafnium, vanadium, columbium, tantalum, molybdenum, and tungsten. The highest strength and resistance to deformation were shown by the tantalum carbide-carbon combination. It was also found that a linear relationship exists between electrical resistivity and flexural strength. This relationship was found accurate enough to be used for predictions.

Solid Lubricants

Another area in which NASA has investigated particulate materials involves the production of improved solid lubricants. Work done at NASA Lewis Research Center on high-temperature-resistant solid lubricants is reported in ref. 118. In this work it was found that sintered nickel-chromium alloys could be infiltrated with molten ceramics. The primary lubricating components are calcium fluoride and barium fluoride. In addition, some formulations used calcium silicates, calcium oxide, and lithium fluoride to form protective coatings and/or to reduce the melting temperatures.

Self-lubricating metal ceramic composites were developed that showed good oxidation resistance during exposure to air at 1500°F (816°C) for long durations. At a sliding velocity of 500 ft/min, the friction coefficients were 0.25 to 0.05 from 80 to 1700°F (26.7 to 927°C).

A summary of information on solid lubricants is also given in NASA Special Publication SP-5059, Solid Lubricants (ref. 119).

Dispersion-Strengthened Alloys

The phenomena of dispersion strengthening permits a metal or alloy to maintain its structural strength at temperatures greater than 200 to 250°F (93 to 121°C) to temperatures that approach 90 percent of the melting point of the metal (figures 24 and 25). In dispersion-strengthened materials, insoluble particulates are uniformly dispersed with controlled spacing throughout the matrix (ref. 48). The function of the particles involves complex theories. A very simple explanation is that the particles retard the

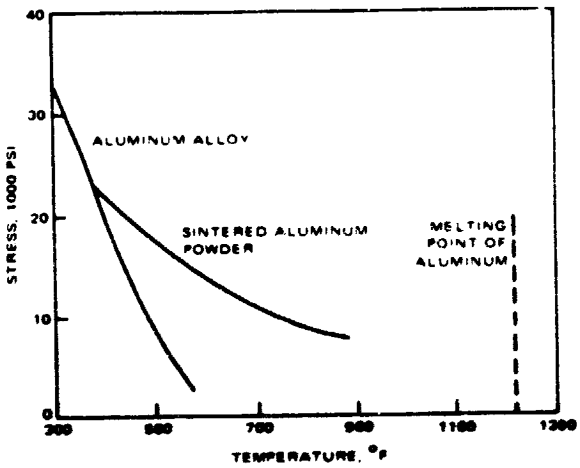


Figure 24.— Stress versus temperature curves for rupture in 1000 hours for sintered aluminum powder and a high strength aluminum alloy. (from ref. 48)

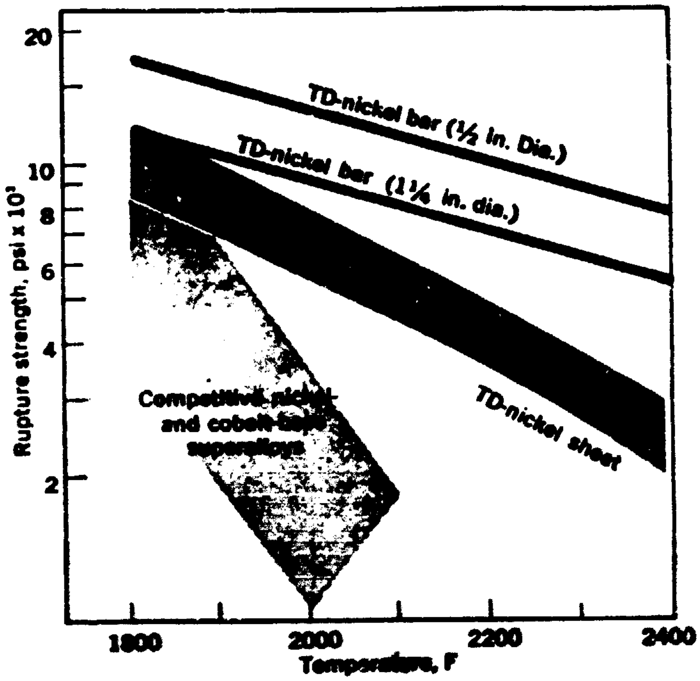


Figure 25.— Stress versus temperature curves for rupture in 1000 hours for TD nickel and nickel and cobalt alloys. (from ref. 122)

propagation of stress-induced dislocations and thus render structural strength to the matrix at higher temperatures.

The dispersed particle constituent is only a small proportion of the composite, seldom exceeding 3 percent by volume. Particles are very small, varying from submicron to 7 microns. Properties of the dispersion-strengthened composite are controlled by the particle characteristics. Critical properties include solubility, refractory characteristics, size, volume fraction, and spacing (ref. 1).

The most commonly used particles are oxides. The method of introducing them into the matrix is governed by the materials and influences the properties. Mechanical mixing of fine metal powders with fine metal oxide particles is most commonly used by NASA (ref. 48). This process is wholly a powder metallurgy operation. Recent NASA developments (ref. 120) have eliminated the excessive agglomeration of the dispersed particles, which had been a major drawback to the method.

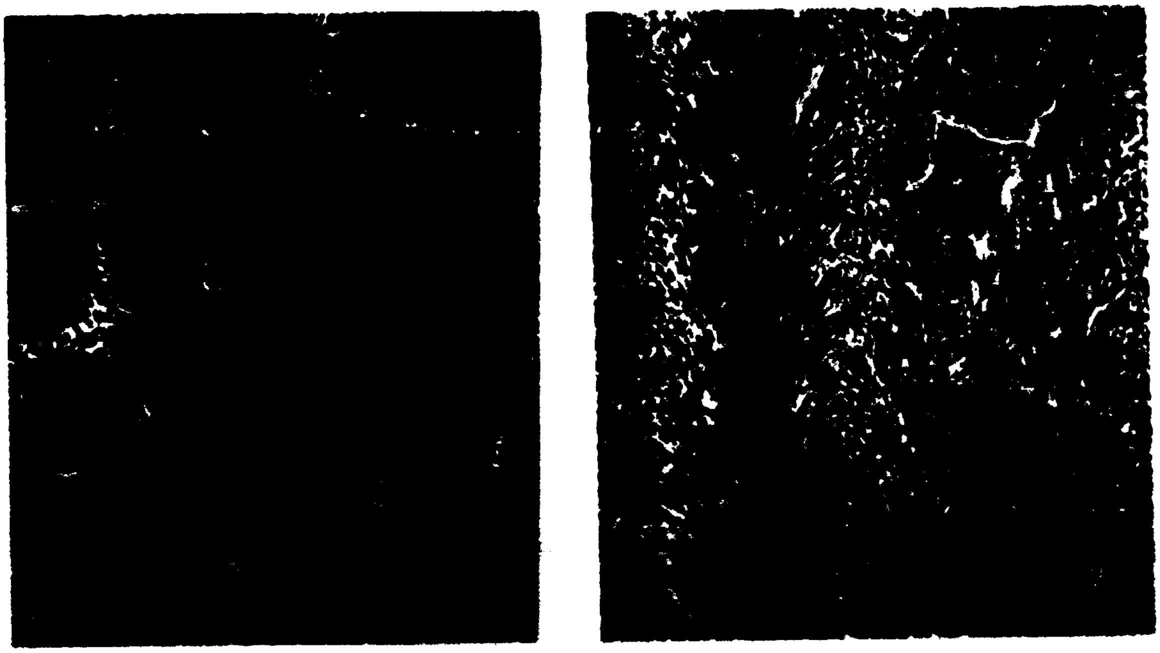
Several dispersion-strengthened alloys have been developed, although very few are commercially available. Of these, sintered aluminum powder (SAP), which is aluminum dispersed with aluminum oxide, is considered the prototype. Development was announced in 1950 (ref. 121). Strength properties com- prepared with those of wrought aluminum alloys for prolonged heating conditions are shown in figure 24. Another commercial product, designated TD nickel (thoria dispersed) is nickel with 2 volume percent thorium dioxide (ThO_2) particles. The strength properties compared with superalloy properties are shown in figure 25. This composite also has better corrosion resistance than nickel at 2000°F (1093°C) (ref. 1). Another commercial product is tungsten with 2 volume percent ThO_2 particles. This composite is usually in wire form and has superior strength compared with tungsten at 3500°F (1926°C). Several other composites have also been developed. These include TD nickel-chromium alloys, beryllium oxide-copper, lead oxide-lead alloys, and lead oxide and copper dispersed in lead alloys (ref. 48).

The primary advantage of dispersion-strengthened metals is the strength retention at temperatures approaching the melting point of the base metal. TD nickel has superior strength compared with superalloys above 1800°F (982°C). SAP has strength superior to wrought aluminum at temperatures above 500°F (260°C). However, both of these composites have lower strengths than their competitors below these respective critical temperatures (ref. 121). Hence, their strength-to-density advantage, and probably their cost effectiveness, may be unacceptable at lower operating temperatures. Additional problem areas not resolved are joining methods, fabrication methods and techniques, and knowledge of long-term, high-temperature creep properties, to name a few (ref. 121).

Directional Solidified Eutectic Alloys

A new approach to particulate composites involves producing the composite by casting with the fibers formed within the part. Through the use of controlled casting practice and selected alloy compositions, called eutectics, particles of high strength and/or special physical properties are produced, aligned, and bound to the matrix in one process. The process requires the use of high purity materials, controlled temperature gradients, and controlled solidification. For example, if a eutectic alloy is cooled conventionally, the solidified alloy will have a conventional microstructure, as shown in figure 26.

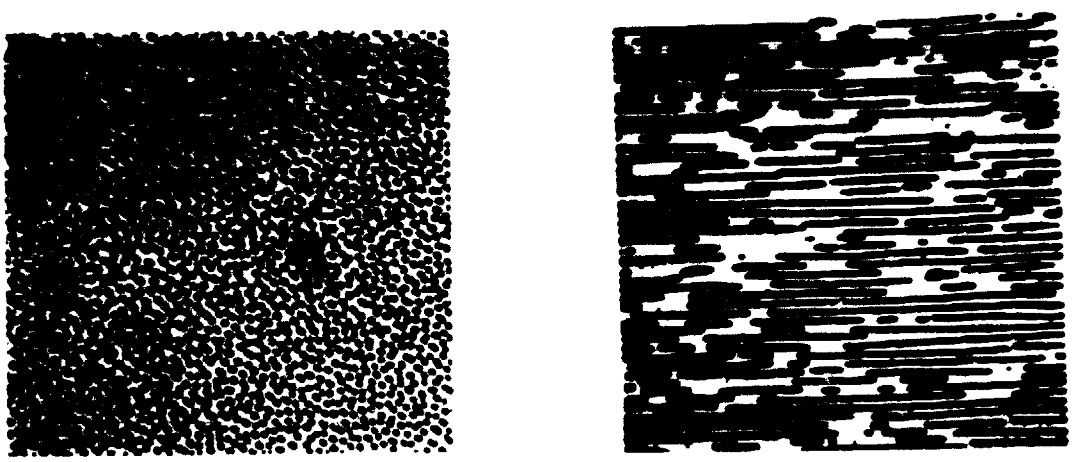
Directional solidification of the eutectic alloy is achieved by slowly withdrawing the mold from the furnace. A directional heat flow pattern is developed, and the controlled cooling renders directionality to the two phases comparable to the microstructure of figure 27. Excellent bonding of particulates to the matrix is achieved through directional solidification. Intermetallic compounds and refractory compounds produce higher strength particulates than those formed from a single element or a solid solution.



a) transverse section

b) longitudinal section

Figure 26.– A representative eutectic microstructure Magnification: 200X. (ref. 123)



a) transverse section
magnification: 400X

b) longitudinal section
magnification: 160X

Figure 27.– Microstructure of directionally solidified Al-Al_3Ni; eutectic dark phase is the Al_2 Ni particulate. (ref. 124)

(Reprinted by permission from Broutman-Krock (Editors), "Modern Composite Materials," 1967, Addison-Wesley, Reading, Mass.)

The aluminum-aluminum nickel ($Al-Al_3Ni$) eutectic was the first alloy system found that could become a composite through directional solidification (ref. 124). The $Al-Al_3Ni$ eutectic consists of 10 volume percent Al_3Ni intermetallic particulates embedded in aluminum matrix. The superior properties of the directionally solidified composite compared with the conventionally processed alloy are shown in figure 28. When stresses were applied at various angles with respect to microstructural directionality, significant decreases in tensile strength were obtained, as is illustrated in figure 29.

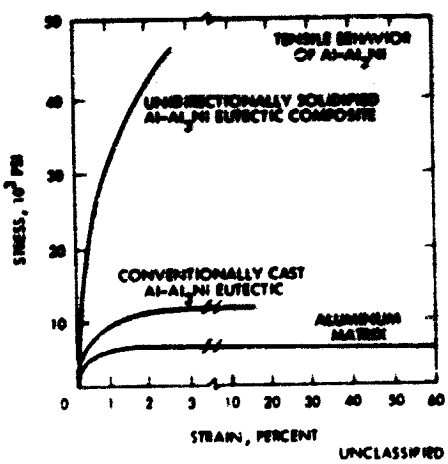


Figure 28.— Tensile behavior of conventionally cast and directionally solidified $Al-Al_3Ni$ eutectic. (from ref. 36)

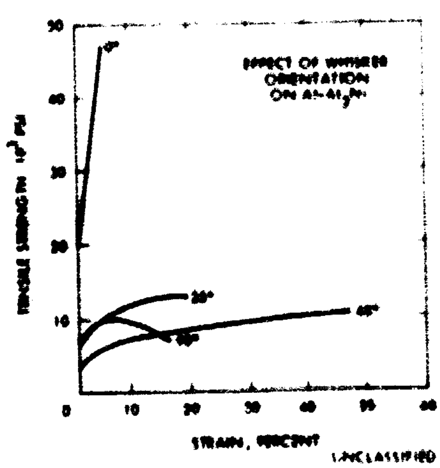


Figure 29.— Effect of stress direction on the mechanical properties of the $Al-Al_3Ni$ directionally solidified material. (from ref. 36)

There are hundreds of eutectic compositions. Many, but not all, eutectic materials form composite type microstructures. Investigation of promising candidates is being conducted by several laboratories. The Siemens Research Laboratories (Germany) have found that the directionally solidified indium antimonide-nickel antimonide eutectic exhibits a large magnetoresistance effect and also polarizes infrared light. Siemens now markets several devices based on these materials (ref. 125). NASA is studying directionally solidified composites having special optical, magnetic, and electronic properties (ref. 125). In addition, NASA is planning to investigate casting of these composites in space in the hope of improving performance characteristics by taking advantage of zero gravity conditions (refs. 125, 126). Additional studies of eutectic alloys have been supported by NASA (refs. 127, 128).

NASA is considering aligned eutectic composites for shuttle external insulation panel fasteners where service temperatures approach 2200°F (1204°C). Several composites are being tested for shear strengths associated with fastener service loads. An interesting part of the investigation is the testing of aligned eutectic alloy threaded screws (ref. 129).

Whisker Composites

Whisker composites are superstrength, rigid, lightweight materials for the future. They are, essentially, elongated crystals. They have been produced in a range of fine sizes from submicron (0.0004 inch) to greater than 0.001 inch in diameter (see figure 30). The length-to-diameter ratios have been 50 to 10,000; most whisker lengths are a fraction of an inch, although they at times have been grown to lengths from 1 to 2 inches. The smaller diameter

Figure 30.– Photomicrographs showing aluminum whiskers. The whiskers have high length-to-diameter ratios and are virtually free from defects. No attempt had yet been made to separate and strengthen these whiskers after their formation. (from ref. 134)

"(By permission of John Wiley & Sons, Inc.)"

crystals have higher strength, but longer crystals are easier to align in the matrix (ref. 130). Whiskers with tensile strengths greater than 2,000,000 p and elastic modulii greater than 100,000 psi have been produced in the labor (ref. 50).

Government agencies (the Air Force, the Navy, NASA) have supported private industries and their efforts to develop whisker composites. NASA h encouraged the development of whisker composites and supported whisker production development and fiber alignment techniques (refs. 131, 132).

Today's structural steels generally have strengths less than 125,000 psi the highest strength steels in use have tensile properties of 280,000 psi and are being used for specialty aircraft applications, primarily in landing gear. Yet, iron has a theoretical strength of 2,900,000 psi and iron whiskers with 1,900,000 psi tensile strength have been produced in the laboratory (ref. 13 Similarly, fibers usually have from 1/5th to 1/15th of the strength of whiske from the same material. The great differences in strength are attributed to minute internal defects (called dislocations) common to most materials. In quality whiskers, defects are absent or are insignificantly small and the su are extremely smooth. Some attained nominal properties of whiskers are presented in the table XXI.

Whiskers have high elastic qualities; they can exhibit greater than 1 percent elastic deformation before plastic deformation or failure. Elastic strain values of 3 percent have been obtained with alumina whiskers and 4.9 percent with iron whiskers (ref. 134). Some whiskers fracture immediately after experiencing elastic deformation. Others have distinct yield points and experience lengthy plastic extensions after the yield point has been reached.

In addition to super strength and rigidity, some silicon carbide or aluminum oxide whiskers possess special physical characteristics that have potential for specialized optical, magnetic, or electronic needs.

The whiskers, of course, serve to support the applied loads and impart stiffness (high moduli) to the composite. They may require a coating such as nickel or other metals to permit wetting and bonding to the matrix. The coating may also function to prevent the whisker from reacting with the matrix, while the matrix serves to space and to bind the whiskers. The matrix also transmits applied loads to the whiskers and affords protection against the environment.

Two recent techniques for producing whiskers on a pilot line basis are a) vapor phase reaction and b) a vapor-liquid-solution (VLS) technique. Quality whiskers have been produced in the laboratory using other techniques which are not conducive to pilot line or production quantities. Currently, whisker growth is accomplished by a batch process in which capsules containing crystals are moved through a furnace with a continuously controlled atmosphere (or vacuum) (see figure 31). Processes to produce whisker composites include at least (a) whisker alignment, (b) addition of the matrix, and (c) consolidation of the

TABLE XXI. – ATTAINED PROPERTIES OF VARIOUS TYPES OF WHISKERS

Material	Density (lbs/cu. ft)	Melting Point (°F)	Experimental Tensile Strength (10^6 psi)	Elastic Modulus (10^6 psi)	Strength / Density (10^6)	Modulus / Density (10^6)
CERAMICS*						
Alumina	0.143	3780	2-4	100-350	14-28	700-2,450
Beryllia	0.10	4620	2-2.8	100	20-28	1,000
Boron carbide	0.091	4440	1	65	11	714
Graphite	0.06	6500	3	142	50	2,370
Silicon carbide	0.115	4200	1-5	100-150	8.7-43	470-1,304
Silicon nitride	0.12	4200	0.5-2	55	4.2-17	458
METALS**						
Chromium	0.260	3436	1.29	35	5.0	[illegible]
Iron	0.283	2800	1.9	29	6.7	102
Nickel	0.324	2647	0.56	31	1.7	[illegible]
Copper	0.322	1980	0.43	18	1.3	[illegible]

Notes: *Adapted from ref. 130.
**Adapted from ref. 134.

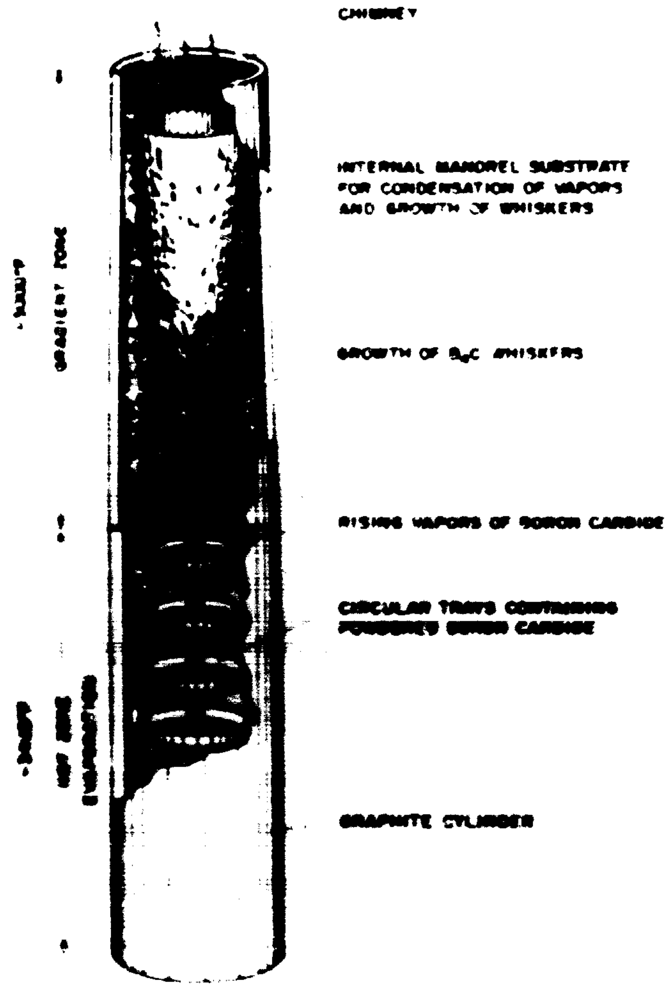


Figure 31.– A sketch of a capsule used for growing boron carbide whiskers. (from ref. 50)

combined constituents into a firm, dense body. Details on processes to achieve whisker growth and install whiskers in composites are described in refs. 50, 131, 133, 134, and 135.

Alumina (sapphire), silicon carbide, silicon nitride, and aluminum whiskers are commercially available in pilot line quantities. Costs are high compared with those of other composite filaments. Whisker composites, however, are not commercially available today. Before they do become commercially available, further development efforts are required. They include:

- Development of processes that will grow larger quantities of whiskers (free from gross defects and branching) at reasonable costs.
- Development of automated processes that will clean and grade the whiskers to specific sizes (according to length and diameter).
- Development of automated processes for continuously aligning the whiskers and for incorporating them into the matrix.
- Development of consolidating processes that will not fracture or chemically degrade the whiskers (ref. 134).

The superstrength of whisker composites at elevated temperatures offers such a potential that continued development is warranted.

Flake Composites

Flake composites consist of thin, two-dimensional particles oriented in a planar relationship and dispersed in a matrix or held together by an interface binder. Flakes can be densely packed in a matrix because of their flat shape; thus high in-plane strengths are produced as well as rigidity equal in all directions, as distinguished from the unidirectional strength of fibers. The overlap of flakes provides a barrier to fluids and vapors. Where overlapping flakes touch, it is possible with metal flakes to provide electrical or thermal conductivity. With nonconductive glass or mica flakes, the composite has good dielectric and thermal insulation properties (ref. 1).

The number of flake materials is limited to aluminum, silver, mica, and glass. Binders and matrices may be compatible organic or inorganic materials. Aluminum is often combined with cellulose, vinyl, or acrylic resins to make decorative and metal corrosion impermeable barriers (coatings). Silver flakes are combined with epoxy resins to make electrically conductive coatings.

Glass flakes are generally used in an epoxy resin matrix because of its superior wetting ability. This excellent combination of strength and electrical properties has resulted in the production of battery and instrument cases, printed circuit boards, and molded insulators.

Mica flakes are generally bound into a composite with glass. This material can be compression-molded and is used to make high-strength electrical insulators for use at temperatures near 600°F (316°C).

The Application of Composites to Agriculture

INTRODUCTION

The agricultural industry is in reality a number of industries, each differing significantly from the others but all tied to the land. The various divisions in agriculture are shown in table XXII, which also shows the differences in land usage and equipment.

TABLE XXII. – AGRICULTURAL DIVISIONS

Division	Land Use and Equipment
Wheat, grain, corn, etc.	Large land masses; heavy equipment
Truck farming	Small and large plots; hand implements and large equipment
Orchards	Medium plots; some large equipment
Livestock (cattle, poultry, dairy, sheep, etc.)	Large land mass; little equipment
Lumbering	Large land mass; some heavy equipment

In addition to the dependency on land, another element common to all agricultural divisions is the relatively low cost per pound, compared with most manufactured products, of the products sold (as listed in table XXII). Furthermore, the work is usually performed by relatively unskilled labor. Thus, because of the low-cost nature of the product and the type of labor, there is very little incentive to use the lightweight, high-strength, high-cost composite materials. In addition, weight is usually not a serious problem; corrosion is only moderate, and high temperatures are nonexistent so that there is no incentive for applying some of the exotic corrosion and heat resistant alloys. In general, any composite materials used in agriculture should be modest in cost, have good outdoor weathering resistance, and have the moderate strengths and weights associated with currently used materials. The use of composites in agriculture is thus necessarily low. There are, of course, some exceptions, detailed later. However, since mechanization is increasing rapidly in all segments of agriculture, it is to be expected that composite utilization will also increase, particularly with the probable price reductions.

APPLICATIONS BY AGRICULTURAL DIVISION

Suggested applications of the various types of composite materials are discussed for each agricultural division listed in table XXII.

Possible Applications for Grain Production

In the various grain-farming industries, fiber-reinforced composites can be useful in the construction of portable silos, water tanks, etc., using filament-winding techniques (see Chapter 2) developed by NASA or NASA-sponsored contractors (refs. 35, 136). In general, the fibers used would be the lower cost ones, i.e., glass and possibly PRD 49, graphite, or combinations of glass fibers and graphite.

Air-supported barns (figure 32) and other inflatable structures for permanent or temporary use can be made of Beta fiberglass, fiber-reinforced Mylar, or polyethylene films (refs. 78, 92, 137). Beta fiberglass buildings are said to have a life expectancy of at least 20 years, at a cost substantially below that of

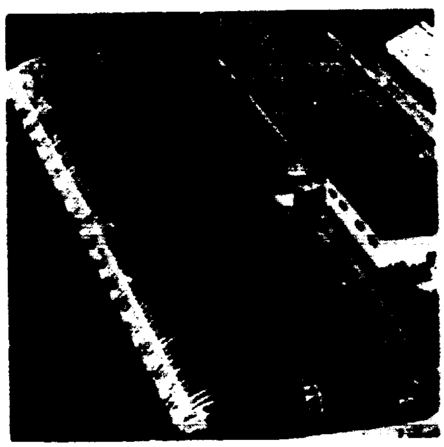


Figure 32.— Air-supported barns,
(from ref. 137)

conventional barns. The material also has the advantage of translucency, which results in barns with better illumination during daylight hours than conventional structures. Structures using the very light films, while not too permanent, have the very obvious advantage of low cost, light weight, and ease and speed of construction. They would thus be ideally suited where fast, temporary shelter is required. Films could also be used for field coverage of harvested crops.

Lubrication of farm equipment is an ever-present problem, since such equipment is used under continuous exposure to dust, wind, weather, etc. One NASA development that may, to some extent, help alleviate the problem is a permanently lubricated gear made from a laminate of TFE Teflon-bronze and steel (or other metal). The Teflon-impregnated bronze is brazed to a steel backing to result in a gear specially suitable for high-pressure applications (ref. 82).

Possible Applications for Truck Farming

As in the grain production activities, laminates could also be of use in truck farming for the construction of air-supported barns. Beta fiberglass or films are also of potential use here (refs. 78, 92). Information on plastic film greenhouses (figure 32) of polethylene, made both in the conventional framework support manner and also air-supported, has been published (ref. 138). Air-inflatable polyvinyl film greenhouses have been reported to be in use for the production of lettuce and tomatoes (ref. 137).

Possible Applications for Orchards

Several different types of composites have potential usefulness in orchard farming. Fiber-reinforced metal components can be utilized in the construction of lightweight ladders, cherry picker booms, harvesting frames, and similar structures. These would be made by the infiltration of boron-epoxy or graphite-epoxy into metal shapes, a technique described in Chapter 2. Various concepts for this type of hybrid composite are illustrated in figure 33 (ref. 21). As shown, the fiber is encased in either a metal extrusion or a similar shape made of sheet metal. Epoxy resin is infiltrated into the fibers and cured; the result is a bonded, hybrid composite structure.

Laminates are also useful for orchard application in air-supported barns or other inflatable structures. Fiber-reinforced films, such as described previously and in Chapter 2, could also be utilized in the construction of barns and other structures. Fabric-reinforced films can be used for portions of harvesting frames for mass removal techniques of fruit and nut harvesting.

A skeletal composite recently developed by NASA is of interest for orchard application. The composite is a lightweight, nylon, monofilament-metallized Mylar mesh (refs. 139, 140). This material could beutilized as tree netting. Draped over fruit bearing trees, such netting would prevent birds from eating the fruit and yet be light enough not to damage the smaller branches of the tree or the fruit. The nylon is birdproof, and the shimmering effect produced by the aluminum metallized Mylar is said to repel the birds. This type of netting is shown in figure 34. The netting itself is knitted on conventional knitting machines using commercially available yarns. It is highly reflective and extremely lightweight, nominally 5 gm/m^2. The availability of suitable fine

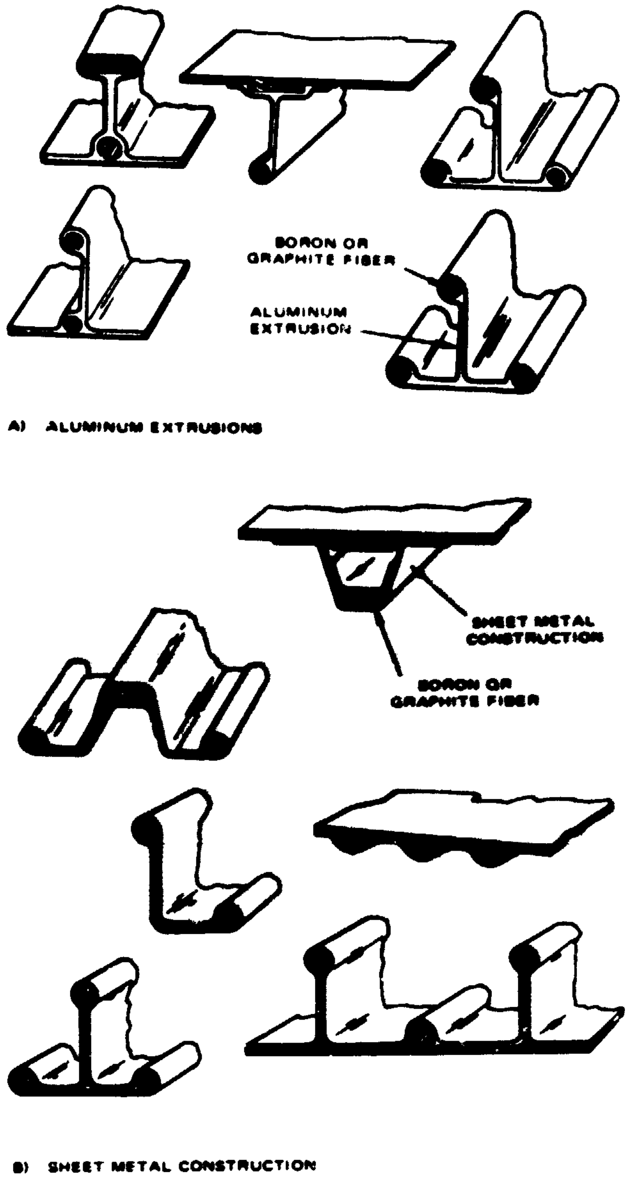


Figure 33.– Hybrid composite concepts. (from ref. 21)
(Reprinted by permission of the Society of Aerospace Material and Process Engineers.)

meshes has been severely limited in the past by fabrication problems. The new fabric, however, can be produced in large quantity at relatively low cost. The two yarn components used are a 15-denier nylon monofilament, 1.5 mils in diameter, and aluminized Mylar tape, 0.5 mil thick and 10 mils wide. The Mylar is coated on both sides with aluminum which, in turn, is covered with a chemically resistant coating. The fabric is a circular knit mesh, fabricated

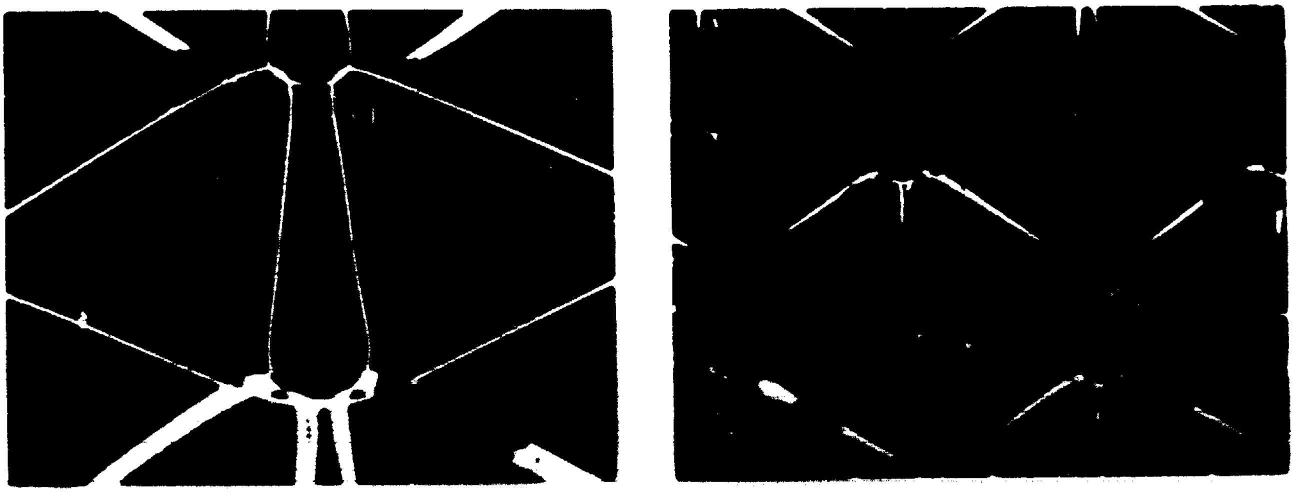


Figure 34.– NASA lightweight, reflective mesh fabric. (from ref. 139)

as a continuous, seamless cylinder that may be split to form a continuous sheet. The basic shape of the elements making up the mesh fabric is triangular, as can be seen in figure 34, with side lengths of approximately 3 mm.

Possible Applications for Livestock Farming

Air-supported barns and other inflatable structures, made of laminates as discussed previously, can also be used by the livestock industry. Again, the laminates of interest would include Beta fiberglass, fiber-reinforced Mylar and polyethylene, and cable-supported vinyl film.

Low-cost cryostats made from readily available materials, as described in Chapter 2, have a potential use. Such a cryostat could be utilized in the storage of seminal fluid for artificial insemination of cattle. Figure 35 shows the construction of such a cryostat, which is said to cost approximately $10. A 50-liter Dewar flask, costing approximately $150, will store liquid nitrogen for three weeks, whereas a low-cost cryostat of equal capacity will store liquid nitrogen for approximately one week (ref. 74).

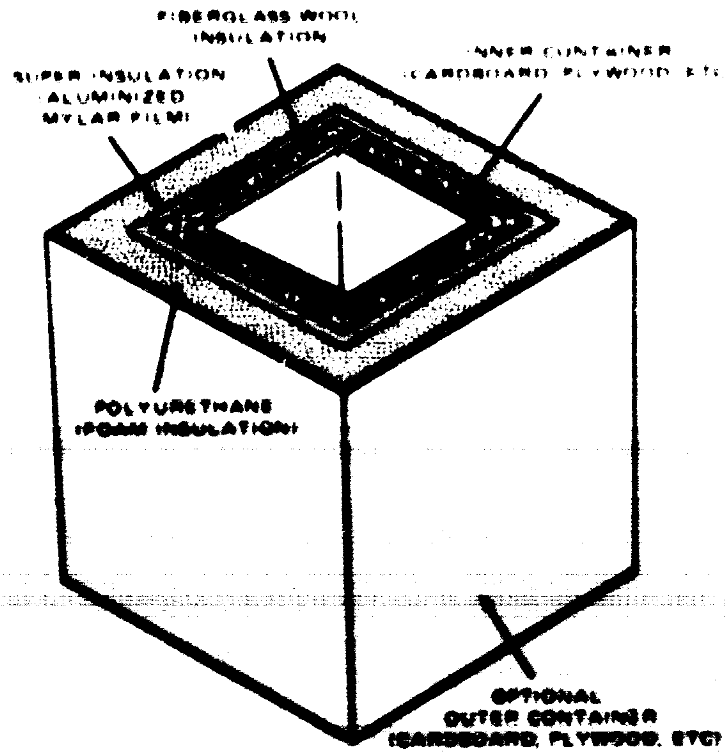


Figure 35.– Low-cost cryostat.
(from ref. 74)

Possible Applications for Lumbering

In the lumbering industry, fiber-reinforced composites have several possible applications. Fiberglass-epoxy or graphite-epoxy laminates can be used in the construction of lightweight tripods, A frames, etc. (ref. 141). Low-cost balloon structures can be made of fiber-reinforced films such as Mylar and/or polyethylene. These balloons, made relatively cheaply, can have lifting capacities of thousands of pounds. Such balloons have been used for lumber removal from inaccessible areas in Washington, Oregon, and Australia (refs. 142, 143, 144, 145).

Applications of Composites in Chemical and Petrochemical Industries

The chemical and petrochemical industries are usually considered to be those industries dealing with chemicals obtained from minerals, the air, the sea, agricultural products, and from petroleum. These industries refine, modify, or combine these basic materials into the myriads of raw stock chemicals or possibly finished products that are used in all phases of life. For the purposes of this chapter, the chemical and petrochemical industries are considered synonymous and are jointly classified as the chemical industry. This latter term is considered here to comprise two distinctly separate branches. One branch has already been defined; i.e., the use of chemicals to produce other chemicals, raw stocks, or finished products. This branch could also be employed in the preparation of the individual components used in making various types of composites. Thus, manufacturers currently engaged in making phenolic or epoxy resins might also manufacture high-temperature resistance pyrrone or polybenzimidole resins. Glass fiber manufacturers might investigate the many new glass formulas developed under NASA sponsorship (ref. 43). The other branch might be called the chemical plant construction and equipment industry, that is, the segment of the chemical industry which builds the specialized chemical plants and/or the machinery and equipment that are unique to the chemical industry.

The applications of composites in plant construction and equipment are discussed first.

CHEMICAL PLANT STRUCTURES

Chemical plants are unique in that, in many cases, the plants are simply open frameworks, erected mainly to support adjoining equipment, e.g., an oil refinery. In other cases the entire operation is completed indoors, just as in other manufacturing units.

The chemical plants, regardless of their type, do have special equipment requirements. These include conveyors to handle the raw materials. Such conveyors might be open belt conveyors carrying crushed ore, coal, coke, etc. Another conveyor might be an enclosed screw used to move dusty materials from one floor to another. Possibly the most widely used conveyor is a pump and piping system, used for transport of liquids, slurries, or gases. Associated with the pump and piping system are valves, pressure regulators, motors, etc. Usually in close proximity to the conveyor system is a storage area of some kind. This could be as simple as a bin for storage of bulk solids or as complex as a specially insulated tank for storage of cryogenic fluids.

Fundamental to most chemical processes is some type of chemical reaction, taking place in a reactor vessel. Such a reactor might be merely a large kettle, as is used for varnish cooking, or it might be an enclosed, glass lined, internal mixer reactor vessel with heating and cooling coils capable of controlling a reaction of several tons of material within $\pm 1^{\circ}F$ ($\pm 0.56^{\circ}C$). Conversely, the reactor might be the large catalytic cracking tower used to obtain gasoline from crude oil. To carry out the reaction completely or efficiently, usually a great deal of supplementary equipment is required. Such equipment may be special high-temperature heaters or furnaces; or possibly a heat exchanger system, filters, dryers, ovens, etc. These reactions could involve very corrosive materials, or be carried out at extremely high or low temperatures, or all three conditions could exist. Thus it may readily be seen that this large diversity of plants, equipment, and processes could well use many types of composite materials, i.e., fiber-reinforced composites for high strengths with lighter weight, bimetallic laminates for exceptional corrosion resistance, foam or foil as insulation systems for high or low temperature reactions, etc.

TYPES OF POTENTIAL APPLICATIONS

The specific contributions which the NASA work on composites can offer to the two branches of the chemical industry are divided into three sections:

1. Analytical and design investigations in which the mathematical and/or theoretical basis for particular composites or structures are established.
2. Materials and processes evaluations; here composite materials which are in the form of rods, tubes, sheets, etc., are tested to determine properties or to develop new processes for the composite material production.
3. Specific hardware or product developments from which details are derived of types of materials used and/or processes employed to produce a particular structure or product. While most of these investigations directly apply to an aerospace usage, there are a number which might be useful for application to a chemical plant. Examples of such a product might be metalized Mylar-aluminum

foil insulation for cryogenic storage tanks or a silicide ceramic coating used on a metal substrate for high temperature oxidation resistance. The major portion of these hardware developments may at present be too expensive for utilization because of the incorporation of exotic components, such as columbium coatings, silicon carbide whiskers, boron fibers, etc. However, the initiation of the use of these materials could lead to volume exploitation which would, in turn, lead to lower prices and consequent higher production, etc.

Analytical and Design Investigations

The design of a chemical plant or specific types of chemical equipment presents certain problems not as common in any other industry. An equipment failure in a chemical plant could very easily lead to catastrophic results, e.g., an explosion, very bad corrosion, release of toxic fumes, etc. Thus, analytical data on design usage of these relatively new materials assume major importance.

The majority of the investigations on composite materials (by NASA and others) has been on boron or graphite filamentary-reinforced composites, since these are the materials that give the desired improvements in strength, modulus, and weight reductions. Thus it is not surprising that almost all the analyses and mathematical treatments are concerned with filamentary reinforced composites. Reports on a number of analytical investigations have been issued by NASA on various aspects of filamentary design. One such report is an overall treatment of the problems of testing composites as compared with monolithic structures (ref. 146). A similar report deals with theoretical predictions of stiffness and strength properties in filamentary composites, and with structural aspects of filamentary composites designed for biaxial loads (ref. 147). Somewhat similar treatment is given in refs. 20, 148, 149 and 150. These data could be very useful in the design of pressure vessels, tanks, piping, and similar structures.

Materials and Processes Investigations

A number of studies have been made by NASA facilities and NASA funded contractors in which some type of composite raw stock (as opposed to a specific part) was investigated. The work in many cases considered a new material, such as a new fiber combined with a well known matrix, e.g., PRD-49-1 with epoxy resin (ref. 45) or a new processing technique for previously used materials, e.g., continuous casting of boron fiber-reinforced parts (ref. 151) or a new composite made from previously unused materials, e.g., metal-ceramic composites. In each case results were obtained from tests on specific materials. Included in most of the reports, also, are some analyses of the tests and the test results, so that the reader may know how the tests compare with tests on similar materials, possible variations, significance of the results, etc.

There are a great many projects directly concerned with various filamentary reinforced test samples, investigations of processes for making the test samples, and also development of specific hardware items using filamentary reinforcements. In the main, the filaments consist of either boron or graphite fibers and, to a considerably lesser extent, tungsten fibers and various types of whisker reinforcements such as carbides, oxides, etc. The matrix material for graphite fibers is usually epoxy resin. Boron fibers are embedded in epoxy resin and in aluminum and magnesium by infiltration or diffusion bonding. The tungsten fibers and many of the whisker reinforcements are usually used in high temperature applications infiltrated with molten copper or in conjunction with powder metallurgy techniques with various high temperature alloys. Chapter 2 gives a more detailed description of the various types of the filamentary composites.

Of the many reports available on filamentary reinforced composites, the ones of greatest interest to the chemical industry are those dealing with test specimens representing structures that could be used for tanks, pipes, storage structures, etc. Again it should be emphasized that, in the main, these composites are used for their excellent strength-to-weight ratio. Thus they would be ideal for any portable or airborne requirements.

One project of specific interest to the chemical industry is concerned with the development of continuous forming and curing techniques for production of circular structural composite shapes for space vehicle applications (ref. 35). This investigation, which at the time of writing was not yet completed, should lead to the production of lightweight, corrosion resistant tanks, pipes, etc. When fully developed, the technique can produce long tanks or pipes up to 20 feet in diameter, at nominal cost, from epoxy-fiberglass or from graphite or boron filaments. The process consists of continuous production of epoxy-fiberglass extruded shapes, either as rings or continuous spirals. The shapes are then bonded to form tanks, pipes, etc. The ultimate products are similar to, but can be larger in diameter and made by a different process, than the European "Drostholm" continuous filament winding process (ref. 136).

One of the most significant developments in the use of filamentary composites is the hybrid construction technique referred to in Chapter 2. In connection with the development of this concept, several investigations have been made of the compressive properties of tubes reinforced with boron and S-glass (refs. 18, 152, 153). The hybrid technique has been further developed to encompass the use of selective reinforcement by boron filaments (refs. 20, 21). In this latter technique, boron filaments are placed in voids in metal shapes and infiltrated with epoxy resin. The resulting structures in compression are 25 percent lighter in weight than their all-metal counterparts of equal strength. Such materials would be particularly applicable to portable derricks, equipment support structures, and any other equipment designed for portability. Another use would be for tanks and reactor vessels of aluminum when the metal must be used for its chemical properties but size or weight limitations make an all-metal construction marginal. A somewhat similar technique involves reinforcement of aluminum by boron fibers, except here the materials are combined by diffusion bonding (ref. 26). (See also Chapter 2.)

Techniques for reinforcement of copper by tungsten filaments have been extensively investigated by NASA Lewis Research Center. Composites containing approximately 12 to 75 volume percent of tungsten show strength increases up to almost 500 percent. The possibility thus exists of using copper as part of structural design in those processes in which large copper busses are used, e.g., in aluminum refining. Refs. 51, 52, and 154 give data on preparation of the composites and ref. 155 gives data on the electrical properties. In general, the resistivity of the composites was found to follow a hyperbolic function with fiber content, and conductivity was found to follow a linear relation with fiber content.

Specific Product Developments

The following project descriptions apply mainly to the chemical plant and equipment branch of the chemical industry. There are also, however, a number of projects on new resins, foams, adhesives, etc., that are directly applicable to the manufacture of resins, formulators, and similar compositions.

Filamentary Reinforced Composites.— The fabrication and testing of glass fiber-reinforced metal shell tanks used in high pressure (1000-9000 psi) cryogenic service have been reported (ref. 156). Somewhat similar tanks, using a cryogenic forming technique and a fiberglass overwrap, have also been described (ref. 157). Significant weight savings over all-metal construction were found.

An extensive analysis of hybrid design chiefly using boron filamentary reinforcement of aluminum metal structures is given in ref. 158. While the paper is primarily written for aircraft structural design, the examples shown can well be adapted for the design of high pressure reactors, tanks, and plant structures. A somewhat similar analysis of selective reinforcement of metal structures is given in ref. 41 for a single type of structure, an engine support. It was shown that when boron-aluminum composite tubes are used as a compression strut, they are found superior to other composites or to all-metal tubes, on the basis of the highest strength-to-weight ratio.

An investigation of optimum designs for a spacecraft heat exchanger indicated that boron-reinforced aluminum gave the best results on a strength-to-weight basis. The high thermal conductivity of the composite and its relative stiffness might also be utilized for high pressure heat exchangers in chemical processing (ref. 23).

Bimetallic and Coating Investigations.— Bimetallic laminates and coated metals for corrosive or high temperature environments are discussed in Chapter 2. The use of bimetallic materials such as stainless steel on mild steel for reactor vessels, storage tanks, etc., is well known in the chemical industry. Ref. 80 describes fabrication of bimetallic materials by explosive welding and vapor deposition which result in stainless-steel-clad titanium sheets for LOX (liquid oxygen) applications. Coatings as thin as 0.0001 inch of stainless steel afforded protection against the titanium-LOX reaction. Ref. 81 describes explosively bonded bimetallics of stainless steel and nickel-based alloys coated with several types of refractory metals. Tantalum and 321 stainless steel appeared best for temperatures to 1600°F (871°C) for up to 2700 hours. Ref. 87 lists cobalt chromium aluminum yttrium coatings applied to nickel base alloys by electron beam vapor deposition. These coatings gave adequate oxidation protection for at least 1100 hours at 2000°F (1093°C).

Work done on nonmetallic coatings for high-temperature applications is discussed in ref. 88 which describes an air-sprayed zirconia-based coating suitable for temperatures up to 4000°F (2203°C). Slurry-applied silicide coatings for temperatures up to 2400°F (1316°C) for short time use are described in ref. 90.

Bonding and Joining.— A number of techniques for bonding and joining various materials have been studied (ref. 85). Included are techniques for brazing aluminum to stainless steel, titanium to aluminum, and molybdenum to stainless steel. A number of adhesive bonding techniques for various materials are also included. All these techniques can be utilized in production of special chemical-resistant equipment.

A somewhat similar publication details methods of joining ceramics to metals and graphite to metals by a variety of techniques (ref. 102). The direct fusion joining of ceramic materials to ceramics and to metals by electron-beam welding is most promising. The methods that can be used to join graphite to graphite and to metals are limited to the nonfusion joining techniques, i.e., solid-phase joining and liquid-solid-phase joining.

Thermal Insulation.— Coincident with the development of the aerospace industry, the field of cryogenics in the United States increased manyfold. Economical storage of cryogenic fluids for use in chemical reactions, in metal working, etc., is therefore an important factor affecting its application. Since liquid hydrogen and liquid oxygen are used so extensively in spacecraft, NASA has sponsored a number of projects to develop efficient cryogenic insulation systems. Details on a number of cryogenic insulation systems utilizing multilayer metallized Mylar and similar film systems and urethane foam materials are given in Chapter 2. NASA special publication SP-5027, ref. 73, and ref. 72, are general discussions of thermal insulation systems. Refs. 64, 65, 66, 68, 136, and 159 give details of the various cryogenic insulation systems developed. Ref. 74 gives details of a low-cost cryostat suitable for use by laboratories, small shops, etc. Such a low-cost structure is shown in figure 35 in Chapter 3. Ref. 76 details a low cost system of cryogenic insulation for use on pipes. This insulation system is a composite of aluminized fiberglass tape, cork, Mylar, aluminum foil, and adhesive. Figure 36 illustrates the concept.

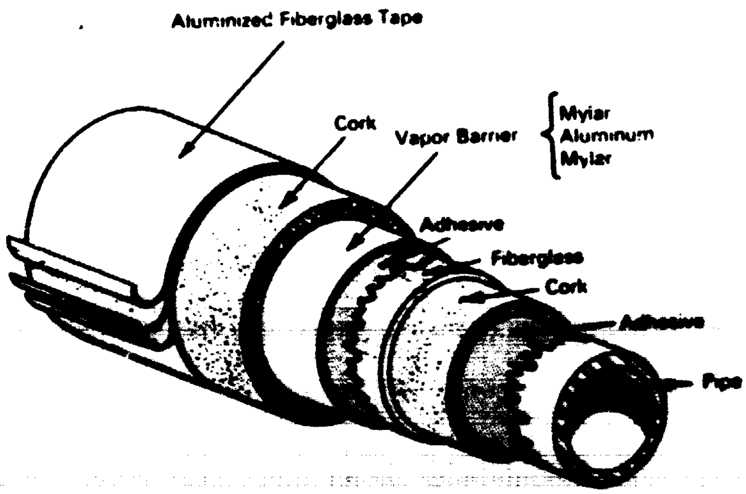


Figure 36.– Low cost cryogenic pipe insulation. (from ref. 76)

In addition to the development of low temperature insulation, a number of insulation systems for very high temperatures have also been developed. These include systems that would have direct application as furnace insulations, reactor linings, etc. One such insulation is a foam based on an aluminum phosphate matrix and either silicon microballoons or carbon microballoons. This low cost material is available in densities ranging from 18 to 60 lb/ft^3 and has a heat resistance of up to 2000°F (1093°C) (ref. 111). Other insulations are based on the bonded silica, zirconia, mullite, etc., fibrous insulation systems proposed for re-entry spacecraft (refs. 160, 161, 162). A system of multilayer insulation using molybdenum foil and silica cloth suitable for temperatures up to 2000°F (1093°C) has been reported (ref. 75). A similar system using tantalum foil and carbon fabric is also reported satisfactory to 4000°F (2203°C). Such insulations should be suitable for use around burners and reactors, particularly those involving nuclear reactions.

Solid Lubricants.— Solid lubricants are of particular interest to the chemical industry since their use permits operation of reactor mixers, stirrers, etc., with minimum danger of contamination. Solid lubricants are also used advantageously for high temperature applications such as conveyor belts, furnace doors, etc. Several types of solid lubricants have been investigated by NASA; a general survey is given in ref. 119.

Solid lubricants based on calcium fluoride-barium fluoride eutectics have been described as suitable for temperatures from 500° to 1700°F (260° to 927°C) (ref. 118). Some of these lubricants can be formulated to impart improved oxidation resistance properties to the substrate material.

A "white graphite" material, prepared by the reaction of graphite and fluorine, has been reported (ref. 163). This lubricant seems particularly attractive for chemical processing, food machinery, textile processing, etc., because of its non-staining characteristics. The "white graphite" is said to have approximately the same characteristics as molybdenum disulfide up to 900°F (482°C), which is approximately 150°F (66°C) above the limit for molybdenum disulfide.

Ref. 164 describes several solid lubricants, one using a glass binder and another bonded with a high temperature resistance pyrrone polymer.

Gaskets and Seals.— Gaskets and seals used in reactors, filter presses, pumps, etc., have been covered in a NASA special publication (ref. 165). Techniques of preparing seals of glass cloth and aromatic polymers such as polyimide or polybenzimidazole for use in liquid hydrogen and nuclear radiation environments have been reported (ref. 166). Somewhat similar bearings and seals used in turbo-pumps for liquid hydrogen, using polytrifluorochloroethylene filled with glass fibers or graphite, are described in ref. 167. Another radiation resistance bearing retainer material, based on polyimide resin and 5-glass fabric, which has good wear resistance, lubricity, and stability, is described in ref. 168.

Filter Materials.— Several new materials have been developed that might serve as filter materials for special applications. One such material is Beta fiberglass (ref. 92). This material is a glass fabric made with extremely fine fibers; it was used by NASA as a flame resistant part of the space suit for the astronauts. As such, it is coated with TFE Teflon for increased abrasion resistance. For use in a filter press, it could probably be used uncoated and should be a very fine filter for non-alkaline, extremely corrosive, or very high temperature filtration, $\approx 1000^\circ F$ ($\approx 538^\circ C$).

Another type of material that should be useful for very high temperature filtrations are graphite or carbon fibers. Conventional carbon fibers are very fine, ≈ 0.0008 cm in diameter. A new technique producing monofilament carbon fibers, 0.008 to 0.016 cm in diameter, has recently been announced (ref. 40). These fibers, or cloths woven from the fibers, should be useful because of their relatively large size for all types of non-oxidizing filtration of liquids or gases at temperatures up to at least $2200^\circ F$ ($1204^\circ C$). Information is also available on woven graphite fabrics that show appreciably high strengths at temperatures up to $2500^\circ F$ ($1371^\circ C$) in non-oxidizing atmospheres (ref. 29). In oxidizing atmospheres the fabrics can be used at temperatures as high as $1400^\circ F$ ($760^\circ C$) for short periods of time. Such materials might be used for stack filtration of hot gases, particularly if the materials are coated with silicone or silica to form silicon carbide on the surface, as preliminary tests indicate.

Pyrrone Resins. – One resin system, developed at NASA Langley Research Center, is known as the polyimidazopyrrolone ("pyrrone") polymers. These polymers, which can be used for adhesives, fiberglass and graphite laminates, and chemically blown and syntactic foams, are thermosetting resins that resist degradation in air and show good strength at temperatures from 400° to 700°F (204° to 371°C) (ref. 169). Several different techniques for preparation of pyrrone resins and foams are given (refs. 31, 108, 170, 171, 172, 173). Included in the references are processing data on compression molding of the pyrrone resins. Data on the physical properties at 600°F (316°C) and radiation stability of the unfilled pyrrone resins are given in ref. 174.

Polyimide Resins. – The polyimide polymers are another class of high-temperature resistant polymers investigated by a number of NASA-funded organizations. A low-void polyimide resin system can be used for making excellent high-temperature resistant glass and graphite laminates (ref. 175). The same type of resins used for the laminates can also be used to make thermally stable adhesives (ref. 84). Polyimide monomers with improved shelf life and higher solubility are reported in ref. 176.

Cryogenic Adhesives. – Two new adhesive systems developed for cryogenic service have been reported (refs. 177 and 178). One is an epoxy formulation (ref. 178) and the other, a urethane-epoxy adduct (ref. 177).

Foams. – As mentioned in Chapters 2, 8, and 10, a good deal of effort has been expended by NASA, particularly the Ames Research Center, on development of foam materials for fire resistance and fire retardance. Two classes of materials have been developed: (1) filled polyurethane and polyisocyanurate foams that are fire resistant and fire suppressant (refs. 103, 104) and (2) intumescent paints which on heat application foam up and also act as flame quenchers by gas liberation (refs. 105, 106). It is considered that these materials could be of use in a chemical plant as protective materials in hazardous areas or for hazardous equipment. The materials might also be considered for their commercial aspects, e.g., to be added to a formulator's product line.

Another type of polyurethane formulation is described in ref. 110. It is a very rapidly reacting polyurethane foam formulation which can be put up in kits for emergency flotation or other uses in which a quick plastic foam is required.

A storage-stable, thermally activated polyurethane composition has been invented (ref. 147). Such a single component compound needs no mixing, only heat to cause foaming; thus, it can also be used as a fire suppressant or for heat activated packaging, etc.

Reinforced Films and Fabrics.— Fabric-reinforced films as covers for open tanks to reduce air pollution have been used by Eastman Kodak and other chemical processors (ref. 138). The Dacron fiber-reinforced Mylar or polyethylene films discussed in Chapter 2 could be used for this application. These same films could be used for temporary weather protection or for semi-permanent air-supported warehouses. Beta fabric, a TFE Teflon-coated fiberglass fabric, is expected to have a life expectancy of 20 years when used as an air-supported warehouse material (ref. 92).

Applications of Composites in Consumer Goods

A listing of potential uses of composites in consumer goods would include all types of household items and a number of recreational items. Table XXIII lists the types of products that fall into the consumer goods category.

TABLE XXIII. - CONSUMER GOODS

1. **Household Items**

   Furniture
   Home Appliances
   - **Stoves, refrigerators, washing machines, miscellaneous (can openers, mixers, fans, etc.)**

   Soft Goods
   - **Drapery, rugs, carpets, etc.**

   Bedding
   Clothing, shoes, rainwear
   Food and food packaging

2. **Recreational Items**

   Indoor
   - Radio, television, hi-fi equipment, etc.
   - Photographic equipment
   - Models (aircraft, trains, ship, etc.)
   - Miscellaneous (aquaria, games, etc.)

   Outdoor
   - Sporting goods (small)
   - Tennis racquets, pole vaulting poles, skis, ski boots, ski poles
   - C nping equipment
   - Gardening equipment
   - Sporting goods (large items)
   - Boats
   - Skimobiles
   - Gliders (as distinuished from light aircraft)
   - Hot-air and gas-filled balloons

In general, cost will be the limiting factor in the application of composites to household items. The high strength-to-weight ratio exhibited by most of the fibrous composites will be overshadowed by the element of cost for those items containing boron or graphite fibers. It is conceivable, however, that hybrid composites (metal reinforced with high modulus fibers) will be used to some extent for household goods applications. On the other hand, recreational items in many cases are insensitive to price; e.g., the yacht Intrepid, selected to defend the America's Cup in 1970, utilized a boron epoxy spinnaker pole. This pole weighed 32 pounds compared with 85 pounds for an aluminum pole (ref. [illegible]). A weight saving of 63 percent over the aluminum pole resulted, but the cost was extremely high. Other recreational items are also currently being made to utilize other properties of the composites.

HOUSEHOLD APPLICATIONS

Furniture Applications of Composites

In the last few years, a virtual revolution has taken place in the furniture industry as many types of plastic materials are supplanting wood. Among the plastics used are hard foam materials, which are cast or molded into replicas of carved wooden forms. Soft foams are also used as constituents of the upholstery. In most cases, the wooden replica foam material is a polyurethane, a vinyl, or polystyrene. One of the problems in the use of the plastics materials is fire susceptibility. To obtain fire suppressant properties as well as self-extinguishing properties in the foam materials, thermally activated components can be added to the foams. Such materials, which act to help extinguish flames, have been developed to be added to the foamant, before the foaming reaction (ref. 103). These materials, used by NASA Ames Research Center in development of spacecraft and aircraft fire-suppressant foams, are more fully discussed in Chapters 2, 8, and 10.

A possible use of a fiber-reinforced composite in furniture would be a graphite-epoxy composite molded in the form of a leaf spring or a similar spring. This spring could be used as a component of a rocking chair in place of the springs currently used. NASA Langley Research Center has investigated the use of bearingless helicopter rotor blades made of a unidirectional graphite-epoxy composite with a relatively low torsional stiffness. Twisting deformation of spar segments of these blades eliminates the need for mechanical pitch bearings (ref. 181). This same type of application could be used for elimination of metal springs, with a consequent weight and noise reduction.

One application that would exploit the favorable strength-weight ratio of a hybrid fiber-reinforced metal would be the construction of household extension step stools. Since such stools are frequently carried around the house by the housewife, any weight reduction would be well received. The hybrid concept, combining metal and high modulus fibers, could offer such weight savings and, at the same time, be considerably cheaper in price compared with an all-composite construction. Figure 33 in Chapter 3 shows a number of representative shapes that can be made using this concept (ref. 21). The application of this concept to full-size step ladders and extension ladders would allow even greater utilization of the hybrid concept.

Home Appliances

In view of the very cost conscious nature of the home appliance industry, it appears that, at the time of writing, very few of the composite materials would be applicable. The possibility does exist that, given price decreases, washing machine agitators and wringer tubs could be made of fiber-reinforced composite materials. The advantages would, of course, be weight savings and the use of noncorrosive materials, so that enameled iron and the more expensive porcelain tubs might be eliminated. Molded gear housings can also be made of short fiber composites, with consequent weight savings. Such molded gear cases have been reported (ref. 182). Permanently lubricated steel-bronze-TFE Teflon gears might be fabricated using techniques that have been developed by NASA (ref. 183). These gears could, of course, be used in the composite housings, with the elimination of the need for lubrication.

Insulation systems developed by NASA for use on spacecraft would be applicable to stoves and refrigerators and wall insulation systems in homes, particularly for mobile homes. Some of these systems, originally developed for insulation on cryogenic tanks, could well be utilized for refrigerators or for portable cold "picnic" baskets. Ref. 64 gives details on several types of insulation systems utilizing metalized Mylar films and fabric spacers. A simple, efficient insulation system for walls and portable cold boxes is given in ref. 74. Refs. 72 and 73 summarize a number of developments in the fields of cryogenic insulation, but which possibly could also be used for home refrigerators.

The high heat-resistant resins such as the pyrrones and polyimides could be used as molding resins for the production of pot and pan handles. Currently, such handles are usually made of phenolic resins combined with a wood-flour filler. Temperatures much above 300°F (149°C) quickly cause destruction of the handle. The pyrrone resins (refs. 31, 169, 172) and polyimide resins (refs. 175, 184, 185) can both be used for temperatures of 450 to 500°F (232 to 260°C) for long periods of time. Both materials can be filled with the same type of fillers now used for the phenolics to give the same strengths but with better heat resistance. Pyrrone foams have also been formulated that, since they are heat insulators, might be even better protection for handles than the filled pyrrone moldings (ref. 108). These should be more comfortable and safer to use than the current handles.

Soft Goods Applications of Composites

Soft goods, such as drapes, carpets, bedding, upholstery, etc., can all benefit from the fire prevention work done at NASA Houston Manned Spacecraft Center. A number of fibrous materials were investigated to determine their fire susceptibilities, either when used alone or in combination with other materials. These fibrous materials were to be used as components of space suits, support straps, various types of flexible containers, papers, seat upholstery, etc. (refs. 91, 94, 96). Many of the developments cited in the references can be directly applied to household usage.

One such development is a proprietary European process, called Proban (ref. 96) which has been used to make fire retardant woolen upholstery in European aircraft. This process can be applied to drapes, upholstery, and some typ. of wool carpeting. Polyamide (nylon) fibers that are nonflammable in air have also been developed. These nylon materials woven into fabrics and coated with nonflammable fluoroelastomers have been made into artificial leather-like, nonflammable products that can be used for all types of upholstery applications. A number of other, somewhat more expensive, fibers are also described in the references. These include Beta glass fabric, which consists of extremely fine glass fibers, woven into fabric and coated with TFE Teflon for improved abrasion resistance; Kynol, a phenolic type of fiber with very high temperature resistance; and polybenzimidazol fibers, also for high temperature use.

Nonflammable blankets, pillows, and mattresses can be made using the fibers mentioned above and coating materials. Special fire-resistant clothing for industrial or fire-fighting use is discussed in Chapter 8.

RECREATIONAL ITEMS

There appear to be no specific advantages to the use of composite materials for indoor recreational items. For outdoor applications, however, there are a number of applications in which the factors of high strength and/or lightweight can be used to definite advantage.

Small Outdoor Recreational Items

One of the first commercial applications for fiber-reinforced composites is sporting goods. Graphite filament-reinforced epoxy golf club shafts have recently been developed (ref. 186). The graphite fiber-reinforced shaft is reputed to be lighter than metal ones, and by proper orientation of the fibers, it more efficiently stores energy during the swing for release to the ball on impact. Table XXIV presents a comparison of the weight and cost of a graphite shaft, a fiberglass-graphite shaft, and a steel shaft.

Other graphite fiber-reinforced sporting goods components available commercially include archery bows and tennis racquets, shown in figure 37 (refs. 5, 187). Skis and ski poles are reported to be in the developmental stage (ref. 5). Great Britain has produced graphite-reinforced oars for the

TABLE XXIV.– COMPARISON OF COMPOSITE VERSUS STEEL SHAFT GOLF CLUBS

Type of Shaft	Weight (ounces)	Cost of Club
100% graphite shaft	2.6	$100
80% fiberglass - 20% graphite shaft	3.7	25
Steel shaft	4.5	20

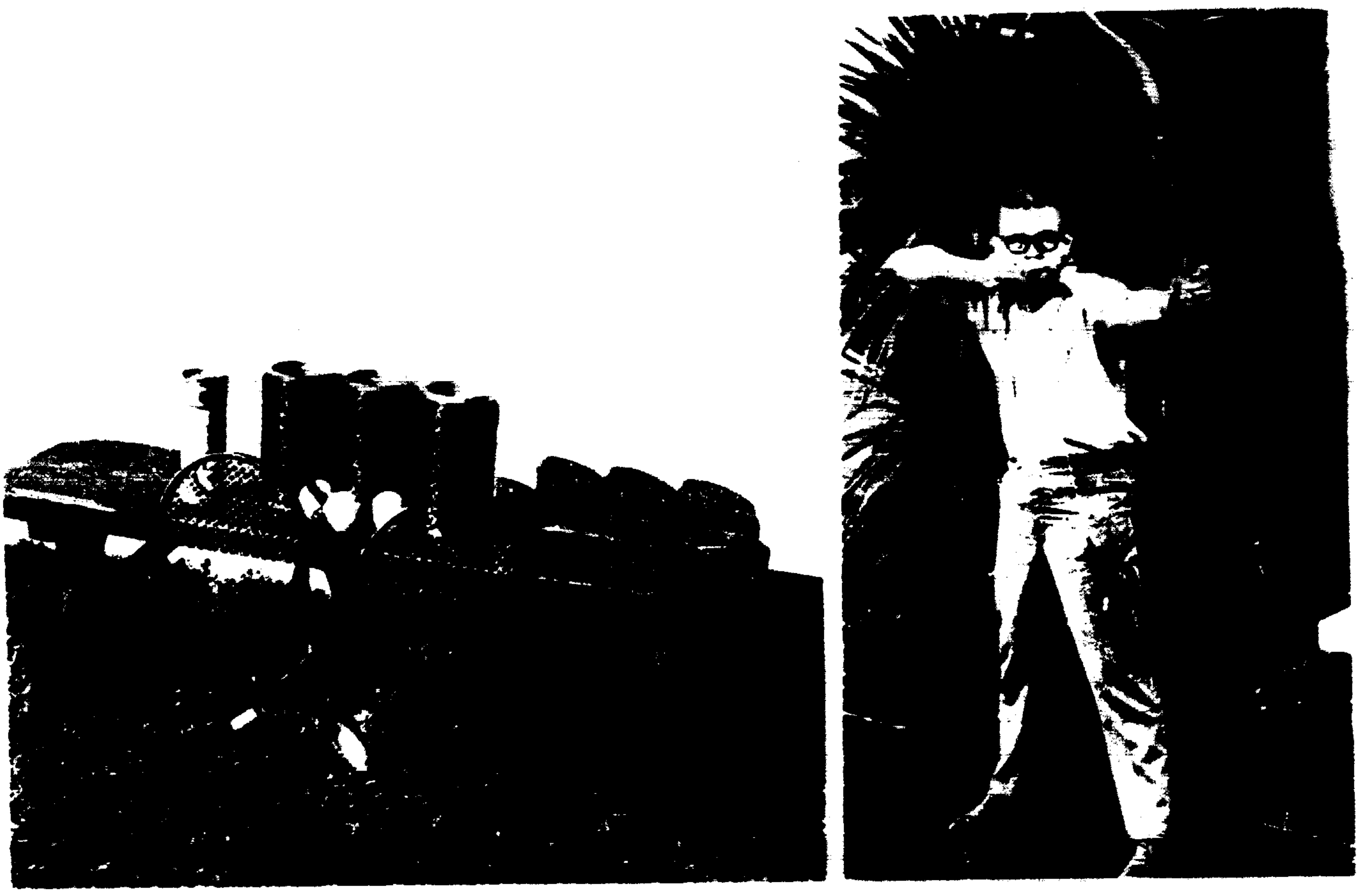


Figure 37.– Carbon-epoxy reinforced tennis racquets and archery bows and arrows. (from ref. 5)

(Reprinted by permission of Penton Publishing Co.)

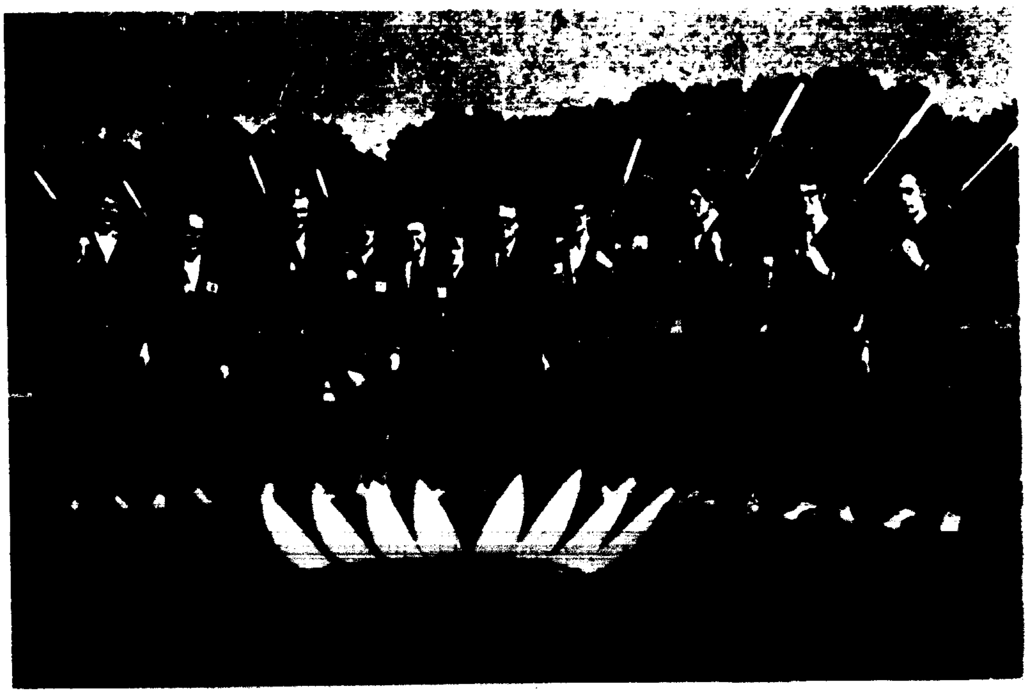


Figure 38.– Graphite reinforced oars. (from ref. 188) (Reprinted by permission of the Society of Plastics Engineers.)

British Olympic rowing squad. These oars, illustrated in figure 38, are 30% lighter, 10% stiffer, and have 25% less side face area, which acts to reduce wind resistance to a considerable degree (ref. 188).

Pole vaulting poles made from custom-ordered blends of graphite and fiberglass will undoubtedly be used soon. Such blends are necessary to achieve special properties of resilience and weight distribution for each individual.

Camping equipment is a field in which fiber-reinforced materials can be used in a number of applications. These could range from back-pack frames to tent poles and even ax handles, in short, to any part carried or transported that would benefit from weight reduction with no loss in stiffness. Laminated composites can also be of considerable benefit applied to camping equipment. Fiber-reinforced Mylar or polyethylene could well be used in the production of extremely lightweight tents and shelters. Alternate layers of metallized film and very thin, lightweight fabrics can be combined into blankets that give a high degree of thermal efficiency with very little bulk or weight. Such blankets are currently being marketed.

For the camper and/or general user, graphite fiber or blends of graphite and glass fibers could be combined to give very light and strong fishing poles. Such poles can have varying degrees of stiffness and can be considerably lighter in weight than fiberglass. They could bring about as much of a revolution in fishing poles as did the change from bamboo to fiberglass poles.

A new fiber recently introduced by the DuPont Co., PRD 49-1, has a modulus of 22 million compared with graphite's 50 to 75 million. The fiber is also approximately 25 percent lighter and, at the time of writing, is approximately a half to a third the cost of graphite fibers. It is to be expected, then, that this fiber will be extensively used in many applications now specified or contemplated for graphite fibers. This fiber appears particularly suitable for consumer items because of its relatively low cost. Ref. 45 and Chapter 2 further discuss the PRD 49-1 fiber.

Large Recreational Items

One recreational item in the United States and a utility item in many parts of the world is the bicycle. As a recreational item there would probably be a ready market for a bicycle with a frame of high modulus-epoxy reinforced aluminum tubing, if the weight reduction were high enough. Weight reductions of as high as 50 percent might be achieved in frames using fiber reinforcement of aluminum tubing, as detailed in Chapter 2. Similar weight reductions might also be achieved in rims and handlebars by the use of the hybrid composites.

A major advantage of hybrid construction, in addition to weight savings, is the facility with which joints can be made. This factor could lower costs compared with the all-fiber composites. Specific details on truss fabrication, including bonded joint design, have been published and should be directly applicable to bicycle frame design (ref. 15).

Another field for composite application to large recreational structures is boats. In boats, the weight savings in graphite or boron-reinforced aluminum booms and masts can well justify their construction, particularly if the boat is used for very special events, such as the America's Cup competition. Usually, for such an application, cost is a secondary consideration compared with performance. For the average citizen's boat, however, the hybrid composite, in which high modulus fibers are combined with a metal structure, should result in parts with higher strength and stiffness than all-metal or wood and at costs considerably less than that of an all-fiber composite. Possibly masts, booms, and spars utilizing PRD 49-1 could be made at reasonable costs to compete with the hybrid composites.

In addition to the use of fiber-reinforced booms and masts in sailboats, the sails themselves could be made of the fiber or of yarn-reinforced plastic films. Such sails should be relatively cheap and light and would occupy little volume when stored in the boat. Another definite advantage of such sails is their transparency, which should add to safety afloat.

A possible use for fiber-reinforced structures for power boats is in the construction of hydrofoils. Such parts would be immune to the corrosion suffered by metal hydrofoils, while at the same time they could be made lighter and as strong, or stronger, for the same weight. As in other applications, the hybrid construction might be substituted for the all-fiber construction with an appreciable savings in cost.

An obvious use for lightweight, stiff, strong structures in recreational vehicles is the production of wing spars, fuselage stringers, etc., in gliders. One English glider is being made with a graphite wing spar (ref. 189). Another such glider is reported being made in Germany. Here the application of boron and/or graphite would be used wherever optimum performance was required and cost could be secondary, as in the design of competition yachts. The application of the PRD 49-1 fibers to result in lower cost with somewhat lower performance might well prove advantageous.

Wing, fuselage, and empennage coverings for gliders can be made of the Dacron fiber-reinforced Mylar or polyethylene films described in Chapter 2. These films, because of fiber reinforcement, have rip-stop characteristics that would be necessary for use in a glider application. An additional benefit is that, as in sail usage in boats, the films are transparent and allow an increased field of view. They would thus contribute to safety.

Fiber-reinforced, laminated films could also be used in the construction of hot air balloons. Currently such balloons are made using coated rip-stop nylon fabric. Reinforced film should result in a weight saving and a cost reduction. Ref. 142 gives details about the use of such films in balloon applications.

The same fiber-reinforced polyethylene or Mylar laminated films could also be used in the construction of small greenhouses for backyard gardeners, using just a few sticks or a box and the film. The obvious advantage, here, in addition to cost is the ease of erecting and dismantling such a simple greenhouse.

Chapter 6

Applications of Composites in Construction

The construction industry in reality comprises two industries: (a) construction of buildings, bridges, structures, temporary shelters, roads, etc., and (b) construction equipment such as derricks, scaffolds, earth moving equipment, etc. In both cases, weight saving for almost all applications, offers no advantage. On the contrary, because of wind loading conditions, in most cases the structures must be heavy enough to remain firmly emplaced during the heaviest of gales. The same is true of most construction equipment. By the same token, since most of the heavy weight materials are among the cheaper materials, it follows that heavy construction will also be the cheaper construction for most conventional structures.

BUILDING CONSTRUCTION

The major product of the construction industry is, of course, buildings. Most buildings are still being built in the traditional way, i.e., by the use of a wooden or metal framework supporting the flooring, walls, and ceilings. There is very little incentive, solely for weight savings, to substitute other materials for the wooden or metal frameworks now being used for normal construction. Code restrictions are, of course, another reason inhibiting the usage of new materials for the framework. Thus, for a number of reasons, with cost as a major factor, new composite materials appear unlikely to be adopted for major framework construction in the near future. The adaptation of materials such as the new "trip" steels (transformation-induced elasticity), which combine high strength and ductility, is assured. However, there are a number of building components that can be made of composite materials, in which certain characteristics of the composite can be used to advantage.

Truss Construction

A number of commercial buildings being erected currently depend on various types of truss construction, either custom made or of modular construction, for support of ceilings and roofs. Normally such trusses are made of pressed or rolled steel, aluminum tubing, or wood, etc, as shown in figure 39. Similar trusses could be made of fiber-reinforced aluminum tubing (refs. 15, 18, 152, 153) or, at a decrease in cost, of hybrid (infiltrated fiber-reinforced metal) construction detailed in refs. 20 and 21 and described in Chapter 2. The major advantage in using a composite truss is the longer spans available at lighter weights compared with conventional materials. Thus, fewer columnar supports would be needed so that a larger usable floor space could be realized. The bearing walls could also be made of somewhat lighter construction. The actual usage of the composite trusses would probably be more dependent on cost reduction of the component materials than on the possible structural advantages outlined above. However, if as the result of volume production the cost of the fibers does decrease markedly, then such applications would indeed be attractive.

Interior Walls and Doors

Load bearing walls, attached to the frameworks, will probably continue to be made in the customary manner using metal lath and plaster or dry wall

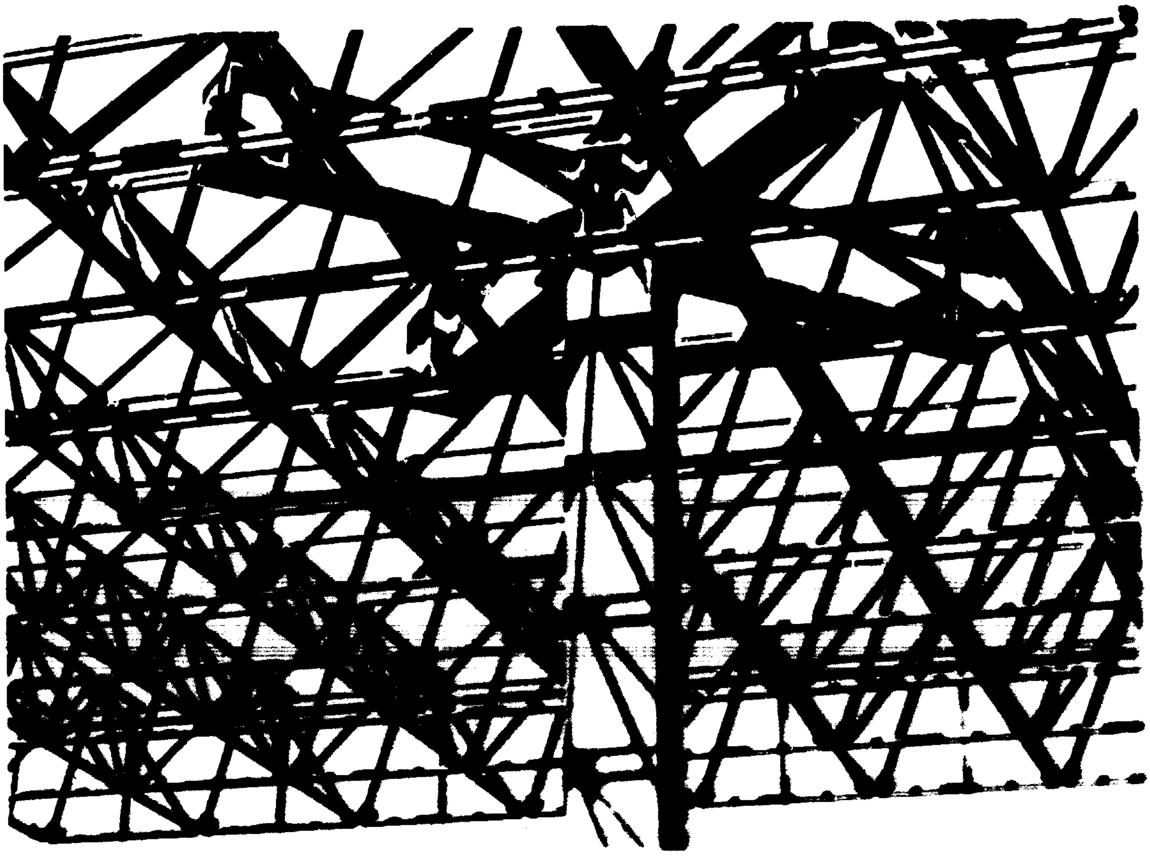


Figure 39.- Building truss construction

construction with wood or metal trim. Interior partition walls, which are non-load bearing, however, do use a large quantity of low cost aluminum extrustions or sheet metal structures and closures. Here, the metal section is used as a decorative trim and to help support and stiffen the wall. In general, simple extrusions or formed metals are used for such applications; however, in applications in which additional stiffness without extra weight or bulk is desired, then the hybrid construction might well be used. This type of composite could well be used to obtain the extra stiffness without increasing the weight excessively (refs. 20, 21).

A great many wall and door constructions used as non-load bearing partitions today are being made of hollow construction in which the interior consists of urethane foam. To obtain the optimum in fire retardancy, the urethane foam could incorporate the type of flame suppressants developed by NASA (refs. 103, 104). However, it should be noted that, at the time of writing, the flame suppressants reported have not yet been perfected to the point at which there are no toxic gases generated during a fire. A very low cost, glucose-based polymer, which can be foamed in place and which is self extinguishing, has been reported (ref. 94).

Wall and ceiling insulation for cold storage facilities and possibly for housing could be made using the multiple film insulation techniques developed (refs. 64, 72, 73). All the insulation methods listed use one type or another of metalized film layers separated by thin fabric spacers, i.e., the MLI insulation system (see Chapter 2). Variations of this insulation system might also be used as insulation for hot water pipes, heating ducts, etc.

Floors and Ceilings

No practical, cost effective applications for composite materials in floors are currently known. Ceilings for temporary construction, such as in unfinished buildings, warehouses, etc., could well be made of polyethylene or Mylar film reinforced with dacron fibers, such as described in ref. 78. These materials, made transparent or translucent, could be used between the lighting fixtures and the viewer to furnish a source of glare-free, diffuse light, while at the same time hiding the bare beams, trusses, lighting fixtures, ducts, etc., from sight. The films would also act as a ceiling to prevent the loss of warm air that might take place in a large, high-roofed warehouse or other building used temporarily for an office building or as an emergency personnel shelter, etc. The fiber reinforcement in the film would make it much easier to install, prevent tears from propagating, etc., compared with unreinforced film.

Mobile Homes

Mobile homes are one aspect of construction that can benefit from the high strength, lightweight products resulting from composite utilization. The mobile home chassis and framework, whether planned for a permanently parked mobile home or as a truly mobile trailer, could well utilize both the high strength and lightweight resulting from the hybrid infiltrated fiber-reinforced metal shapes (Chapter 3, refs. 20, 21). Figure 33 illustrates typical shapes made using this technique.

Fabrication of the side panels, ceiling, and flooring could be made using honeycomb construction. The honeycomb sandwich might be aluminum core and facings, paper core with plastic laminate faces, or a combination of one aluminum face and one plastic face with either a metallic or a non-metallic core. A number of methods have been published for the fabrication of honeycomb structures using integral built-in heating systems or easily made heaters that can be detached from the sandwich after the cure is complete (ref. 98). The use of these systems then obviates the need for large ovens or presses, which might be extremely expensive if small quantities of sandwich structure are required. For applications in which high strength aluminum honeycomb sandwich structures are required, methods are available that can be used to produce large sections by furnace brazing (refs. 101, 190). This technique requires furnaces with heating ranges up to approximately 1000°F (538°C) and capacities large enough to process full-sized panels. Despite the high initial cost, such a technique could be very valuable if large quantities of sandwich structures are required.

Building Equipment

To make a building useful above mere shelter, the structure must be supplied with all the additional components and equipment that are considered necessary for modern building construction. These include plumbing, heating, and lighting equipment as a minimum. To be truly modern the building should include air conditioning and, if over two levels, elevators.

Plumbing equipment.— With regard to conventional pipes and valves used in normal plumbing installations, it is likely that composites can be economically utilized, compared with currently used materials and parts. Large noncorrosive liquid storage tanks can be made by the technique described in ref. 35. In this method, circular sections of fiberglass-epoxy (or other composites) can be made as separate sections or on a continuous, spiral basis. The sections or spirals can then be bonded together to form tanks or pipes up to 20 feet in diameter.

A low-cost insulation system for pipes conveying cryogenic fluids has been developed (ref. 76). This system, utilizing aluminized fiberglass tape, cork, Mylar film, aluminum foil, and adhesive, is not quite so efficient as a vacuum jacket system for pipes but is considerably cheaper from both material and installation standpoints. Figure 36 in Chapter 4 shows the system, which is recommended for both temporary and permanent installations. The cost is reported to be approximately 1/10 the cost of a vacuum system, and the efficiency is approximately 1/20 that of a vacuum jacket system.

Large, manually controlled valves can benefit by the use of TFE Teflon to reduce friction on the rotating or sliding surfaces. A technique for joining steel to a TFE-Teflon-bronze composite has been published (refs. 82, 183). The technique is based on diffusion bonding using copper granules and is reported to be faster and to give better bonds than previously used adhesive bonding.

Air conditioning and heating.— Ducts used solely for air conditioning, particularly for temporary use, could well be made of laminated films insulated with some of the film multilayer insulations described in Chapter 2. The ducts could be made very simply as tubes, supported at intervals by thin wire rings. Permanent ducts for both heating and air conditioning could be made using the Drostholm continuous filament winding process to make the ducts (ref. 136). However, instead of the epoxy or polyester resins usually used in this process, the NASA-developed pyrrone resins might be used, provided that the costs were lowered sufficiently. These resins, described in refs. 169, 31, 172, show good strengths up to 400 to 700°F (204 to 371°C) and can be utilized as laminating resins or as foams (ref. 108). Similarly, polyimide resins could also be used for the same applications, when costs are lowered (refs. 175, 191). The specific advantage of such ducts over metal would be the elimination of both corrosion and also the noise accompanying thermal contraction, expansion, and vibration of metal ducts.

Lighting.— The use of laminated film to act as a light diffuser has already been mentioned. Another use for the films is in temporary constructions in which the film could be used as a windbreak in inclement weather, at the same time allowing light to be admitted. The fiber reinforcement again acts to strengthen the films considerably, especially against rips and tears that would occur in film normally exposed to the wind.

Elevators.– Building elevators are one aspect of construction in which lightweight composites can be utilized. By using aerospace techniques, e.g., honeycomb construction or graphite-reinforced lightweight floors and walls, considerable weight could be saved over conventional steel elevator car construction. This weight saving, translated into power savings, could be significant over a long period of time. Again, for such weight savings to be truly practical, the cost of the materials, i.e., the fibers, honeycomb, etc., will also have to be reduced considerably.

NON-BUILDING CONSTRUCTION

Non-building construction in which composite materials could be utilized includes construction equipment, bridges, and such miscellaneous items as antennas.

Construction Equipment

Construction equipment, ranging from simple devices such as ladders and catwalks to more elaborate equipment such as derricks, cranes, scaffolds, etc., can all utilize fiber-reinforced composites, since in almost all cases the equipment is portable and, in many cases, also mobile. Structures such as ladders, scaffolds, etc., can be made using special extruded or formed shapes, such as are shown in figure 33, in which the metal is reinforced with fibers that are resin infiltrated. This hybrid construction could also be used to make much larger structures such as derricks, cranes, etc. (refs. 20, 21, 158). An example of an extremely, low-weight, high-strength structure of fiber-reinforced tubing construction is given in ref. 141. A truss, 15 feet high, is described which is made of eight graphite-fiber-epoxy reinforced tubes (figure 40). The total weight of the truss is approximately 80 pounds. Each tube is capable of supporting a 20,000-pound compression load. Such a structure, while currently very costly, would appear to be ideal for emergency airborne equipment, airborne oil exploration, etc.

Figure 40.– Graphite composite support truss. (from ref. 141)
(Reprinted by permission of Hercules, Inc.)

Miscellaneous

Bridges, using standard metal truss construction and erected for temporary use, can benefit from use of hybrid components, since such lightweight, high strength parts can be easily removed and transported after the necessity is over. A number of types of hybrid construction have been reported (refs. 20, 21). The theory of hybrid structures, materials selection, and basic structural design has also been reported (ref. 158). Bridges erected for permanent use, however, must meet the same type of windload requirements as buildings. Thus, there is no real reason for lightness, and in many cases, light weight might not be desirable, irrespective of the fact that light weight also might mean "very costly."

An example of large non-building structures that can benefit from the lightness and stiffness of a graphite-epoxy composite are antenna reflectors of the type used to communicate with space TV relays, spacecraft, etc. In addition to the desirable characteristics of lightness and stiffness, the graphite-epoxy composites also have a very special characteristic of a near-zero coefficient of expansion. Thus, such a structure as the Goldstone antenna reflector (figure 41) or the Jodrell Banks reflector would maintain its curvature (and accuracy) during temperature extremes much better than if made of conventional aluminum or steel construction (ref. 192).

Figure 41.– Goldstone tracking antenna. (from ref. 192)

Applications of Composites in Machinery

Materials strongly influence many parameters in the design formula of almost every kind of machine, from machine tools and business machines to textile and food processing machinery. Such parameters would include function, durability, reliability, weight, appearance, cost, and producibility. The search for materials that fit the formula with ever increasing performance is endless. The versatility of composites suggests solutions to many problems and offers performance improvements in many design parameters.

VIBRATION

Rotation machinery cannot be prevented from vibrating altogether, but excessive vibration can be very harmful. The consequences can range from undesirable noise to complete destruction of the equipment. Machine tools for cutting metal are also subject to vibration because of the intermittent loading in many types of cutting operations. Quite often the cause can be structural resonance; that is, certain parts of the machine, or the entire assembled machine, may have a resonant frequency near the operating speed or some low multiple of the operating speed. The vibration may be reduced by changing the resonant or natural frequency of the part or assembled machine. This process can be accomplished by changing mass, mass distribution, or stiffness. The frequency is related to mass and stiffness by the formula

$$\text{resonant or natural frequency is proportional to } \sqrt{\frac{\text{stiffness}}{\text{mass}}}$$

Therefore, to increase the resonant frequency above the natural frequency of the exciting device, the stiffness of the machine structure should be increased or the mass reduced. Both of these can be accomplished by a process developed for NASA. This method consists of infiltrating lengthy hollow areas (generally holes) in metal structures with boron fiber/epoxy resin composite material (refs. 4, 21). Details of this infiltrating process are discussed in Chapter 2. Heavy metal, removed from the vibrating machine by drilling holes in strategic locations, is replaced with lighter, stiffer composite material. The replacement satisfies the frequency equation; the resonant frequency is increased, and the harmful vibration is eliminated.

Another approach to the vibration problem is to include boron fiber/epoxy resin composite or boron/aluminum composite in the original design. These materials have a specific modulus three to five times that of high strength steel and would provide a greater margin of freedom from the possibility of resonant frequency vibration. In addition, lighter weight machines would be easier to move and cost less to ship, thus offsetting the cost of the composite materials. Details of other forms of structural composites suitable for use in machinery are presented in Chapter 2. Among these is a lower cost hybrid concept that combines boron/epoxy composite with sheet metal forms (ref. 20).

LUBRICATION

In machinery almost every type of sliding motion can be found, each of which requires some form of lubrication. In most applications hydrodynamic lubricants (oils, greases) can be used. These are not always convenient or feasible to use; consequently attention has been directed to solid lubricants which have been gaining popularity in recent years. Solid lubricants possess several good properties: stability at extreme temperatures and in chemically reactive environments, light weight, and simplicity because oil recirculating systems are not needed and fewer seals are required.

Gas turbines for generating power have operating efficiencies proportional to operating temperatures. Temperatures above 1500°F (816°C) and approaching 1800°F (982°C) are becoming common. Turbine shafts have greater dynamic stability when bearings are more closely spaced. Consequently, turbine shaft bearings must operate at very high, ever increasing temperatures. Seals for these bearings are necessary to exclude oxidizing hot air and corrosive gases. Solid lubricants are good candidates, but materials more thermally stable and resistant to oxidation than commonly used graphite and molybdenum disulfide (MoS_2) are required (ref. 119). NASA has recently developed new solid lubricants with long term oxidation resistance at 1500°F (816°C). Friction coefficients at 80 to 1700°F (26.7 to 927°C) are only slightly higher than that of MoS_2 at lower temperatures (ref. 118).

Bonded solid lubricants have the disadvantage of finite wear life. High pressure sliding contact is common with meshing gears used in many machine tools. Consequently, solid film lubricants are not suitable for gear teeth. Yet, it would be desirable to eliminate oils or greases because of their need for maintenance and costly lubricating systems.

A new permanently lubricated gear has been developed by NASA (ref. 183). The gear is machined from a laminated blank consisting of layers of bronze powder-filled FEP Teflon bonded to steel in a sandwich construction as shown in figure 42. The bonding method is also a NASA development (refs. 82, 83).

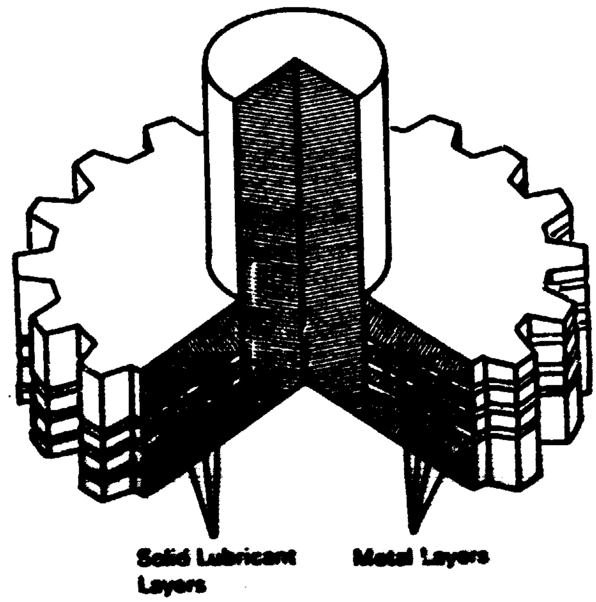


Figure 42.– Self-lubricated laminated gear. (from ref. 183)

The Teflon supplies a minute layer of lubricant that is automatically replaced as the metal wears. The system is especially effective at high tooth pressure and low rotation speed.

Another potential use for the new Teflon laminate is on machinery with exposed gears or mating parts, such as the feed screw on a horizontal lathe. The screws are usually coated with grease which attracts dirt and can soil clothing of the operator. If the half nuts that engage the screw were made with the FEP laminated construction, no messy lubrication would be required. Other possible uses for this construction are journals and pistons in dry cylinders, as shown in figure 43.

With textile machinery, lubrication of machine elements that are exposed and adjacent to fabric is a problem because of the contamination risk. Oils and greases are too risky, and solids containing black lubricants may flake or produce dust. Graphite is a good lubricant, but the color is objectionable in case of contamination. However, a white graphite has been reported by

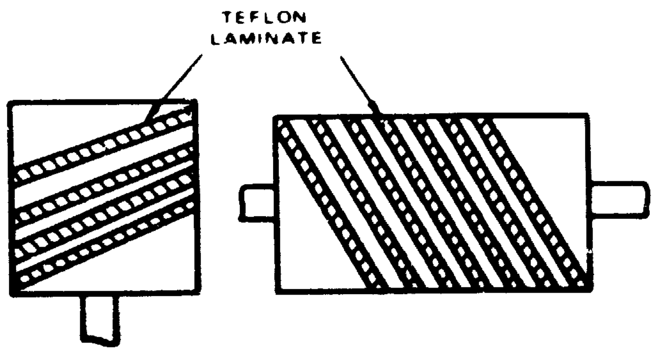


Figure 43.– Piston and journal applications for self-lubricated steel-Teflon lamination.

NASA. Actually it is a graphite-fluoride, pure white, with the lubrication qualities of MoS_2, and usable from sub-zero to 900°F (482°C) (ref. 163). Of course, a contaminated black cloth is still a problem.

WEIGHT REDUCTION

Cost savings and increased portability often benefit from weight reduction. Lower weight moving parts require less power and thus allow use of smaller, lower cost motors. The cascading effect often continues throughout the system. Increased portability can contribute to versatility and can reduce shipping and installation costs.

Advanced fiber-reinforced composites substituted for heavy monolithic metals can save weight because of the higher specific strength and stiffness of the composites. Properties of many of these materials are presented in Chapter 2.

Power transmission shafts are an example of an application in which composites could effect an important weight savings. In a recent study (ref. 5) of lighter weight replacements for an aluminum shaft, two shafts were constructed, one of boron fiber/epoxy resin and one of graphite fiber/epoxy resin. Performance requirements were an unsupported shaft length including end fittings of 97.25 inches, an ultimate strength of 20,000 lb.-in., and a minimum first critical speed of 5,200 rpm. The resulting boron fiber design was 5 inches in diameter with a wall thickness of 0.052 inch and a weight of 5.3 pounds for each shaft.

Three tubes placed end to end with fittings and bearing supports between made up the entire drive shaft system. The aluminum shaft system required two additional fittings and bearings. The overall weight saving of the boron/epoxy vs. the aluminum shaft system was 30 percent. It met all performance requirements. Additional weight saving was achieved with a graphite fiber/epoxy composite tube. These tubes each weighed one pound less than the boron fiber tubes.

Other machine elements could be reduced in weight by using advanced composites of the type developed by NASA. In a recent study of a load bearing gear case (ref. 182), a cover made of a boron-fiberglass/epoxy resin composite (figures 44 and 45) weighed 4.3 pounds less than the original 32.9-pound magnesium cover. Analysis of a proposed graphite/epoxy composite cover estimated an 11.3-pound total saving. The composites also had superior corrosion resistance.

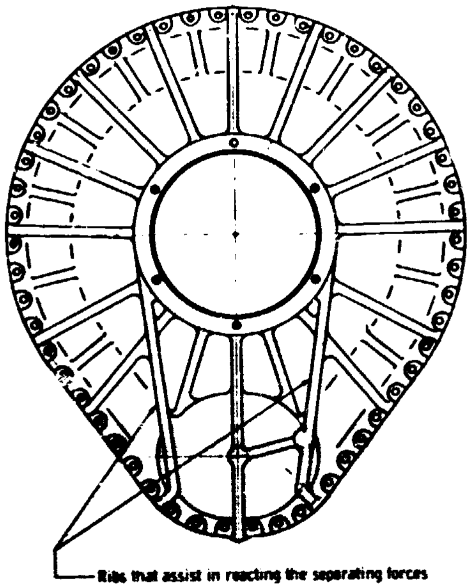


Figure 44.— Internal view of composite gear case. (from ref. 182)

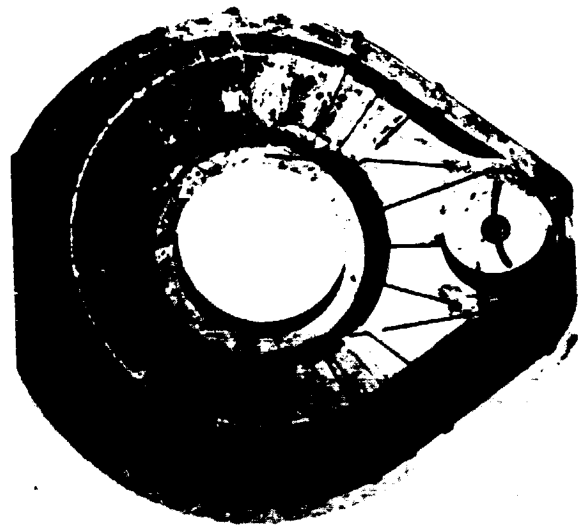


Figure 45.— Front view of composite gear case. (from ref. 182)

STRENGTH/STIFFNESS IMPROVEMENT

Occasionally, a need arises to upgrade the performance of an existing machine. This modification usually requires strengthening and stiffening the structural elements to support increased loads, either static or dynamic. Because most machines have metal structural elements, refurbishing requires replacement or reinforcement with more metal, which is often difficult to apply and which adds substantial weight. The added weight may require more substantial supporting structure, which further increases cost. In addition, the resonant frequency of the machine may be decreased to a point at which vibration is objectionable, if not harmful.

Fiber composites can be useful here because of their exceptionally high specific stiffness and strength. In addition, the fiber/resin composites are relatively easy to apply. NASA has developed techniques for enhancing metal components with applied fiber/resin composites (refs. 14, [illegible]) [illegible]

of the concept, the performance of a textile loom was improved [illegible]

strips of graphite fiber-reinforced plastic to the [illegible]

improve stiffness. This modification permitted the [illegible]

50 percent (ref. 5).

Chapter 8

Applications of Composites in Biomedicine and Safety

A host of new materials that hold great promise for the medical and safety engineer has been developed as a by-product of NASA's space program. One of the most promising groups of these materials is the composites. The high strength and stiffness characteristic of some of the composites have been utilized in a number of important applications identified by NASA engineers and Biomedical Application Teams (ref. 193). Other applications utilize the fire resistance properties of special fabrics, the insulating properties of composite films, the corrosion resistance of certain composite components, etc. The concepts have been supported by still other investigators (ref. 194). For example, a very effective prosthetic device can be made from carbon fibers in an epoxy resin matrix, which, when coated with carbon, is biocompatible (ref. 195). In another example of a by-product of space research, layers of flameproof cloth and metallized fabric developed for the Apollo Program have been combined into an exceptionally fire-resistant and lightweight fireman's suit.

Some of the exciting possibilities for application of composites in biomedicine and safety are:

- Fiber Reinforced Composites – Artificial limbs, harnesses and braces, heart valves, artificial bone, implant devices, helmets, dental restorative materials, and fireproof materials.
- Laminar Composites – Implant materials, thermal insulating blankets, and fireproof clothing.
- Skeletal Composites – Implant material, orthotic cushions, and pads.
- Particulate Composites – Dental restorative materials, surgical implants.

EXTERNAL PROSTHETICS

The largest number of lost limbs are due to wars and industrial and automotive related accidents. There also exists a large number of physically defective infants, born either without limbs or with severely deformed limbs. Infants born without arms or legs and children and adults deprived of limbs through disease or accident face a common physical-psychological problem. Engineering-medical research teams have been trying to alleviate the problem by developing ingenious prosthetic devices that resemble human limbs and function like them. Harnesses, artificial limbs, and orthotic support devices have been developed, improved, and made more aesthetically acceptable by the incorporation of new ideas and composite materials derived from government-sponsored aerospace research and development programs.

Harnesses

Harnesses are required for the attachment and support of artificial limbs. Early harnesses were made of impervious materials, such as steel-reinforced leather, which restricted normal dissipation of heat and moisture, and were also quite heavy. For example, a conventional Oxford arm harness for a child nine years old weighs over 4 pounds.

Research personnel at Chailey Heritage of Chailey, Sussex, U.K., were able to reduce the weight of the harness to less than half a pound by the substitution of graphite-fiber-reinforced plastic for steel (ref. 196). Such a harness was easier to make than the conventional Oxford arm harness, and the composite harness is more comfortable and easier to maintain. The high specific modulus and strength of carbon-fiber-reinforced plastic (CFRP) made this material attractive for the application. The Chailey Harness, as described by Ring and Benford, is a simple polyester resin-graphite fiber lay-up on a polyethylene foam coated plaster-of-Paris cast of a child's torso. The foamed polyethylene serves not only as a mold for the reinforcement but also as permanent internal flexible pad to ensure user comfort. Figure 46 shows how the polyester-graphite is laid as a reinforcement into channels in the polyethylene.

Figure 46.- Polyethylene strips nailed to a plaster-of-Paris cast for an artificial arm harness. (from ref. 196)

(Preprinted by permission of Chailey Heritage, Craft School and Hospital, Sussex, England.)

Each harness produced has different strength characteristics because it is shaped to different body configurations.

The successful application by Ring and Benford of graphite fibers to a child's harness, and the continued development of even more advanced fibers, make it possible to envision even lighter harnesses for other appendages. Work at NASA Langley Research Center on high modulus graphite fiber-epoxy and boron fiber-epoxy tubes, rods, and similar parts will also be directly applicable to these devices (refs. 15, 152).

Artificial Limbs

Artificial limbs are made from a variety of materials, including wood, lightweight metals, reinforced plastic, and various steel alloys. Stainless steel, however, has become the preferred material for supporting devices because of its durability, dependability, and structural properties. Steel-reinforced artificial hands, arms, legs, and feet have been extremely helpful in rehabilitating the amputee, the paralyzed, the neuromuscularly weak, and the patient who has birth defect anomalies. The bulk and weight of these steel devices, however, present a considerable problem, particularly to patients with neuromuscular weaknesses.

NASA has developed a variety of hybrid composites for aerospace applications consisting of boron, graphite, and glass imbedded in a matrix of epoxy resin (ref. 193). Excellent structural properties and low weight make the cured composites a good replacement for steel. They can be readily contoured to a patient's shape which is an advantage that facilitates fabrication, reduces fabrication costs, and improves user acceptance. These composites hold great promise for solving the weight and bulk problems of current artificial limbs and leg braces. As projected price reductions are realized, greater commercial exploitation of composites in prosthetic devices can be expected.

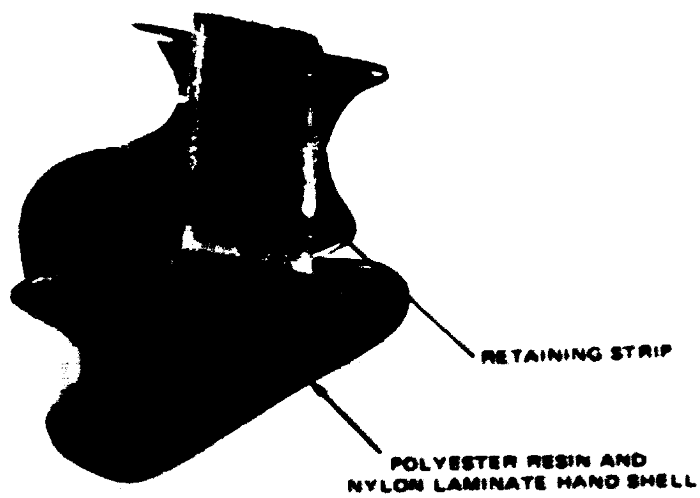
In recent years, plastic laminate composites supplanted leather in the construction of artificial limb sockets. While the plastic laminated sockets did not degrade with use as the leather ones had done, they were impervious to water vapor, and sweat accumulated, which became a source of discomfort and irritation to the amputee. Drilling holes in the laminate to eliminate this condition destroyed the continuity of the reinforcing fabric and greatly reduced the structural soundness of the prosthesis. To overcome the loss in socket strength, a new approach to making porous plastic protheses was investigated with considerable success. This new socket consisted of an outer layer of knit Banlon (stockinet of tubular knit jersey, 5.4 oz/yd^2), three layers of knit nylon (stockinet, tubular-rib-knit, 9.4 oz/yd^2), and another layer of Banlon (ref. 197). Each layer of fabric was impregnated with epoxy resin and heat cured under light pressure. The new socket was developed to obtain adequate structural properties, excellent long-term stability in perspiration, and low weight, and the capability of being washed with soap and water (ref. 197). Patients using the improved socket reported reduced perspiration, added comfort, and a decrease in skin problems (ref. 198).

Orthotic Support Devices

A wide variety of orthotic support devices has been developed to meet the needs of a large patient population with neuromuscular and skeletal disorders which impair or completely inhibit the function of a hand, a wrist, or an entire upper extremity. The ability to oppose the thumb to the flexing fingers may be lost. In these instances, various types of orthotic systems have been produced to prevent or correct deformities, to restore function, or to accomplish all three. A key feature of these systems is the stabilization of the thumb in opposition to the fingers.

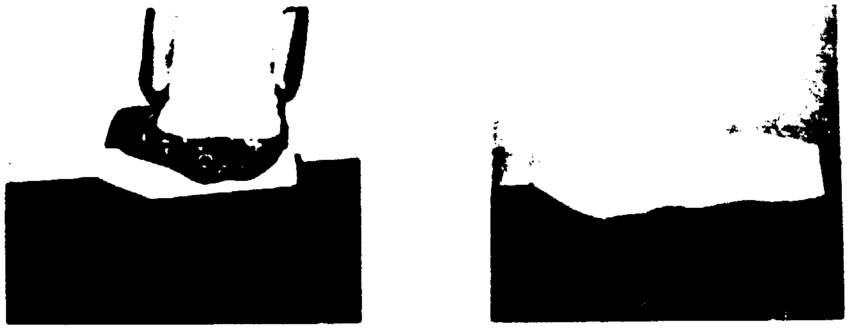
Typical of these assistive devices is the Engen Plastic Hand Orthosis (ref. 199), which in its simplest form consists of a polyester resin and nylon laminate shell that is prepared with vacuum molding techniques. This short opponens orthosis (figure 47) is then tailored to fit the patient's hand. During the evolution of this device, larger, complex units were developed to remedy more involved skeletal disorders. These larger devices relied on steel and wood braces and were heavy and bulky; patient acceptance was difficult. It appears that the NASA-developed composite, discussed earlier for application to artificial limbs, could also be used to advantage here to lighten the device and reduce its bulk.

NASA-sponsored research into thermal insulating systems and cushioning devices resulted in the development of two unique foam materials that have been used in rehabilitation centers and medical centers to improve patient care and comfort. One was a polyurethane foam material being used at NASA's Ames Research Center to counteract crew seating discomfort associated with long space flight (ref. 193). The foam possesses unusual temperature and compression rate properties which allow the material, under high local pressure, to flow until a soft uniform supporting pressure is exerted across the entire body (figure 48). This unique foam is now being used as bed a.



b.

Figure 47.– Two views of the short opponens orthosis. (from ref. 199)



(1) (2)

Figure 48.— Polyurethane foam material: (1) under the influence of a patient's local body heat, the foam produces a local cushion flow to provide fitted, uniform support to aid in prevention of decubitus ulcers; (2) the foam possesses unique compression rate sensitivity. Its fluid-elastic properties assure a comfortable flow-fitted support, with hard high-pressure points yielding into soft low-pressure uniformity. (from ref. 193)

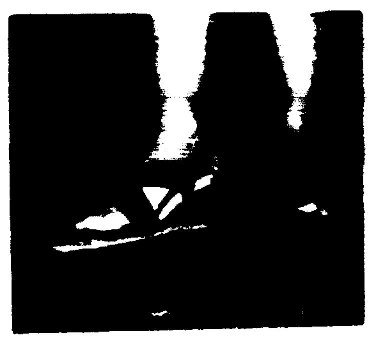
pads, cushions for wheel chairs, linings for prostheses to prevent tissue damage, and padding for joint bender splints.

In another case, NASA technology (ref. 193) was used by physicians at a rehabilitation center to provide immediate relief for patients from pain and discomfort by rapid fabrication of foamed orthotic devices, such as arch supports (figure 49). The entire process from foaming the arch support to placing it in a shoe takes only 10 to 15 minutes. Indications are that the foam-in-place material could prove to be an effective, economical means for providing immediate custom-fitted temporary orthotic support aids for a variety of medical purposes.

(1)

(2)

(3)



(4)

Figure 49.— Foam-in-place arch supports: (1) arch support foamed to the contour of the patient's foot; (2) free foam arch support trimmed to fit patient's shoe; (3) trimmed arch support ready for insertion into shoe; (4) arch support in place in shoe, ready for immediate use. (from ref. 193)

INTERNAL PROSTHETIC DEVICES

Materials used for internal prosthetics must satisfy two primary requirements: (1) they must be compatible with the tissue and body fluids, and (2) they must have the mechanical properties needed to perform their functions. Compatibility of an implant implies that it will cause minimum disturbance of tissues and fluids and, conversely, that the tissues and fluids will not significantly degrade it (ref. 200). In general, materials considered for use as implants are highly inert chemically as well as having the requisite mechanical properties. Metals, some plastics, and ceramics have been used with varying degrees of success (ref. 201).

Fiber-reinforced polyester and epoxy materials are attractive, since tailoring the proportion of fiber reinforcement can produce bone-like materials with moduli of elasticity closely approaching that of natural bone (3×10^6 psi) (ref. 202). Metals, on the other hand, have moduli of from 15 to 30×10^6 psi.

Orthopedic Devices

For convenience, orthopedic devices may be considered in two classes: fixation devices and prostheses. Fixation devices are used to hold bone parts in place until healing has progressed to the point at which such support is no longer necessary. They may be removed six to 18 months after implantation. Prostheses are used to replace parts that either are not expected to grow or have been removed because of birth defects, disease or accidents. Since such devices must serve for the remaining lifetime of the patient, material and design requirements are stringent. Figure 50 illustrates a typical fixation device, and figure 51 shows a typical prosthetic device (ref. 200). Both illustrations refer to metal parts made of stainless steel, titanium or cast cobalt alloy.

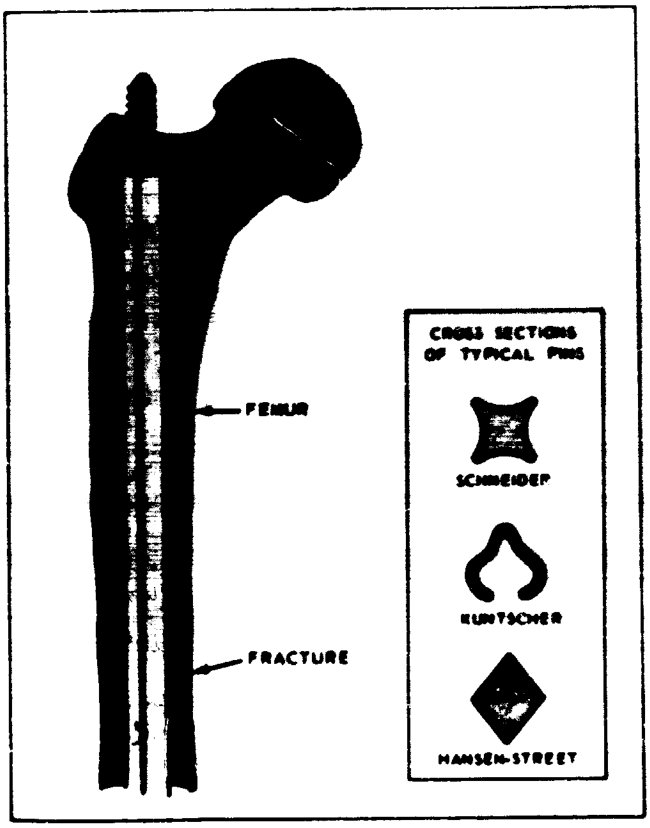


Figure 50.– Positioning of intramedullary pin to hold a fractured thigh bone (femur) during healing. Such pins must be compatible with the body, have a shape that will hold the bone parts in place during twisting, have a length and cross section adequate for the application, and provide strength against compression, bending, and torsion. The threaded end at the top allows attachment of devices for insertion and withdrawal of the pin. The diamond-shaped Hansen-Street pin is illustrated. Cross sections of other pins are shown in the inset. (from ref. 200)

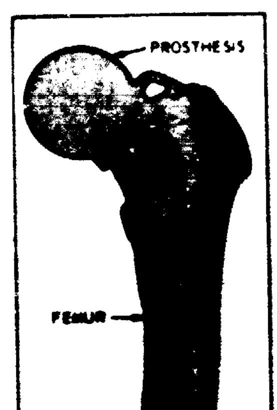


Figure 51.– Prosthesis replacing head and neck of femur. Such devices are implanted when the head and neck of the bone are badly diseased or broken. In addition to proper dimensions and adequate strength, the devices must have a smooth surface on the head, which fits into the acetabulum of the pelvis, as part of a ball and socket joint. (from ref. 200)

With respect to fixation devices, [illegible] such as boron-epoxy and graphite epoxy [illegible] NASA Langley Research Center (refs. [illegible] and [illegible]), [illegible] are considerably lighter than stainless steel [illegible] the objections to the use of epoxy resins in implants [illegible] lead to the formation of fibrous tissue (ref. [illegible]). NASA developments [illegible] field of implantable sensors may well be used to minimize this effect. In reference 204, data are given on composite coatings used over epoxy encapsulated sensors. These coatings consist of a wax layer, covered with a vinyl lacquer over which an additional coat of silicone rubber is applied. Figure 52 illustrates the use of this coating system with objects to be implanted (ref. 204).

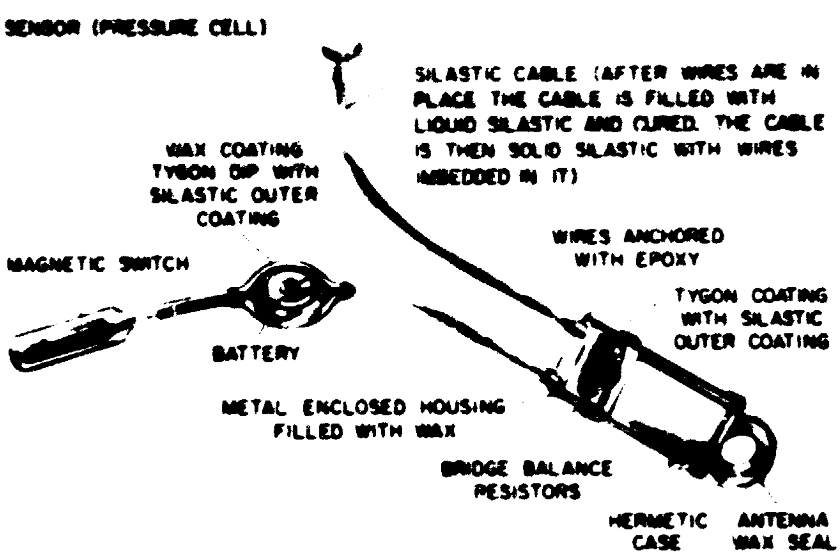


Figure 52.– Composite coating for implants which are subsequently encapsulated. (from ref. 204)

Coatings might also be useful with all types of metal implants to prevent or minimize corrosion. Corrosion can occur, for example, as the result of attack by body fluids (ref. 205). The wax, vinyl, silicone coating system might be used here to protect the implant. Another source of attack on metals is the piezoelectric effect of bone. This effect comes from a small current generated by movement of the bone. Corrosion caused by the current, releases ions into the bone tissue that destroy local bone cells and cause the metal implant to loosen (ref. 206). A dielectric coating would minimize the effect of electric current on the metal device.

Tantalum has had a long history of use as surgical implants because it is inert in the body. It is an extremely ductile material that can be drawn into wire sutures, made into gauze for abdominal wall repairs, and used as a structural member in repair of long bones (ref. 207). An improvement over tantalum gauze material might be the use of chromel "R" (Ni-Cr alloy) wires coated with polytetrafluoroethylene. This material, developed for use in Apollo-space suits, may be considerably stronger and just as ductile and soft as the tantalum gauze and would have adequate biocompatibility. Since the material is in the form of gauze, it would undoubtedly bond satisfactorily with the tissues (ref. 208). A recent NASA Lewis Research Center development consists of a technique for production of a high-strength tantalum composite made up of tantalum sheet and fibers embedded in a matrix of tantalum powder. Rolling the mixture to very high levels of reductions resulted in material which had almost twice the strength of the original tantalum (ref. 209).

The application of newly developed, special "superalloy" coatings might provide improved corrosion resistance. These coatings, developed under NASA sponsorship, consist of several types of composites based on cobalt-chromium-aluminum-yttrium systems applied to the substrate by electron-beam vapor deposition. Considerable increase in oxidation resistance was found (ref. 210).

F[illegible]

The NASA encouraged [illegible] applications has produced a material satisfactory [illegible] what brittle because of its glassy state (ref. [illegible]). A possible [illegible] improving the impact strength, and possibly the overall strength of the vitreous carbon, would be to make a composite of zirconium or zirconium oxide particles mixed with the carbon precursor before it is fired to the vitreous state. Work done at NASA Lewis Research Center by C. P. Blankenship indicates that a tungsten-zirconium oxide composite (tungsten matrix and zirconium-oxide particles) has a tensile strength twice that of the parent tungsten (ref. 211). Since the zirconium oxide will withstand temperatures up to at least 3497°F (1925°C), it would undoubtedly satisfactorily withstand the high-temperature pyrolization required to make the vitreous carbon. Animal implantation work has been done using zirconium with satisfactory biocompatibility (ref. 207).

Nonorthopedic Devices

There are a number of implantable devices that are used for nonorthopedic purposes. Possibly the best known of these are the various heart valves, which are fabricated with a variety of materials. Figure 53 shows two types of these valves, differing mainly in the type of closure (ref. 212). The valves consist of metal alloy (Vitallium) struts and a silicone rubber ball filled with barium sulfate for radiopacity. A Teflon-polypropylene composite fabric and a Teflon knit-fabric covering for the strut are also used. A graphite-pyrolytic graphite composite disc forms

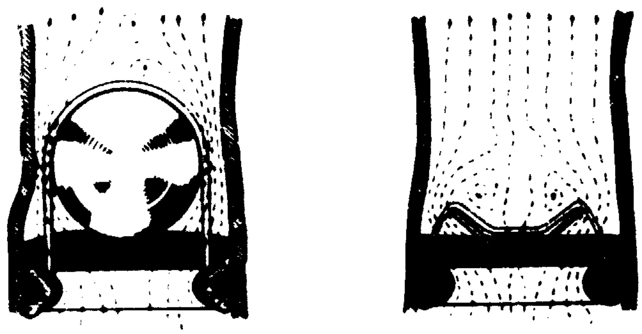


Figure 53.– Flow patterns of Starr-Edwards (a) and Kalke-Lillehie (b) valves in aortic position. Note free central and lateral flows with the (b) prosthesis. (from ref. 212)

the valve closure on the Kalke-Lillehie valve. The Teflon fabrics developed for "shirt-sleeve" coverall garments under the Apollo spacesuit mentioned by Radnovsky of NASA Manned Spacecraft Center (ref. 208) may well be used for these applications. In addition, vitreous carbon is reported to be under investigation as a material for the sealing ball and possibly for the disc seal (ref. 195).

OTHER BIOMEDICAL APPLICATIONS OF COMPOSITES

Inflatable Splints

The G. T. Schjeldahl Company, under NASA Langley Research Center sponsorship, has developed a number of reinforced films, such as Mylar reinforced with Dacron and glass fiber yarns. Such films can be used for fabrication of balloons and other inflatable structures and assemblies that can withstand considerably greater tensile loads than those made from conventional nonreinforced films. These reinforced films can be used in inflatable splints. These splints would be made as simple cuff-like tubular structures which, after insertion of an arm or leg, could be inflated to maintain the limb in a rigid position. Figure 54 shows the way in which such a splint might be applied. The specific advantages of inflatable splints would be light weight, very small size, and easy portability. The latter characteristic would make them particularly attractive for emergency use by ski patrols, paramedics, etc. The cost should be nominal.

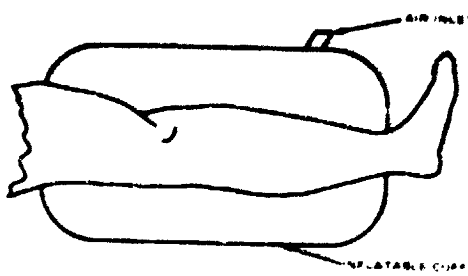


Figure 54.— Inflatable splint concept.

Emergency Blankets

The development of metallized film, particularly aluminized Mylar, for heat insulation has been greatly aided by NASA sponsorship. The metallized film is currently being exploited by sporting goods companies in the manufacture of "space blankets". These blankets are simply thin (0.001 inch thick) radiation shields that reflect body heat. Because they can be very compactly packaged, they should be useful as emergency blankets by ski patrols, paramedics, etc.

Metallized film can also be wrapped around an injured arm or leg to control the loss of heat. The inflatable splint described can also be metallized if retention of heat is desired.

Plastic Foam Splints

A permanent type of splint can also be made very rapidly from a combination of the tubular films and a urethane foam-in-place material. In such an application, the foam materials, after they are mixed but before they are foamed, are injected into a double tubular cuff around a limb. In a very short period of time, a rigid splint will form. The formulation used for such a rapid foam reaction can be found in ref. 213.

Cryogenic Insulation

In connection with work on cryogenic fluids, the AEC in conjunction with the NASA Space Nuclear Propulsion Office has sponsored work on development of inexpensive, cryogenic insulation systems. Thus simple, inexpensive cryostats are now available for use by small hospitals, research laboratories, and other organizations that do not normally use cryogenic fluids in large quantities. These cryostats (see Chapter 3, figure 35) have insulation made of commercially available materials such as cardboard, aluminized Mylar, corkboard, and aluminum foil-lined fiberglass tape. Such insulation has been found satisfactory in many applications in which cryostats with vacuum jacketing were previously considered necessary (ref. 110).

Improved Blood-Pressure Cuff

An improved blood-pressure cuff has been developed by NASA for monitoring astronauts and other flight personnel. This cuff is reported to be smaller, lighter, less stiff, and lens restrictive to arm movement than the standard 7-inch clinical cuff (ref. 214). Shown in figure 55, it is essentially a laminar composite consisting of a nylon cover sewed to an attached piece of Velcro. The assembly contains the small pressurization unit.

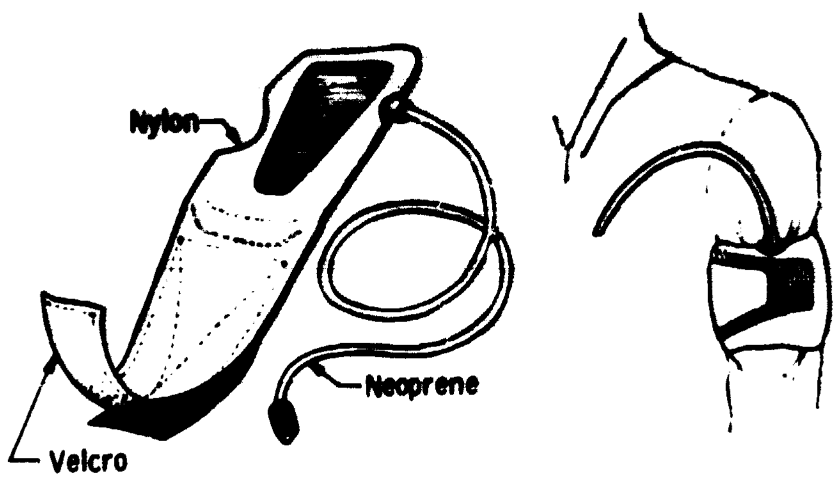


Figure 55.– Mercury blood-pressure cuff. (from ref. 214)

Dental Restorative Materials

Shortly after World War II, the dental profession initiated the use of cure-in-place acrylic resins to be used in place of the widely used amalgams (mercury and powdered zinc or silver) or the somewhat less frequently used silicate cements and porcelains. It was hoped that the biocompatible, easy-to-use acrylic resins (used unfilled) would not have the deficiencies of the older materials. By 1955 it was found that the acrylics had also evidenced a number of undesirable characteristics that considerably restricted their usage. The deficiencies of the various restorative materials at the start of the 60's are listed in Table XXV.

TABLE XXV. - DEFICIENCIES OF DENTAL RESTORATIVE MATERIALS

Silicate Cement Type Restoratives	Porcelains	Metal Alloys	Unfilled PMMA
High degree of solubility Stain badly Ultimately poor aesthetic properties	Brittle Desired resilience and toughness lacking Expensive	Poor aesthetic properties High coefficients of thermal conductivity	Polymerization shrinkage High coefficient of thermal expansion Poor abrasion Oral fluids absorbed Reduced compressive strength

In the early 60's, work was initiated to form composite restoratives by reinforcement of the polymethylmethacrylate (PMMA) with inorganic materials such as glass fibers, beads, powders, quartz, calcium phosphate, and other fillers. Johnson conducted a study to determine the efficacy of glass fiber and beads (ref. 215). Glass fillers did not retain a smooth tooth surface after initial grinding or during normal wear; however, another development, the use of specific coupling agents to promote adhesion between PMMA and fillers and to the tooth, was found very promising. These developments and the development of thermosetting aromatic acrylates are described in refs. 215 and 216.

The results of these investigations into inorganic fillers combined with specific coupling agents and improved acrylic resins are materials now produced by several pharmaceutical organizations (ref. 217). These materials are considerably improved over the original amalgams, silicates, and acrylic formulations. The new formulations have better aesthetics than the older materials, are not so critical in mixing, and have better marginal adaptation. The physical properties are as good as those of the older amalgams without the possibility of mercury contamination. The major disadvantage of these resin-composites is the somewhat poor wear resistance shown by the materials when tested in vivo. (Laboratory tests indicate that they have wear resistance as good as or better than amalgams or silicates.) It is then theorized that the combination of saliva, moisture, and the tooth grinding action all combine to cause the excessive wear. Improvements in the filler system used with the resins may improve the wear resistance of these materials. The materials suggested are the types being developed at NASA Lewis Research Center and by NASA subcontractors for use in turbine blades and nozzle throats; these materials include various types of carbides and oxides of such materials as zirconium, aluminum, and thorium (refs. 50, 211). Their known hardness and inertness should make them attractive candidates for this application.

Dental Implants

Dental implants are used as supports for dentures in cases in which normal healthy gum and bone are not available. Titanium, tantalum, and Vitallium, all of which have disadvantages, are presently used for this purpose.

One promising raw material to replace metal, according to von Fraunhofer, is vitreous carbon (ref. 218). This material, being pure carbon, is completely noncorrosive and thus is highly resistant to oral and tissue fluids. It contains no additives, plasticizers, and/or stabilizers, such as those found in polymers, which can be leached out with effects similar to the release of ions by corrosion of metals. Work is now being done on inclusion of carbon fibers in the vitreous matrix to increase the impact strength (ref. 219). Another possible technique for reinforcing the vitreous carbon might be the inclusion of zirconium or zirconium oxide as reported by Blankenship of NASA Lewis Research Center (ref. 211).

SAFETY APPLICATIONS

Since the inception of the manned space flight program, NASA has been actively engaged, with the assistance of industry in a search for nonflammable materials for use in spacecraft. A great variety of fibers, elastomers, and composites have been developed that can now be fabricated into nonflammable end items, either used alone or in conjunction with other materials. Many of the nonflammable and fire-resistant materials and much of the supporting spacecraft technology can be used to make a significant contribution toward fire safety in industries, institutions, and the home. A limited list would include enclosures, heat and chemical shields, helmets, face masks, curtains, upholstery, clothing, bedding, fume ducts, and electric-arc shields. Spearheading the development and application of nonflammable materials has been the Manned Spacecraft Center Crew Equipment Branch under Dr. Matthew Radnofsky and the Ames Research Center under Dr. John Parker. This work has drawn national interest and assumed great significance in advancing the application of flameproof and thermal insulating man-rated materials.

Such physical considerations as durability and aesthetics become important when materials developed for short-term space use are exposed to the rigors of repeated use in competition with traditional materials. Aesthetic qualities are less easily obtained with many of the new materials which are presently receiving prime technological attention. Because many of these fibrous materials cannot be dyed and are available only in white or in varying shades of brown, work has been directed toward spraying, laminating, embossing, and printing to achieve decorative results with the new materials.

Textiles

A large number of textile materials were investigated for use on the Apollo Program. Table XXVI lists the various material designations, the base fiber, and the unique properties or characteristics of each material (ref. 220). Potential applications of flame-resistant aerospace materials are briefly listed in Table XXVII.

Several fabric materials are used in spacecraft but are not presently considered for aircraft or other commercial application. Polybenzimidazole (PBI) is an excellent fabric from almost every point of view, including nonflammability; but it is presently very expensive. Teflon fabric is nonflammable but has unsatisfactory hand and low tensile strength. Metallic fibers are expensive and lack durability. A new fabric from German Enka closely simulates cotton and is nonflammable, but it is available only in experimental quantities. Table XXVIII provides flammability test results on fiber and elastomeric materials.

TABLE XXVI. – CHARACTERISTICS OF COMPOSITES INVESTIGATED FOR THE APOLLO PROGRAM

Fiber or Fabric Designation	Base Fiber	Characteristics					Remarks	Usage
		Ten. Str. gm/denier	Elongation %	Sp. Gr.	Service Temp. °F (°C)	Thermal Conductivity BTU/ft²/°F/hr/in		
Beta	fiberglass	15	4	2.45	-390 to +900 (-184 to +482)	4.97	poor abrasion resistance	
Teflon	polytetrafluoro-ethylene	1.4	15	2.1	-400 to +500 (-240 to +260)	1.7	low tensile strength, good chemical resistance	chemically resistant coveralls
PBI	polybenzimidazole	4.5	12-1[illegible]	1.34	-65 to +800 (-54 to +427)	0.9	very expensive	harnesses, straps, tethers, nonflammable suit fabric
Asbeston	cotton fiber blended with Beta or Nomex	2.5-3.1	2-3	2.10-2.60	-200 to +2400 (-129 to +1316)	0.59	good durability	
Nomex	aromatic polyamide	5.5	17	1.35	-65 to +500 (-54 to +260)	0.9	good, general purpose heat resistant material	liner for Apollo suit

TABLE XXVII.– POTENTIAL APPLICATIONS OF FLAME-RESISTANT AEROSPACE MATERIALS (FROM REF. 220)

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

*Carboxy nitroso rubber.

TABLE XXVIII.– FLAMMABILITY TEST RESULTS ON FIBER AND ELASTOMERIC MATERIALS (from ref. 220)

Materials	Burn rate, in/sec				
	Top Ignition		Bottom Ignition		
	16.5 psia	6.2 psia	16.5 psia	[a]16.5 psia	6.2 psia
Beta	[b]NI	NI	NI	NI	NI
Teflon	SE	SE	0.55	0.30	0.30
PBI	0.20	0.16	0.41	0.35	0.30
Asbeston	[c]SE	SE	SE	SE	SE
Nomex	0.33	0.16	1.00	0.60	0.60
Viton	SE	SE	SE	SE	SE
Fluorel	SE	SE	SE	SE	SE
CNR	SE	SE	SE	SE	SE
Velcro[d]	0.02	0.01	0.50	0.37	0.35
Durette	0.41	0.31	1.00	0.55	0.41
Fypro	0.45	0.33	1.25	0.83	0.71

[a] 60-percent oxygen, 40-percent nitrogen.

[b] NI – No ignition.

[c] SE – Self-extinguishing.

[d] Astro Velcro

There are a number of elastomeric materials which can be used in conjunction with the flame resistant fibrous materials to result in flame resistant coated fabrics. These include fluorinated hydrocarbons, fluorinated silicones, and carboxy nitroso rubber (CNR). All these can be used at high temperatures up to approximately 450°F (232°C), only the fluorinated silicones are satisfactory at subzero temperatures.

Velcro Fasteners

Velcro fasteners, made from nylon, are highly flammable. A new type of fastener, Astro Velcro, is a composite that utilizes a TFE Teflon pile, Beta fibers, and polyester hooks. This fastener (Figure 56) meets Apollo flame resistance requirements. When engaged, Astro Velcro has about 1/5 the flame propagation rate of the engaged nylon Velcro. The peel strength of the Astro Velcro is equivalent to that of nylon Velcro, and approximately the same strength is maintained even after 100 cycles (ref. 220).

Fire Fighter Suits

NASA has developed and fabricated several types of fire-fighting suits and ancillary clothing using many of the new fabrics and fibers discussed previously (ref. 221). A typical example is the Proximity Firefighter suit shown in figure 57. The materials used in this suit are:

- Outer layer – aluminized Fypro fabric 8.5 oz/yd^2.
- Vapor barrier – 4 oz/yd^2 Fypro with 80-percent Fluorel elastomer by weight.

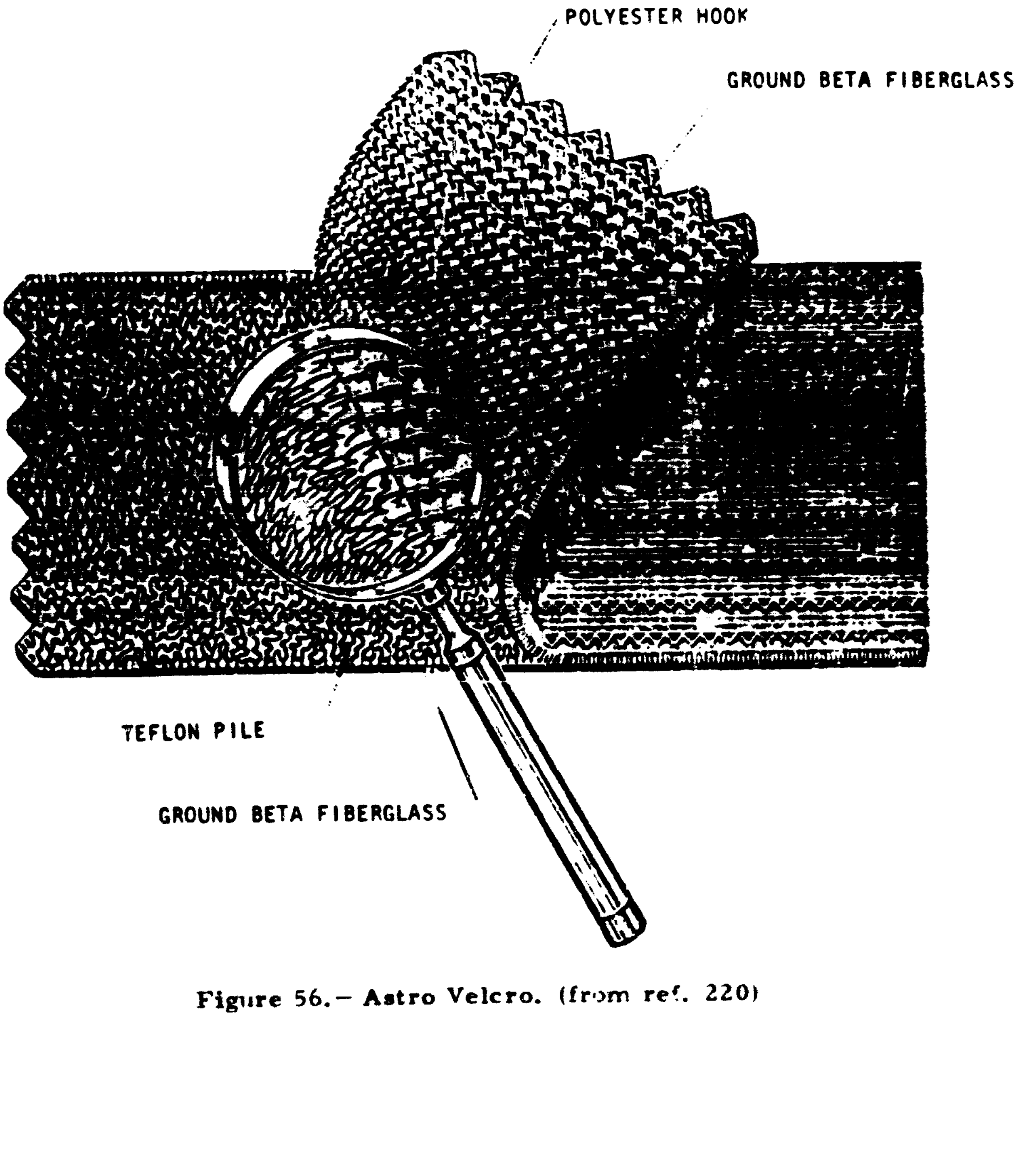


Figure 56.– Astro Velcro. (from ref. 220)

Figure 57.– NASA proximity firefighter suit.

- Insulation – [illegible] oz/yd^2 Durette batting.
- Lining – 4 oz/yd^2 Fypro fabric, continuous filament.

Layers of material are sewn together into a single layup. Construction details are shown in figure 58. Jacket and trousers weigh 5.0 pounds each (ref. 222).

This suit and several others of different design were evaluated over a 5-month period by the Houston (Texas) Fire Department on a continuing basis by firefighters during normal activities. Firemen wearing these garments attested to the functional ability of the clothing to withstand extremely high temperatures while maintaining the firemen in safety and comfort.

The advancements in technology have not been rapidly accepted so that there has been a low level of commercial developmental activity, despite the current flurry of developmental activity precipitated by NASA programs. Consequently, most of the materials mentioned here are expensive and will probably remain expensive until they are produced in volume. For example, the PBI costs approximately $200 a pound, enough for three yards of woven fabric. This material is being evaluated for clothing for Air Force pilots in Vietnam. If sufficient demand is generated to warrant large-scale production, the price would eventually go down to $10 a pound. The Fluorel elastomeric coating is available in powder form at $20 to $25 a pound. In actual use, the elastomer is blended with inexpensive additives to obtain physical properties tailored to the end use. Thus the formulation cost is considerably less than the Fluorel cost, which is also expected to move inversely with volume consumption.

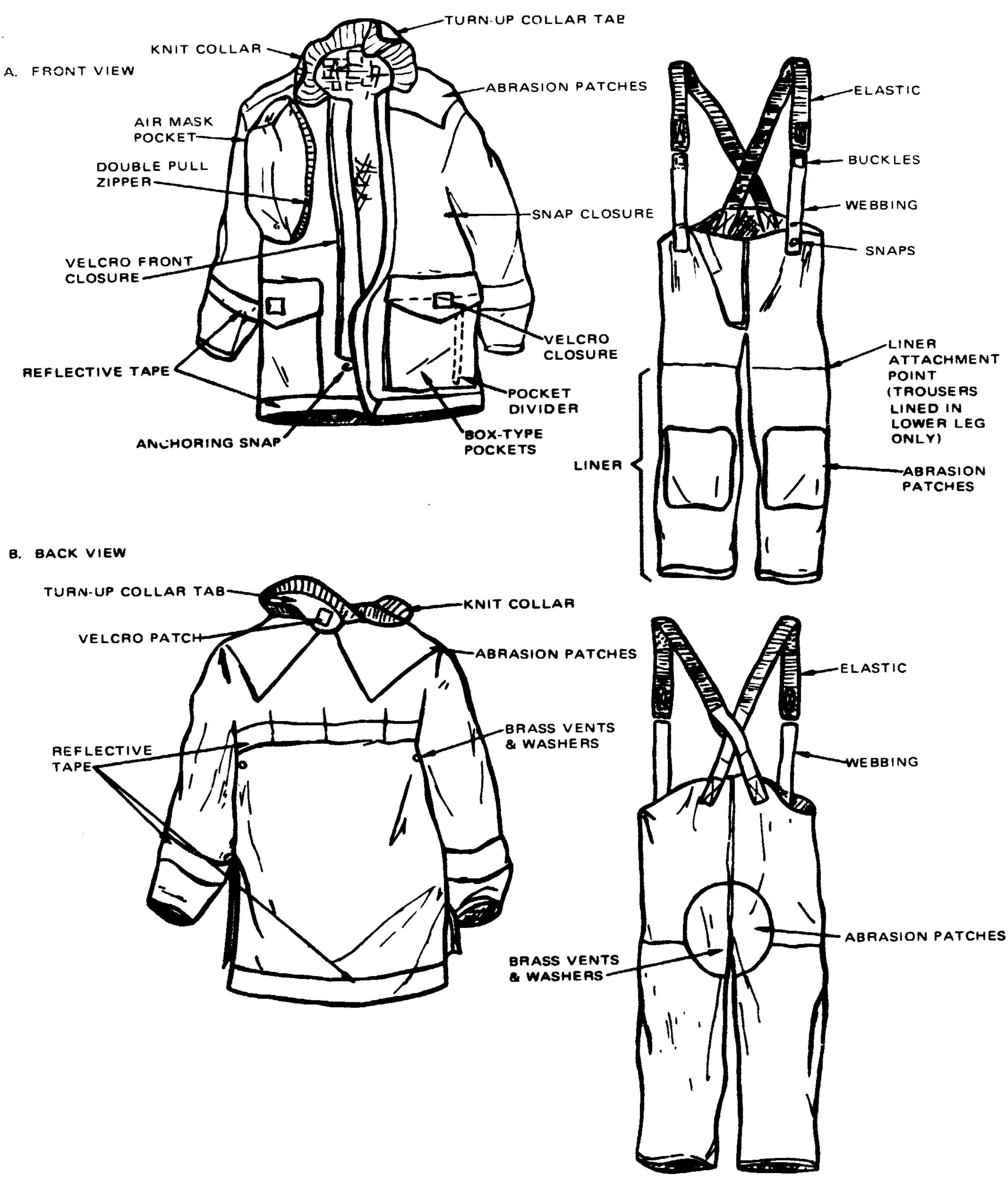


Figure 58.— Firefighters coat and trousers.

A complete tabulation and description of fibers, fabrics, and coatings is available from Dr. Radnofsky at the Manned Spacecraft Center. Material costs are changing rapidly; even so, in relation to the fire hazards in hospitals to patients alone, the costs are very likely worth it.

Helmets

Helmets are extensively used in many high-risk occupations and activities such as firefighting, racing, police work, construction, and industrial operations. The primary purpose of the helmet, the protection of the human skull from damaging impact, is accomplished by absorption of energy through several layers of various materials, each having a specific function. A typical helmet is comprised of a hard outer shell; a relatively soft, energy absorbing layer; a skull-conforming soft layer; a soft nonabrasive, absorbent liner, rim protective beading, and a chin strap. In other words, the helmet is a composite structure in which the materials are carefully selected to meet functional requirements.

Commonly used materials are shown in table XXIX. These materials are functionally acceptable in various degrees depending on the application. However, they all will burn in a normal oxygen environment. The only exception is the vinyl film, but even with such material the fabric backing will burn. Although suitable for many uses, a helmet made of flammable and low-heat-resistant materials would not be suitable for fire fighting or other high-risk occupations.

Since the disastrous Apollo space-capsule fire in 1967, NASA has accelerated its search for fireproof and heat-resistant materials. As pointed cut in the

TABLE XXIX.– HELMET MATERIALS

Construction Detail	Conventional Material	Substitute Fireproof Material
Hard shell	Polycarbonate or Fiberglass/Polyester	Fiberglass/Polyimide*
Energy absorbing layer	Polyethylene foam or styrene bead foam	Ames Research Center urethane or isocyanurate foam
Conforming layer	Polyurethane	No change
Soft absorbent liner	Knitted nylon fabric	Knitted modified aromatic polyamide fiber**
Rim beading	Cotton backed, wire reinforced, vinyl film	Modified aromatic polyamide** backed, wire reinforced, vinyl fiber
Chin strap	Woven nylon netting	Woven untreated polybenzimidazole (PBI) fiber

*Pyralin Pl-2501, Dupont Co.

**Fypro or Durette (X-400), see table XXVIII.

discussion of firefighter suits, many of the new materials adopted by NASA have a potential for commercial safety applications in which fireproofing is a necessity. Another such application is the fire fighter's helmet shown in figure 59. The composite shell was fabricated by North American Rockwell Company, Downey, California, of polyimide/fiberglass, and the helmet was assembled by the American Sports Co., Inc., Compton, California, under contract to NASA Manned Spacecraft Center.

Possible substitute materials for the NASA helmet are also given in table XXIX. Not all of these materials has been tested for the helmet application, but they are reported here as reasonable concepts. Details

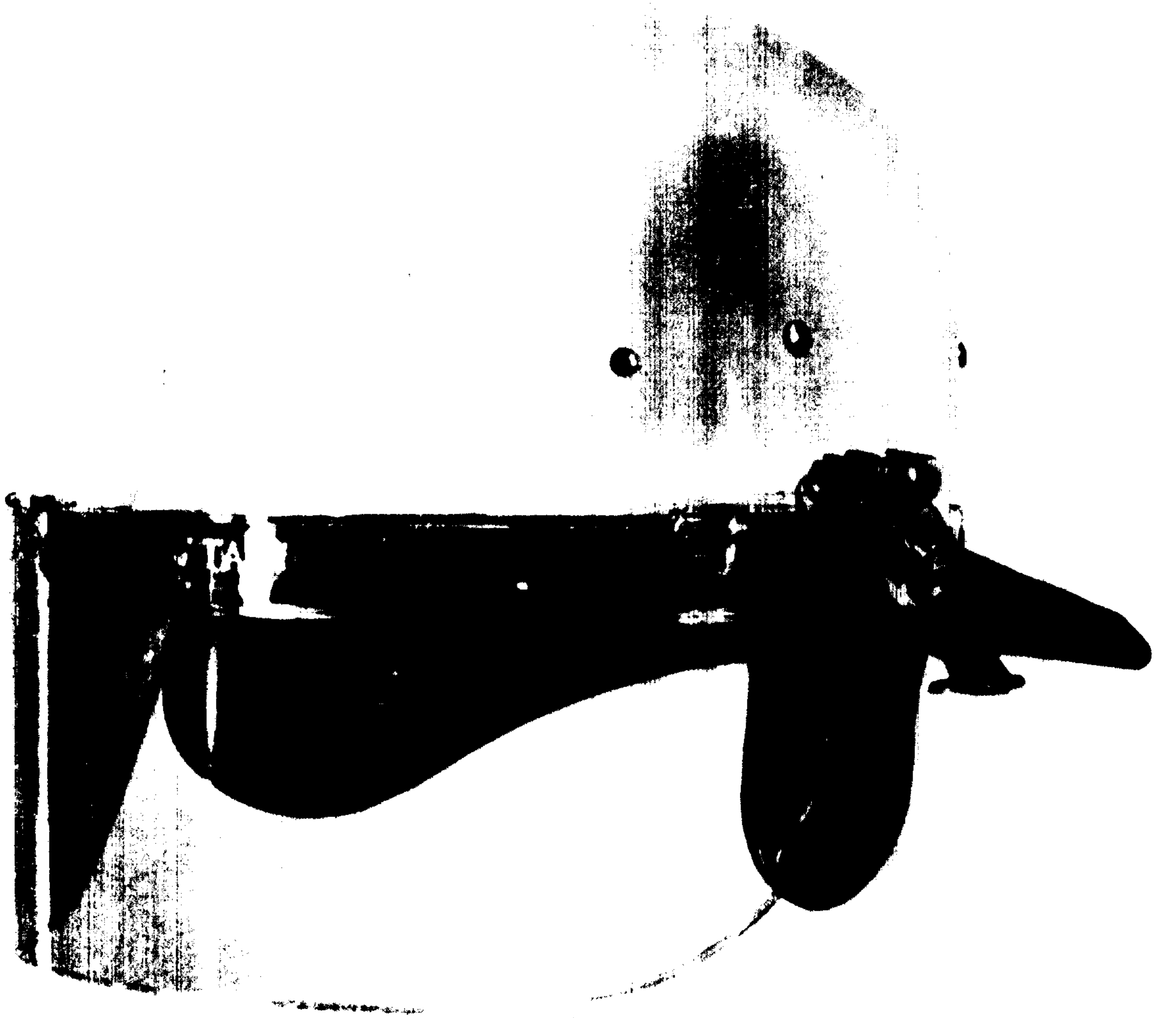


Figure 59.– Firefighters helmet with face shield.
(Courtesy of American Sports Company, Inc.)

of the suggested fabrics are contained in ref. 208. Flame-resistant properties of foam are given in ref. 221, and the properties of composite plastic shells are given in ref. 223.

Applications of Composites in Power Generation and Distribution

The world demand for electric power is increasing by about 7 percent a year, which corresponds to a doubling every 10 years (ref. 224). In the United States the annual use rate is 0.5 billion kilowatts, and this figure is expected to grow to 5 billion kilowatts by the year 2000. Present sources of power are the fossil fuels (oil, gas, and coal) and water (only 2 percent of total). Estimates of fossil fuel reserves indicate that by the year 2050 the demand for power will exceed the supply of fossil fuel.

One answer is to seek alternative sources of energy, such as nuclear, solar, tidal, geothermal, and magnetohydrodynamics (MHD). In general, most of these sources require either large scale for efficiency or remote locations for safety. These requirements in turn create the need for transmitting large amounts of power over long distances. Figure 60 shows an estimate of future transmission voltage over the next 30 years (ref. 224).

A variety of proposals has been presented as solutions to the projected world energy crisis. However, none has been universally accepted. It is beyond the scope of this chapter to detail these approaches; where appropriate, they will be noted as potential end use sites for advanced composite materials. Present and potential applications of composites are discussed in relation to generation and distribution of electrical energy.

GENERATION OF ELECTRICAL ENERGY

As previously noted, a majority of today's electrical energy results from the conversion of thermal into electrical energy by some type of turbine/

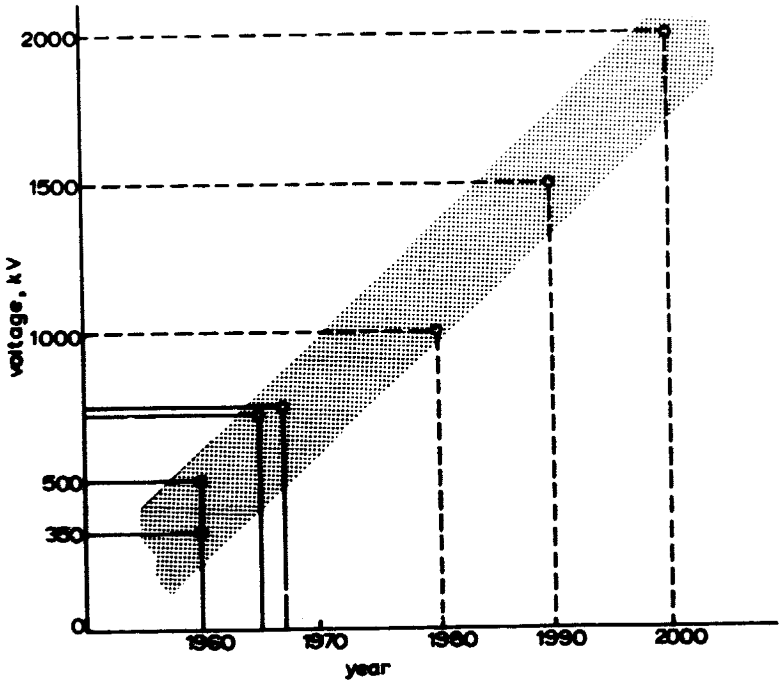


Figure 60.— Estimated increase of AC transmission voltages over the next 30 years. (from ref. 224)

generator system. The turbine may be either steam or gas, and the generator, a.c. or d.c. Alternative sources of thermal energy include nuclear reactors, solar, and geothermal-energy.

Regardless of the source, the ultimate effectivity depends on the thermal efficiency of the system. In general, the higher the operating temperature of the system, the greater the achievable efficiency. Increases in the operational temperature then impose greater demands on the individual elements of the system, i.e., boiler, boiler tubes, buckets, blades, heat exchangers, pressure vessels, bearings, seals, and insulation. It is in these areas that advanced composites will have a significant impact.

Work performed by NASA or NASA-sponsored contractors in the development of gas turbines and jet engines is discussed in Chapter 10. It is likely that many of these data and much of the technology will be directly applicable to lighter weight turbines that operate at higher temperatures with greater efficiency. Similarly, NASA work on composite materials suitable for high temperature seals and bearings (see Chapter 10) will contribute to both turbine and generator effectivity.

Work done by NASA in the stainless steel cladding of metals could result in longer lived boilers, boiler tubes, and other corrosion sensitive elements (ref. 80). At higher pressures, NASA work on glass-fiber overwrapped metal tanks may result in a simplified technique for upgrading existing facilities (ref. 225). Such tanks utilize the maximum load-bearing capabilities of both the metal liner and the filament shell and are significantly lighter in weight than the highest performance, cylindrical and spherical, homogeneous metal tanks.

In the general areas of structural elements of turbines, generators, and transmission support structures, composites such as boron/aluminum and graphite/polyimide can increase the performance of rotary equipment via cascade effects. Some of the new NASA structural concepts and developments are covered in detail in Chapter 10 and can also be readily applied where weight and portability are factors.

When nuclear reactors or MHD generators are considered, even higher temperatures are realized. Here the need for thermally stable materials to serve as structural or insulating elements becomes critical. NASA work in both areas has produced metal, ceramic, and graphite composites which could speed the realization of these power sources (ref. 226).

In the generator itself, two new approaches are worth noting: (1) greater efficiency via an increase in the windings/insulation ratio and (2) the use of cryogenically cooled generators.

The first approach will benefit from NASA work on more efficient electrical insulators such as pyrrone and polyimide wire coatings with high service temperature capabilities (refs. 84, 108).

The second approach, while still developmental, offers a quantum jump in power generation technology (ref. 227). The key to its success is the superconductive state realized in certain materials when they are cooled to -452°F (8°F above absolute zero). Present generators are limited to outputs of about 1500 megawatts (~1/2 the peak power consumption of Manhattan). By way of comparison, it is estimated that a cryogenic generator capable of producing 10,000 megawatts is practical.

DISTRIBUTION OF ELECTRON ENERGY

Figure 60 illustrates the projected increase in AC voltages over the next 30 years. This increase will impose severe requirements on the materials utilized in the transmission of electricity. The problems become even more critical when the public attitude toward standard overhead lines is considered. The alternative of employing underground cables (i.e., buried transmission lines) further complicates the system requirements.

It is generally accepted that a solution to these problems lies in the use of superconductive cables. Figure 61 illustrates a proposed system.

Cryogenic transmission is attractive from a cost standpoint because of the very low energy loss levels. In fact, in comparing cryogenic lines and standard lines, one analysis reports lower capital and operational costs for the superconductive line (ref. 228).

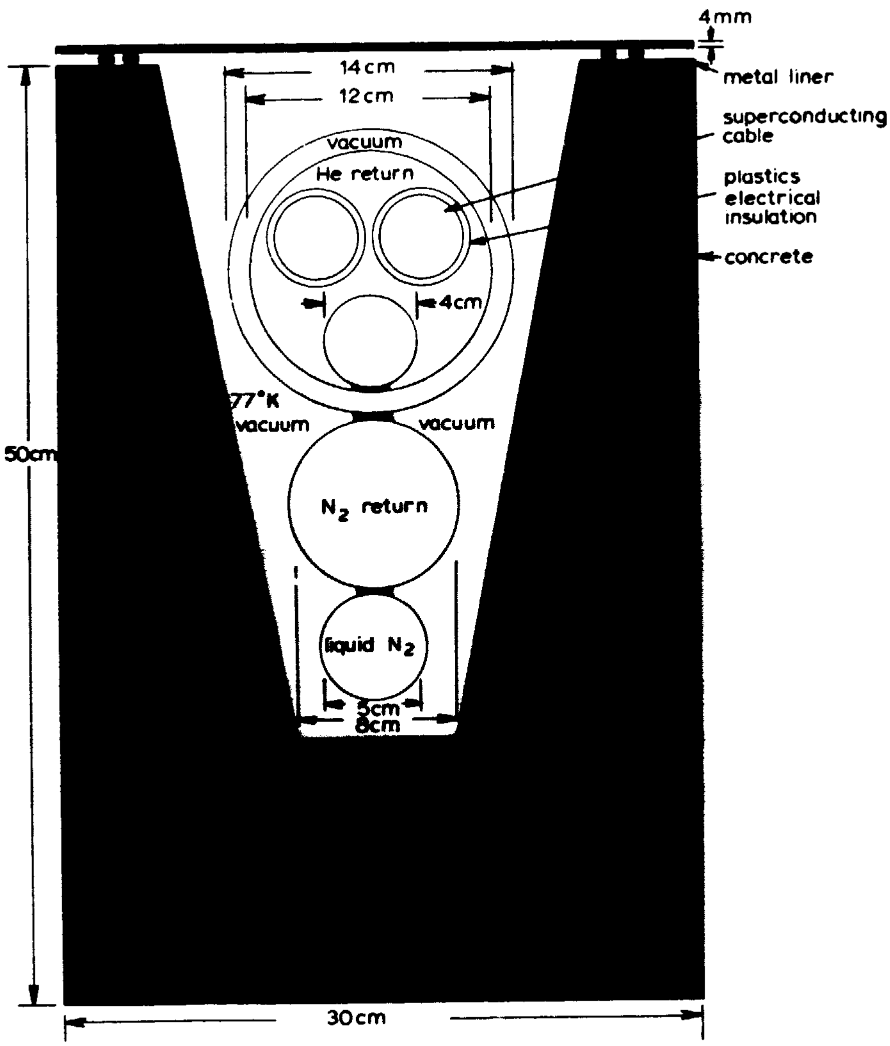


Figure 61. — Cross-section of a proposed superconducting cable. (from ref. 224)

Another benefit of cryogenic transmission is the degree of compactness that can be achieved. Figure 62 illustrates this factor by comparing the conductor cross sectional areas necessary to carry 1500 amperes of current (ref. 229).

The distance between towers in conventional transmission lines is limited by the strength of the conductors. The span between towers may be increased by the use of higher strength tungsten fiber-reinforced copper developed by NASA (ref. 155). Such an increased span could result in a reduction in the cost of

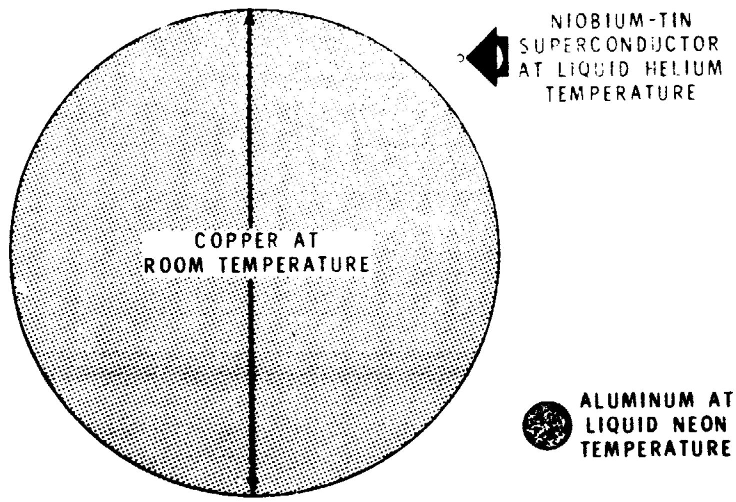


Figure 62.— Comparison of conductor areas required to carry 1500 amperes. (from ref. 229)

establishing and maintaining a high voltage transmission line. Although the resistivity of the tungsten reinforced copper is three times that of pure copper, it is 12 times as strong. In fact, on the basis of the ratio of ultimate strength to resistivity, tungsten/copper is easily the best choice (see figure 63).

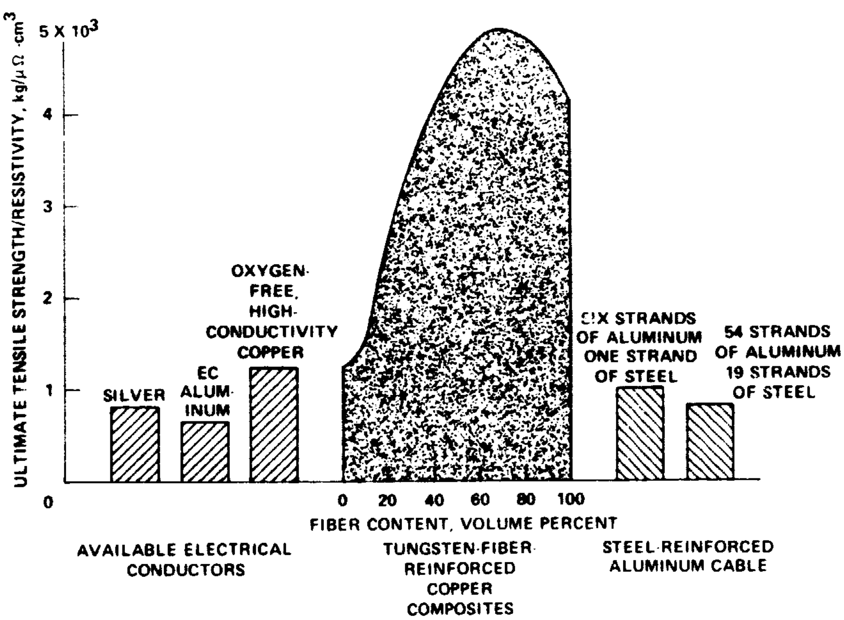


Figure 63.— Comparison of ratio of ultimate tensile strength to resistivity for tungsten-fiber-reinforced copper composites with other electrical conductors. (from ref. 155)

A similar approach might be taken based on the work by NASA in support of graphite fiber-reinforced aluminum (ref. 40).

Application of Composites in Transportation

Transportation is an industry that directly affects everyone. Last year, Americans spent over 200 billion dollars moving people and goods, a figure equivalent to the gross national product of Japan (ref. 230). Approximately 55 percent was allocated solely for the moving of people. Road transportation alone accounts for 83 percent of all monies spent in the movement of both people and goods. However, on a ton-mile basis, the distribution of intercity freight shows that railroads carry 40 percent; trucks, 21 percent; pipelines, 22 percent; canals, 10 percent; and Great Lakes shipping, 6 percent.

In an industry that places emphasis on efficiency and public acceptance, it is likely that the application of new material technologies may have a significant impact. The current use level of glass-reinforced plastics as weight saving elements in automobile and truck manufacturing is about 207 million pounds a year (ref. 231). This level of usage has generally been achieved by its simple substitution for steel or aluminum. More dramatic performance gains can be projected when these composites, and more advanced ones, are introduced at the conceptual design stage.

One of the major hindrances to the widespread application of composites is their initially high price. These materials, however, can be most cost effective in mass production. For example, a study of the structural materials utilized in aircraft showed that the use of composites could facilitate mass production and, therefore, reduce the overall fabrication cost of the aircraft (ref. 232). It was further shown that both injection and compression-molded glass-reinforced plastic vertical stabilizers could be manufactured at a lower cost than conventional sheet metal units, even at current production levels. Table XXX details the results of the study.

TABLE XXX.- COMPARISON OF MANUFACTURING COSTS OF COMPOSITES AND CONVENTIONAL METAL STABILIZERS

Manufacturing Technique	Current Quantities (1000/yr)	High Production Quantities (100,000/yr)	Production Break-even Point with Sheet Metal (units/yr)
Sheet metal	$110	$34	*
Compression-molded	88	28	620
Injection-molded	61	13	360

The potential of advanced composite materials for application to the transportation industry is reviewed in this chapter, and some current and future applications within this industry are presented. Because weight reduction and safety impact on all modes of transportation, they are dealt with as separate subsections within the chapter. The remainder of the text is divided into discussions of specific transportation modes, with comments as to the applicability and impact of advanced composite materials on each type.

WEIGHT REDUCTION

Payload is the measure of a system's effectiveness, especially in freight transport. Any material system that can reduce the dea weight or increase the available carrier capacity may prove cost effective. This relation is particularly true for aircraft, as evidenced by the volume of work performed in making lighter weight structural and propulsion elements. Weight reduction is also important when the performance of rail systems is considered; decreased inertia results in reduced power needs and increased acceleration capabilities, both of which are factors in high-speed, high-frequency transit systems.

Similarly, marine shipping and motor freight may be willing to pay for increased payload and speed. Pipelines, while not directly weight sensitive, may benefit during initial construction and may gain portability from the reduced weight of individual elements.

A considerable volume of information now exists on advanced composite structures that offer reduced weight. For service temperatures below 392 to 482°F (200 to 250°C), emphasis has, in general, been on the polymeric matrix filamentary composites: graphite, S-glass, and wires. In some cases, extensive studies have been made to detail the effectivity and impact of composites on the total system (refs. 158, 232, 233).

One area of recent activity and interest has been the selective reinforcement of metal structures with filamentary composites (refs. 18, 20, 158). These hybrids provide improved properties at lower weights than do all-metal structures. There are two advantages to the hybrid structures:

1. They build directly on the large existing background of fabrication technology for structures; this factor should lead to rapid development of this concept in the industry.
2. They allow the use of joints in the all-metal portion and retain the filamentary composites for uniaxial loading, in which they are most efficient.

As described in Chapter 2, a novel modification of the hybrid approach employs the use of hollow structural sections which are subsequently infiltrated with boron-epoxy (ref. 234). The resultant structures are found to be superior to all-metal counterparts and a weight savings of up to 25 percent is possible. Figure 64 shows a typical beam element with boron-epoxy located within the extruded element (ref. 21). Other elements are illustrated in Chapter 2.

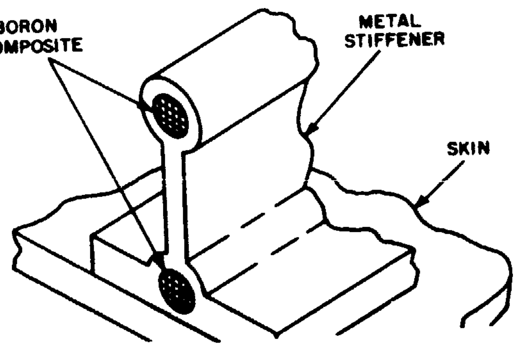


Figure 64. – Typical beam element
(Reprinted by permission of the Society of Aerospace Material and Process Engineers.)

For service usage at temperatures higher than 482°F (250°C), work has centered on either metal matrices or thermally stable polymer matrices. Of the metal matrix systems, boron/aluminum has achieved the highest level of maturity; graphite, however, gives promise of resulting in even more efficient structural elements (ref. 40).

An interesting application of boron-aluminum to a structural component is the fabrication of a propeller, in which the composite is utilized for the retention and spar in the blade. It is expected that this application could result in a large savings in aircraft weight, since the weight of the blade determines the size requirements of power elements and associated structures. Figure 65 shows the configuration of such a blade (ref. 27).

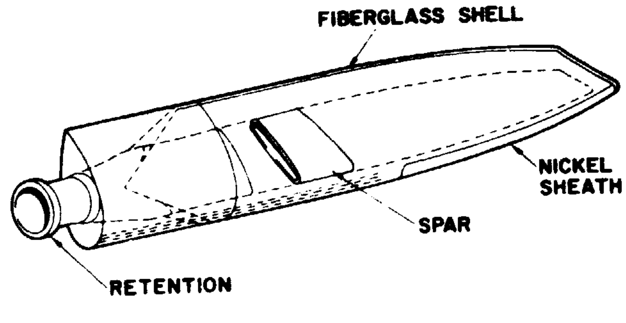


Figure 65. –Spar/shell aircraft propeller blade. (from ref. 27)

An area of particular interest for the metal matrix composites is the propulsion elements of aircraft and air cushion vehicles. Typically, these vehicles utilize some kind of gas turbine for their motive power. Fan blades of reduced weight that can withstand elevated temperatures can, via cascade effects, result in significant gains in payload, thrust per unit weight, and/or range of operation. Work on hollow boron/aluminum third-stage blades, beryllium wire-reinforced titanium blades, unidirectionally solidified nickel alloy blades, and tungsten-rhenium wire-reinforced columbium blades has been reported (ref. 175). A process has recently been described for producing beryllium wire-reinforced aluminum by wet winding in a slurry of aluminum powder in organic binders; the clean burning binders are later burned off and the composite is fabricated by compaction at elevated temperature (ref. 175).

An alternative to the metal matrices for higher temperature composites is offered by thermally stable polymeric matrices, such as polyimide and pyrrone resins. The development of pyrrone laminates and graphite-reinforced polyimides has been reported as well as the exploration of new addition cured polyimides that may be processed by autoclave techniques (ref. 175, 235). These parts can now be produced without the voids normally associated with condensation cured high-temperature resins.

Pyrrone laminates can be used in the production of high-temperature, stiff, lightweight structural panels with foam cores (ref. 236). Similar panels may also be realized by the use of honeycomb cores composed of high-temperature resins and reinforcements. Typical of such an approach are graphite/polyimide honeycomb panels (ref. 141). At higher temperatures, the organic foam element in a structural sandwich is replaced with a metallic honeycomb. Work in this area has resulted in techniques for fabricating a beryllium honeycomb sandwich with four times the stiffness of a comparable aluminum structure (ref. 237). Such honeycomb structures can readily be applied to intake and exhaust structures of gas turbine and jet engine units. An additional benefit, may be realized in reduced noise levels due to the damping characteristics of advanced composite structures (ref. 238).

Other NASA-sponsored work has centered on the evolution of new structural concepts. One example of this approach is the work performed in the application of a new fiber weaving technology (Omniweave ®). This process, detailed in Chapter 2, lends itself to the direct weaving of reinforcement fibers into complex shapes such as I-beams, struts, trusses, and integrally ribbed structural shells (ref. 30).

In another structural concept evaluation, an investigation was made of the fabrication of pre-stressed rotor blades by overwrapping stainless steel spars with fiberglass at cryogenic temperatures. The result is, at room temperature, a part preloaded into compression, which offsets the centrifugal tensile stresses met during operation. This lightweight fail-safe design is applicable to any column structure functioning in axial tension, for example, automobile, truck, and rail body frames (ref. 181).

The Advanced Technology Transport Study tentatively identified the reduction in weight and direct operating costs associated with various levels of composite utilization in aircraft. Table XXXI details these results (ref. 239).

In the area of motor transport, a significant possibility for weight reduction exists in the development of advanced composites of graphite/epoxy and S-glass epoxy. As the requirements for crash-survivable vehicles increase, it becomes more difficult to keep vehicle weight within reasonable limits. The advanced composites may provide the weight reduction necessary. Additionally, these

TABLE XXXI.– LEVELS OF COMPOSITE UTILIZATION WITH COST AND WEIGHT ADVANTAGES

Technology Level	Definition	Weight Reduction (%)	Reduction in Direct Operating Costs (%)	Year Available
1	a) Uniaxial reinforced primary structures boron/epoxy b) Secondary structural panels (PRD-49) c) Secondary control surfaces (graphite/epoxy	-5.7	-1.3	1979
2	a) Add multi-directional reinforcement (boron/epoxy) b) All control surfaces (graphite/epoxy)	-8.6	-2.5	1981
3	a) Add capability for all composite b) Primary structural application (graphite/epoxy)	-19.7	-5.5	1985

TABLE XXXII.– TYPICAL WEIGHT REDUCTIONS OBTAINED WITH COMPOSITES

Composite Material	Application	Advantages
Graphite-reinforced epoxy	Landing gear doors	52 percent reduction in weight compared with standard titanium product (ref. 240).
Boron-aluminum hat elements	Stiffening of titanium panels	25 percent weight reduction and increase in cost effectiveness compared with all-titanium structure (ref. 241).
S-glass and boron-epoxy	Uniaxial, filament-reinforced tubular structures	25 to 50 percent reduction in weight with overall better performance compared with aluminum-tubes (ref. 16).
Boron/epoxy filaments	Reinforcement for aluminum and titanium structures, such as metal fuselage frames	20 percent weight savings. Could be used in commercial aircraft, truck and auto frames, high speed ground vehicles, boat masts (ref. 242).

materials may be engineered to control the regions of failure in order to provide maximum energy absorption and occupant survival.

In summary, a large volume of advanced composite materials data, both design and conceptual, has been developed by NASA or NASA-sponsored contractors that can be directly applied to structural weight reduction within the transportation industry. The payoffs can be realized in payload, range of operation, reduced inertia, and power requirements, all critical factors in efficiency of the overall system. Typical application and weight savings realizable are shown in table XXXII.

SAFETY

The area of safety has now become a real and justified concern of the public as discussed in detail in Chapter 8. The work reported below is based on efforts at reducing the hazards of fires associated with aircraft, but the general principles and materials can be readily applied to auto, truck, rail and marine vehicles.

A number of studies has been made to identify materials of aircraft construction that present a hazard either as flammable materials or as generators of smoke and/or toxic gases during heating (refs. 96, 103, 104, 243). The results of these efforts are a number of composite systems that provide increased survival during a crash or accident-induced fire. Specific examples are a fire-resistant wool which can be dyed and used wherever natural wool is applicable; fluorocarbon elastomers for decorative paneling and leather-like upholstery; and polyurethane seats (cost $3/seat). Polyurethane foams have also been modified to provide increased char and reduced flammability and evolution of toxic gas. Other high-temperature nonflammable foams have been developed for use as fire-resistant firewalls (ref. 109). In one effort NASA is completely refurbishing a Gulfstream aircraft to demonstrate the commercial application of nonflammable materials. These include curtains, rugs, upholstery, and decorative paneling, all color keyed to the aircraft decor (ref. 244).

In a more dramatic example of the impact of thermal isolation and of fireproofing on the safety of aircraft, NASA conducted a controlled-fuel fire crash of the central fuselage of a C-47 airplane. A 13-foot section of the fuselage was fire-proofed. Details of the fire protective materials are shown in

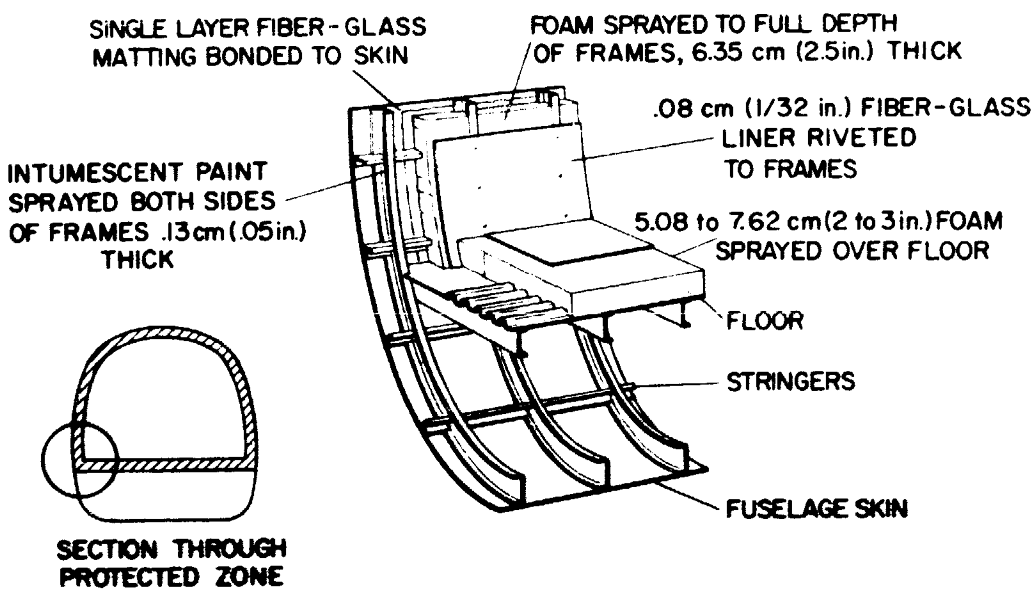


Figure 66.— Installation details of fire-protective materials. (from ref. 245)

figure 66, which shows the placement of the intumescent coating and polyurethane foam. An unprotected 13-foot section was included for reference. The fire was started externally to the test sections since 85 percent of aircraft fires are due to external causes (ref. 245). Figure 67 illustrates the rate of temperature rise in the two sections exposed to the fuel fire. It can be seen that the protected section provided a considerable increase in the time available for escape or rescue. It should also be noted that no evidence of toxic gas build up was noted in the protected section of the fuselage (ref. 107).

The weight penalty associated with the composite materials utilized in the test was estimated to be 0.3 lb/ft^2 of protected area. This estimate represents an increase of 1700 pounds for a 400,000-pound aircraft, which may be reduced to zero if the materials are integrated into the structural design at the conceptual level.

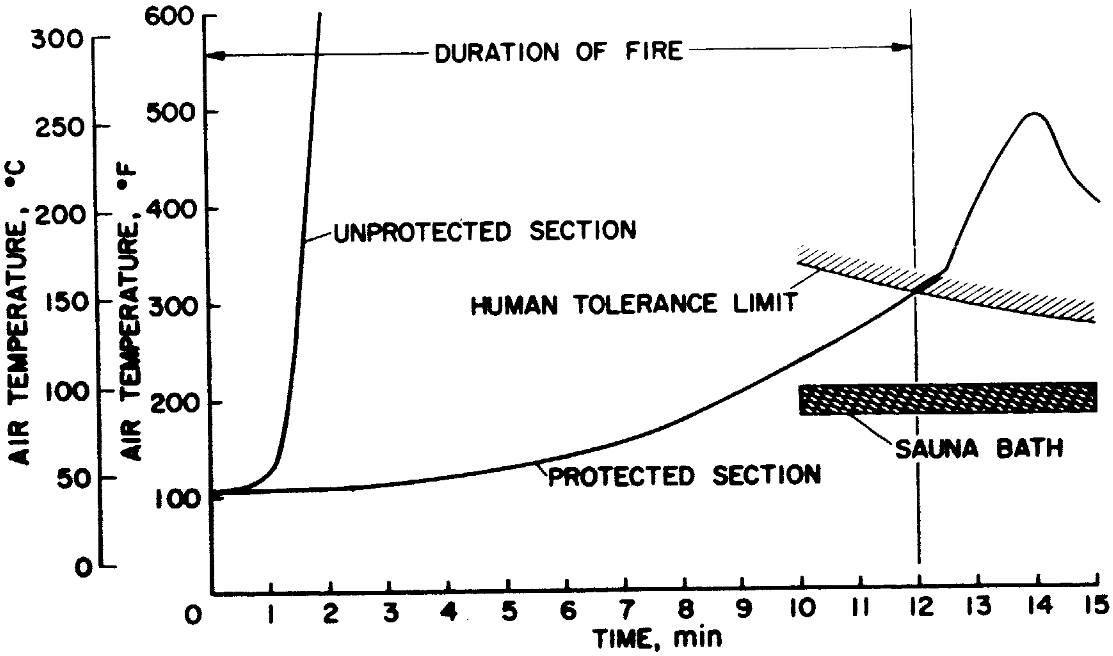


Figure 67.– Cabin air temperature during fire. (from ref. 245)

Ancillary equipment also plays a role in safety, and NASA has contributed to the development of fireproof suits (see Chapter 8) and fireproof inflatable escape slides for aircraft (ref. 246).

SPECIFIC MODES OF TRANSPORTATION

In the following sections the specific applicability of advanced composites is related to the various modes of transport. Since potential weight reduction is discussed separately, specific elements of construction that may result in reduced weight are emphasized only where they also contribute directly to operational efficiency in some other significant manner.

Aircraft

Aircraft transportation includes conventional (CTOL), short (STOL), and vertical (VTOL) takeoff designs. It is generally agreed that V/STOL aircraft offer the greatest potential area for composite applications, principally because of the need for higher power values as take-off length is reduced. Either the dead weight of the aircraft must be reduced or engines of higher specific thrust must be provided. The application of composites to gas turbines and jet engines has been discussed. Other possible areas of applications are discussed here. It has been estimated that technological advances in structures and engines (primarily through the application of composite materials) and aerodynamics will combine to allow 50 percent more payload, to be carried about 1/3 faster, while reducing hover noise by 10 percent. Additionally, the operating costs will drop by about 30 to 50 percent.

NASA is investigating the feasibility of utilizing a continuous, uniaxial composite material (graphite/epoxy) in the fabrication of a helicopter rotor. The composite material will be applied from tip to tip, across the rotor hub to provide low torsional stiffness and thereby allow torsional articulation across the inboard region of the blade. The articulation achieved by elastic deformation will eliminate the need for blade articulation bearings; this concept not only reduces weight and increases rotor efficiency, but it also results in reduced mechanical complexity and maintenance. Currently, a 4-foot diameter rotor is undergoing wind tunnel and fatigue testing (ref. 181).

Boron/epoxy reinforced aluminum stringers are being investigated for the CH-54B Helicopter tail cone. It was determined that fabrication, field inspection, and fatigue life of the proposed system were equal to, or better than, an all-aluminum structure. Additionally, for equal strength, the composite-reinforced tail cone is 30 percent lighter than the current aluminum production item (ref. 247).

In industry, study of the impact of composites on the Heavy Lift Helicopter (payload = 22.5 tons), indicated that ten to fifteen thousand pounds could be saved if advanced filamentary composites comprised 53 percent of the primary and secondary structural weight. The rotor blades were also studied, and it was estimated that the use of graphite/epoxy composites, with an inner SPAR of glass/epoxy, would result in reduced droop. A reduction in the height of the rotor system could be effected, which would reduce the strain on vibrating parts. An additional benefit would be a rotor blade weight reduction of 20 percent. Other areas under study include fuselage and landing gear assemblies. Overall, a 26-percent reduction in maintenance cost is projected as a result of advanced composite applications. The reduction is due to increased fatigue resistance and fracture toughness, coupled with ease of repair (ref. 248).

Composites also offer another advantage in the construction of rotor blades: they can be readily fabricated into complex geometric parts with minimal machining and scrap. Many conceptual designs can be realized that were impractical or impossible to achieve in an all-metal part. For example, it has been demonstrated that rotor blade efficiency could be increased substantially if the cross-sectional geometry of the blade would be varied from hub to tip. This type of design is an ideal application for graphite/epoxy or boron/epoxy composites, which can be molded into almost any desired shape.

Another industry study of the aluminum X-22A V/STOL projects a 100-percent increase in payload through the use of graphite/epoxy composites, which provide an overall empty weight reduction of 30 percent (ref. 249).

In two CTOL applications, advanced composites are finding ready acceptance for high-temperature brakes and graphite/epoxy floor panels. Research has been conducted into the thermophysical characterization of advanced graphite composite materials during transient heating and also into the development of oxidation resistant carbonaceous materials (refs. 250, 251). Both may have a direct impact on the use of reinforced-carbon aircraft brakes. Brakes using discs of carbon/carbon composite material are lighter and operate more smoothly than conventional brakes. They can also provide a 100 percent increase in service life and operate at temperatures [>1800°F (982°C)] beyond the limits of conventional aircraft brakes (ref. 252). It is likely that such materials may also find acceptance as both brakes and clutch components in high-speed motor and rail transport systems.

The use of a graphite/epoxy composite as aircraft floor panels has found limited acceptance, despite their initially higher cost. It has been demonstrated that graphite/epoxy floor panels can be cost effective compared with aluminum/balsa paneling. As a result, graphite/epoxy composite floor panels have been retro-fitted into some of the 747, 707, VC-10, and Trident commercial jet aircraft (ref. 8).

NASA has also sponsored work in the development of fiber over-wrapped high-pressure metal pressure bottles. It was demonstrated that significant weight reductions and increased performance could be realized by over-wrapping metal pressure bottles with S-glass or PRD-49. As a result, the environmental control and life support systems in commercial aircraft could be upgraded, with an overall reduction in dead weight (ref. 45).

External components may benefit from the reduced weight, increased stiffness, and vibrational damping characteristics of composites. Candidates include cases, nacelles, ducts, brackets, housings, and tubes. Composites of the particulate and laminate variety offer potential gains in the construction, fabrication, and operation of aircraft engines. The use of high-temperature bearings and seals can directly benefit from the work on composite materials or components. Work on oxidation resistant carbonaceous materials, high-temperature polymers, and high-strength self-lubricating bearing surfaces are all examples of composite materials applicable to gas tubine and jet engine bearing and seal problems (refs. 83, 164, 251, 253).

Self-lubricating gears and journals have been developed by bonding reinforced Teflon to metal. Reinforced FEP Teflon composite material is bonded to a metal substrate by applying a thin layer of copper on the metal surface, disposing irregularly shaped copper particles on the coated surface, assembling the reinforced Teflon in contact with the particles and heating under pressure at a temperature below the melting point of the Teflon. A diffusion bond stronger than the reinforced Teflon component is produced, thus enabling the fabrication of self-lubricating bodies having high strength (ref. 82).

Rail Transport

The railroads in America are suffering a profit loss due to a lack of technological ingenuity and public acceptance. Public acceptance is unlikely to change with regard to longer trips, but public attitudes toward inner city and intermediate intercity rail transport could benefit from some new concepts. Some obvious elements necessary for an upturn in or reversal of the present trend include speed, safety, comfort, frequency of service, and reasonable cost (achievable through automation). Rail transport is used here to include subways, commuter lines, and monorails and the newer concepts of tracked air cushion vehicles (TACV) and magnetically levitated vehicles (MAGLEV). As the speed increases, the penalty associated with dead weight becomes more severe; increased power requirements reduce acceleration capability, and more complex and softer suspensions are required for passenger comfort. It is therefore a valid goal to seek weight reductions in the structural elements, particularly in the case of air and magnetically supported vehicles which are very weight sensitive.

Composite materials can be specifically designed to take full advantage of their inherent strength, stiffness, and energy absorption characteristics. These can provide significant contributions when the high levels of shock and vibration anticipated in higher speed vehicles are considered.

The electric motors that power most current rail transit vehicles are limited in size, and therefore power, by the side clearances associated with standard rail gauge track. An increase in the power available might be realized via the use of more efficient, higher temperature electrical insulation. Several candidate materials such as pyrrone and polyimide resins have been produced in this area (refs. 82, 236).

Materials such as boron/epoxy, graphite/epoxy, and S-glass/epoxy may find use as face sheets or honeycomb core structural panels. In turn, the core may be a foam or other material specifically selected to provide efficient absorption or blocking of both thermal and noise penetration. NASA has supported efforts at effectively controlling both of these phenomena (refs. 64, 76, 159, 238, 254). An efficient thermal acoustical insulation system could also pay dividends in reduced costs associated with heating and airconditioning of the vehicle.

MAGLEV vehicles require the use of stored liquid helium on board to cool their superconducting magnets. Cryogenic insulation may, therefore, become a critical factor in the realization of the MAGLEV type of vehicle. A series of approaches has been developed for containing liquified gases utilizing foams, multilayered insulation, and reinforced foams (refs. 64, 65, 71, 72, 109, 159, 255). Additionally, the storage of cryogenic fluids may be facilitated by the work on stainless steel-clad titanium (ref. 80).

At the high speeds anticipated (up to 350 mph at atmospheric pressure), it is likely that the uniform surface provided by composites can prove advantageous in reducing the drag due to air friction. Additionally, the lower thermal expansion characteristics of graphite/epoxy composites may prove useful in reducing the gapping or spacing requirements between elements of vehicle construction (ref. 256). The degree of sophistication associated with the TACV suspension may also be affected by the low thermal expansion characteristics of some composites. If tight tolerances between the air cushions and the guideway can be maintained, a less complex suspension system may prove adequate.

As discussed under Safety, it is likely that the improved brakes of carbon/carbon composites may be found cost effective because of their greater safety, longer service life, and reduced maintenance costs (refs. 250, 251). Similarly, longer life and stronger bearing and seal materials may find acceptance (refs. 83, 150, 164). There may also be some impetus to use composites to reduce the weight of standard rail cars, because of increased performance goals and reduced track and roadbed maintenance.

There is little doubt that advanced composites can be successfully applied to rail transport; however, the unresolved state of the preferred mode(s) of rail transport will delay their commercial implementation. Pending resolution of the multiplicity of alternatives, advanced composites will probably find use primarily as elements in conceptual designs.

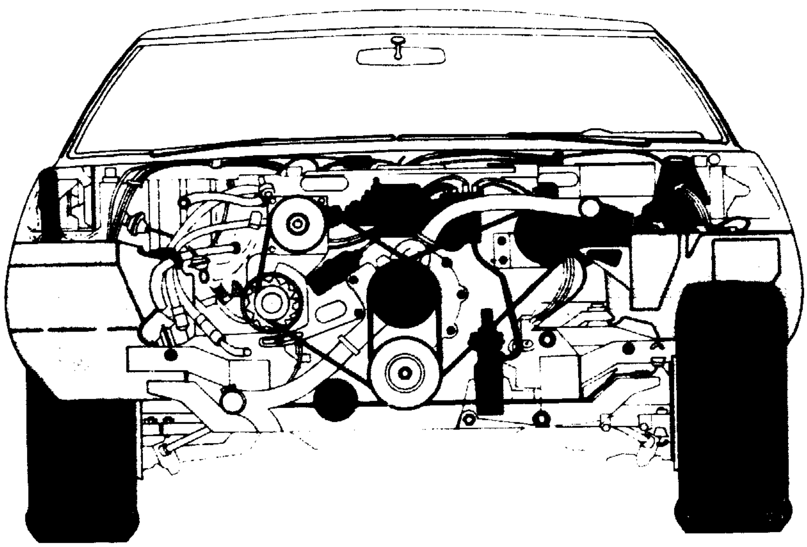
Motor Transport

Motor transport includes, primarily, automobiles, buses, and trucks. Recreational vehicles such as motorcycles, snowmobiles, and all-terrain vehicles are not considered an appreciable portion of the motor transport market.

As mentioned intially, the use of glass-reinforced plastics (GRP) for bodies has already made significant inroads in the auto, bus, truck and various recreational vehicle market. In these applications the high specific strength of GRP is desirable; however, its relatively low modulus (stiffness) has proved a limiting factor. The emergence of both boron/epoxy and graphite/epoxy composites has relieved this situation. These materials are as light as GRP but offer a much greater degree of rigidity. They are as strong and stiff as steel but lighter than aluminum.

Other composites may also provide increased performance at acceptable cost. Undoubtedly this cost will be borne by the consumer, but perhaps the resultant, longer lived and safer vehicles will be commercially desirable. It has been estimated that an extra $50 spent for premium materials during production could result in $500 saved in repair costs over the life of the vehicle. Some of the potential areas of application for premium plastics are pointed out in figure 68 (ref. 231).

The emphasis on safety in automobiles, buses, and trucks will certainly increase the demand for material systems capable of meeting the rigid Federal



Plastic Applications	Property	Finish	Plastic Applications	Property	Finish
Gear shift rod hub bushing	Self-Lub.	N	Steering col. shift bearing	Self-Lub. wear resis.	N
Steering col. jacket bushing	Self-Lub.	N	Steering col. gear shift assem.	Self-Lub. strength	P
Steering col. shift bearing	Self-Lub.	N	Lower bearing washer	Self-Lub.	N
Steering col. shift washer	Self-Lub. spring	N	Heater control guide	Self-Lub.	M.C.
Steering col. gear spacer	Self-Lub.	N	Steering col. shaft seal washer	Elongation	N
Accelerator shaft roller	Self-Lub.	N	Safety belt reel ends	Springiness	M.B.
Accelerator P.D.C. plate	Wear Resist.	M.B.	Safety belt slider	Springiness	M.B.
Clutch pedal damper washer	Self-Lub.	N	Steer. col. gear shift slinger	Chem. Resist.	N
Instr. panel socket assem.	Temp. Resist.	M.B.	Idler end bearing	Wear resist.	N
Bushing	Self-Lub.	N	Window motor thrust washer	Dimen. stability	N
Bushing W/W	Dimen. stability	N	Steering col. bearing washer	Self-Lub.	N
Steering col. tube pivot	Self-Lub.	M.C.	Front seat guide	Self-Lub.	M.B.
Pulley	Wear resistant	M.B.	Door jamb light switch	Dimen. stability	M.B.
Steering col. adapter	Self-Lub.	M.C.	Parking brake cable conduit	Dim. stab. wear res.	N

N -- Natrual . . . MC molded in color . . . MB molded in black . . . P painted

Figure 68. – Areas of potential application.
(from ref. 231)

regulations. Carbon/carbon composite brakes and the work on nonflammability materials for interior construction and decor has been discussed under Aircraft. Work on high-temperature, fire-resistant foams may also find application as firewall thermal and noise barriers (ref. 109).

Alternative means of thermally isolating the vehicle occupants from external heat may be derived from the high efficiency insulation system concepts being studied (refs. 64, 72, 73, 159). These, in turn, may permit a reduction in wall thickness requirements, thereby increasing the available internal volume of the vehicle. In refrigerated trucks, for example, this insulation work may prove cost effective in terms of increased payload and reduced refrigeration needs.

Insulation materials can also be utilized in electric propulsion motors (refs. 84, 235). A reduction in the thickness required for insulation with an increase in the allowable service temperature could result in significant increases in specific power available.

Another area of potential interest is metal cladding. Copper clad aluminum radiators would increase cooling effectivity at reduced weight and cost. Corrosion-resistant, stainless-steel-clad mufflers may also be realizable. Cladding of aluminum with stainless steel will permit reduced cost of vehicle trim.

As pollution level regulations become more stringent, alternative power sources may become mandatory. High-temperature resistant materials, such as metal and polymer matrix filamentary reinforced composites, may find utilization as clading and buckets for gas turbines (refs. 253, 256, 257).

Similarly, alternative fuels such as liquified petroleum and methane may become desirable. Here, the development of lightweight, compact, high-pressure storage bottles may be applicable (refs. 157, 225). This work could also find use in high-pressure steam or other pressurized fluid boilers.

Specialty gears may benefit from the development of a Teflon/metal laminate (ref. 83). Selective placement of fluorocarbon provides a continuous source of low friction material over the gear teeth, which reduces wear and heat buildup induced by friction. Graphite-reinforced polymers also provide similar properties and extend the service temperature range (ref. 150).

The use of advanced composite materials in tire construction may provide greater margins of safety by selective reinforcement in the tire bead area. It is this element that must transmit the load om tire to rim, and uniformity and strength play a critical role. Perhaps the use of high-strength graphite fibers could significantly upgrade the overall load rating of an otherwise standard tire assembly.

In summary, the use of composites in motor transport will have to be justified, not in terms of physical performance levels, but rather in terms of cost effective specific solutions to problems.

Marine Transportation

Included under marine transportation are bulk cargo carriers, barges, tankers, pleasure boats, and submersibles. In general, this class of transport is not so sensitive to weight reduction as other transport modes. In fact, in commercial use these systems operate at the lowest values of horsepower per net ton (~0.2 to 0.4) (ref. 258). Additionally, the weight advantage offered by composites has already been realized in many types of boats by the use of glass-reinforced plastics. In fact, in America, these composites account for about two-thirds of all recreational boats under 60 feet in length. Commercially, GRP is now being utilized in the fabrication of shrimp trawlers up to 74 feet in length. At the present state of the art, GRP construction competes with steel hulls in lengths up to 150 feet. Generally, these composite hulls involve a sandwich type of construction, which results in efficient transfer of load through the structure. Recent developments have also led observers to conclude that, by 1980, all British warships of less than 500 tons will be fabricated from GRP by means of computerized systems and the use of radio-frequency curing techniques (ref. 259).

Glass-reinforced plastic ships offer several benefits. Their reduced sensitivity to marine environments results in a smoother hull with an increase in operational efficiency because of reduced drag effects. There is also minimal corrosion, which leads to reduced maintenance costs. Further, the repair of composite materials is more readily achieved compared with that of metal or wood components.

Advanced composites will find only limited immediate use in commercial shipping because of their relatively high cost, although the advent of automated fabrication concepts will lead ultimately to reduced initial acquisition costs. Potential applications may include masts, booms, and propulsion shafts which could be readily fabricated from graphite/epoxy or boron/epoxy materials, either all-composite or hybrid composites (refs. 234, 241, 260). The lower weight and increased rigidity may offer sufficient payoffs to prove cost effective. A more technologically sophisticated application would be the use of filamentary-reinforced composites in hydrofoil components. In this application, the stiffness, light weight, and good vibrational damping of the composites could all pay real dividends.

Many potential applications for marine transportation have been described in connection with the other modes of transportation. Wear-resistant and self-lubricating composites utilized in rotary seals and bearings could find application in marine propulsion and power units. Similarly, longer lived clutches could be fabricated from composite materials, as previously described. The NASA-sponsored work with nonflammable and fire-proofing foams and composite materials will have a definite impact on the marine transport industry. Refrigerated cargo would benefit from studies into more efficient thermal isolation systems (refs. 64, 73, 159). Finally, cryogenic storage and shipping of liquified gases from the North Sea area will benefit from the NASA-sponsored work on cryogenic insulation systems (refs. 65, 71, 109, 255).

In a limited area of application, composites could play a dominant role in submersibles. The use of graphite or boron-reinforced epoxy for submarine or deep diving hulls would substantially increase their depth capability, at reduced weight. Whether submersibles will play a significant role in transport for undersea farming, fishing, or mining is yet to be determined.

Pipelines

Pipelines are a highly specialized form of transportation and, surprisingly, account for as much as 21 percent of the total U.S. freight traffic per year. Additionally, no point in the U.S. is more than 200 miles from an established pipeline route. Pipelines do not simply carry liquids but have expanded their capability to move slurries (coal in water, for example) and capsules containing dry bulk commodities (soft bags or cannisters propelled by liquid moving in the pipe) (ref. 260).

Filament-wound, glass-reinforced pipe has been manufactured for a number of years, with a number of inherent advantages:

a) It can be manufactured with automated techniques, which cut cost.

b) It has a higher flexibility than steel, which aids in the snaking and laying of pipe in trenches.

c) It has a smooth inner surface which reduces frictional loss and surface buildup.

d) It can be buried in wet ground or marine environments with minimal corrosion protection required.

e) It has lower heat transfer rates than metals, which allows the pumping of heat-thinned materials (crude oil) with less thermal insulation.

f) Its lighter weight allows its transport and assembly in remote areas; for example, a GRP pipe, 20 feet long with an 8-inch bore, rated at 380 psi, weighs only 70 pounds.

In light of these present advantages, it is difficult to see any immediate need for filamentary reinforced pipeline materials of higher performance. However, the recent ecological considerations over the Alaskan pipeline offer a potential area of application. The passage of hot oil [150°F (66°C)] through a buried pipe is considered a threat to the environment because it would thaw the permafrost. Application of the highly efficient insulation systems developed by NASA could reduce this danger to negligible levels (refs. 64, 73, 159).

Another problem is the potential ecological damage that would result from a pipe failure, particularly in regions of known earthquake activity. In such regions, the NASA-sponsored work on hybrid composites, such as magnesium, aluminum and titanium tubes reinforced with boron or S-glass filaments, might result in failsafe designs capable of withstanding the stress levels induced by geological disturbances (refs. 18, 241).

Because of the remote locale of most of the proposed Alaskan pipeline, it is desirable to design it and the support systems with a high level of reliability and low degree of required maintenance. To this end, it may prove attractive to employ the composite bearing and seal materials developed by NASA in the motor, valves, and pumping equipment along the route.

Miscellaneous

The miscellaneous section includes those modes of transport not readily categorized in any of the previous headings. Covered are air cushion vehicles, aerial tramways, and conveyor belts.

Air cushion vehicles.— The Canadian government is investigating the potential of air cushion cargo craft for arctic and subarctic operations. A current prototype is designed to carry a 20-ton payload at speeds up to 60 miles per hour. Power is supplied by two 1300-horsepower gas turbine engines. Although the stated goal of the program is to utilize state-of-the-art materials, it is likely that serious consideration will be given to weight-saving advanced composites, particularly because of the range sensitivity of hovercraft to excess weight. Composites would aid in the transportability of the modular construction used (ref. 261).

Applications of NASA-developed composites could include those previously discussed, such as rotary seals and bearings, fan blades, buckets, lightweight structural elements, thermal and noise isolation systems for crew and/or passenger comfort, selective reinforcement (hybrids) of highly stressed parts, and lightweight deck panels.

Conveyor belts.— Conveyor belts are generally subject to two principal types of resistance, roller and grade resistance. The latter is due to the differences in elevation through which the load moves. Little can be done about the gravitational effect, but the roller or idler pulleys can be made more efficient by the use of NASA studies on those composite materials useful as bearings and seals (refs. 83, 150, 164). The belt construction may also benefit from the inclusion of higher modulus fibers which would reduce the complexity of tension control subsystems.

Homologs of cargo carrying conveyors may ultimately find use as people transport devices within the inner city complex.

Aerial tramways.— Although limited in use, aerial tramways serve a critical need in regions of severe terrain. It is possible that longer cable spans could be realized through the use of braided or otherwise combined graphite and/or boron/steel cables. Additionally, longer spans would reduce construction cost and time by making possible a reduction in the number of towers required. Towers, when required, could be constructed of NASA-developed composites suitable for tube or truss structures, such as the S-glass and boron/epoxy tubes shown in table XXXII (refs. 16, 18, 152, 158).

As noted earlier, bearings and clutches could also benefit from NASA-supported studies (refs. 83, 250).

References

1. Anon: The Promise of Composites. Materials in Design Engineering. Special Report No. 210, Sept. 1963, pp. 79-126.

2. Broutman, L. J. and R. H. Krock: Modern Composite Materials. Addison-Wesley Publishing Co., 1967.

3. Korman, S.: Some New Metal and Metal-Ceramic Composites. NASA SP-5060, 1966.

4. Scipio, L. A.: Structural Design Concepts. NASA SP-5039, 1967.

5. Berg, K. R.; and Filippi, F. J.: Advanced Fiber-Resin Composites. Machine Design, vol. 43, no. 8, Apr. 1, 1971, pp. 160-168.

6. Beall, R. T.; Burton, G. W.; and Rich, W. V.: Development of Advanced Composite Structures for Aircraft. SAMPE Quarterly, vol. 2, no. 1, Oct. 1970, pp. 41-45.

7. Hart-Smith, L. J.: Filamentary Composite Reinforced Metal Aircraft Structures. Society of the Plastics Industry, 28th Annual Western Conference, Coronado, California, 1971, pp. 74-90.

8. Powers, W. M.: The Age of Composites. SAMPE Quarterly, vol. 2, no. 1, Oct. 1970, pp. 9-16.

9. Anon.: Composite Experts Seek More Economical Methods and Materials. Product Engineering, vol. 42, no. 14, Sept. 1971, pp. 36-37.

10. Davies, L. G.; Powers, W. M.; and Shaver, R. G.: Low Cost Metal-Matrix Composite Fabrication. Society of Aerospace Material and Process Engineers, 16th National Symposium and Exhibit, Anaheim, California, vol. 16, Apr. 21-23, 1971.

11. Herring, Harvey W.: Selected Mechanical and Physical Properties of Boron Filaments. NASA TN D 3202, 1966.

12. Anon.: Thermally Stable Polyimides from Solutions of Monomeric Reactants. NASA Tech Brief 71-10442, Nov. 1971.

13. Mangiapane, J. A.: Composite Materials: Metal-Matrix and Polymer-Matrix. SAMPE Quarterly, vol. 2, no. 1, Oct. 1970, pp. 53-61.

14. Dexter, Benson H.; and Davis, John G.: Fabrication and Structural Applications of Advanced Composite Materials (Boron). NASA SP-5075, 1969.

15. Davis, John G., Jr.; and Rummler, Donald R.: Application of Advanced Materials to Truss Structures. Paper presented at 15th National SAMPE Symposium (Los Angeles, California), Apr. 29-May 1, 1969.

16. Engler, Erich; and Hadcock, Richard: Development of Boron-Epoxy Tubular Struts for a One-Third Scale Shuttle Booster Thrust Structure. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

17. Dexter, Benson H.: Compressive and Column Strengths of Aluminum Tubing with Various Amounts of Unidirectional Boron/Epoxy Reinforcement. NASA TN D 5938, 1970.

18. Zender, George W.; and Benson, Dexter H.: Compressive Properties and Column Efficiency of Metals Reinforced on the Surface with Bonded Filaments. NASA TN D-4878, 1968.

19. McCullough, R. L.: Concepts of Fiber-Resin Composites. Marcel Dekker, Inc., 1971.

20. Roy, Paul A.; McElman, John A.; and Henshaw, Jim: Boron Epoxy Reinforced Structural Sections. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

21. Henshaw, J.; Roy, P. J.; and Russell, M. D.: A Practical Method of Fabricating Efficient Aero-Structures, Utilizing Unidirectional Boron Composite with Metal. Paper presented at National SAMPE Technical Conference (Seattle, Washington), Sept. 9-11, 1969.

22. Kreider, Kenneth G.; and Breinan, Edward M.: Where Composites are Being Applied. Materials Technology for Borsic-Aluminum Aircraft Parts. Metal Progress, vol. 97, May 1970, pp. 104-108.

23. O'Kelly, H. P.: Evaluation of Metal Matrix Composites. NAS 9-8260, Aug. 31, 1971.

24. Divecha, A. P.; and Pignone, E. H.: Development of a Method for Fabricating Metallic Matrix Composite Shapes by a Continuous Mechanical Process. NAS 8-27010, 1972.

25. Abrams, Edwin F.; Davies, Lawrence G.; Powers, William M.; and Shaver, Robert G.: Continuous Casting of Metallic Tubular Structural Elements Reinforced with Boron Filaments. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

26. Anon.: Boron Fiber-Reinforced Aluminum Allow Tubing: Experimental. NASA Tech Brief 69-10509, Oct. 1969.

27. Hanby, K. R.: Fiber-Reinforced Metal-Matrix Composites. DMIC Report S-33. July 1, 1971, pp. 57-60.

28. Davies, L. G.; Shaver, R. G.; and Withers, J. C.: Continuous Cast Boron-Light Metal Alloy Performs and Composites. Paper presented at 17th Refractory Composites Working Group Meeting, (Reston, Virginia), June 1970.

29. Hackworth, J. Vaughn: Evaluation of High Strength Graphite Fabrics for Flexible Structures. NASA CR-111777, 1970.

30. Wexler, M.; Fenton, R.; Lowe, D.; Edighoffer, H.; and Belman, R.: Evaluation of Omniweave (GE) Method of Composite Fabrication-Graphite Filament. NAS 8-24777, June 1970.

31. Karre, L. E.; Keller, L. B.; and Miller, L. J.: Development and Processing of Pyrrone Polymers. NASA CR-1310, 1969.

32. Hertz, J.: Investigation into the High-Temperature Strength Degradation of Fiber-Reinforced Resin Composite During Ambient Aging. NAS 8-27435, July-Sept. 1971.

33. Maximoviclt, M.: Development of Design Data for Graphite Reinforced Epoxy and Polyimide Composites. NAS 8-26198, Apr.-Sept. 1971.

34. Hanson, M. P.; and Serafini, T. T.: Effects of Thermal and Environmental Exposure on the Mechanical Properties of Graphite/Polyimide Composites. NASA TM X-67893. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

35. Hardesty, E. E.: Development of Continuous Forming and Curing Techniques for Production of Circular Structural Composite Shapes for Space Vehicle Application. NAS 8-26900, Aug. 1971-Jan. 1972, pp. 624-672.

36. Sinclair, P. Michael: Composites: Designers Wait and Contemplate. Industrial Research, vol. 11, no. 10, Oct. 1969, pp. 59-79.

37. Lalacona, Felix P.: Graphite-Aluminum Composites. Metal Matrix Composites, R. T. Pepper, ed., Oct. 1971.

38. Cataldo, C. E.: Overview of Composites for Space Shuttle Structures. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

39. Signorelli, R. A.: Interview, NASA Lewis Research Center, Oct. 1971.

40. Hough, R. L.: High-Strength Large-Diameter Carbon-Base Fibers. NASA Tech Brief 71-10403, Oct. 1971.

41. Lager, John R.: Composite Space Shuttle Engine Support Structure. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

42. Lubin, George, ed.: Handbook of Fiberglass and Advanced Plastics Composites, Van Nostrand Reinhold Co., 1969.

43. Bacon, J. F.: The Kinetics of Crystallization of Molten Binary and Ternary Oxide Systems and their Application to the Origination of High Modulus Glass Fibers. NASA CR-1856, 1971.

44. Wexler, M.: Manufacture and Delivery of Demonstration I-Beam Framing Component. NASA CR-103098, 1971.

45. Hoggatt, J. T.: High Performance Filament Wound Composites for Pressure Vessel Applications. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

46. Anon.: Du Pont's New High Modulus Organic Fiber for Plastics Reinforcement Ballistic Armor and Tension Cable Applications. E. I. Du Pont De Nemours and Co., Inc., Sept. 15, 1971.

47. Stratton, Warren K.: Evaluation of DuPont's High Modulus Organic Fiber PRD49 Type I. Paper presented at National SAMPE Technical Conference (Anaheim, California), Apr. 21-23, 1971.

48. Korman, Samuel: Some New Metal and Metal-Ceramic Composites. NASA SP-5060, 1966.

49. Roberts, John A.: Metal Filaments. Modern Composite Materials, Addison-Wesley Publishing Company, 1967.

50. Harman, Cameron G.: Non-Glassy Inorganic Fibers and Composites. NASA SP-5055, 1966.

51. Weeton, John W.; McDanels, David L.; Jech, Robert W.; Oldrieve, Robert E.; Petrasek, Donald W.; and Signorelli, Robert A.: Method of Making Fiber Reinforced Metallic Composites. U.S. Patent 3,138,837, June 30, 1964.

52. Weeton, John W.; McDanels, David L.; Jech, Robert W.; Oldrieve, Robert E.; Petrasek, Donald W.; and Signorelli, Robert A.: Reinforced Metallic Composites. U.S. Patent 3,170,773, Feb. 23, 1965.

53. Signorelli, Robert A.; and Weeton, John W.: Metal-Matrix Fiber Composites for High Temperatures. NASA-Aerospace Structural Materials Conference, NASA SP-227, Lewis Research Center, Cleveland, Ohio, Nov. 18-19, 1969.

54. Petrasek, Donald, W.; and Signorelli, Robert A.: Preliminary Evaluation of Tungsten Alloy Fiber - Nickel-Base Alloy Composites for Turbojet Engine Applications. NASA TN D-5575, 1970.

55. McIntyre, Ruluff, D.: High-Strength Tantalum Composite by Thermomechanical Working. NASA TN D-5640, 1970.

56. Anon.: Fiber Composite Materials. Papers presented at a Seminar of the American Society for Metals (Metals Park, Ohio), Oct. 17-18, 1964.

57. Sutton, Willard H.: Fiber-Reinforced Metals. Modern Composite Materials, Addison-Wesley Publishing Company, 1967.

58. Sumner, E. V.: Development of Ultra-High Strength, Low Density, Aluminum Sheet and Plate Composites. NAS 8-11508, July 1966.

59. Davis, Leroy W.: Stainless Wire + Aluminum Matrix = Strong, Light Composite Plate. Metal Progress, vol. 91, Apr. 1967, pp. 105-114.

60. Davis, L. W.: Boron and Steel Reinforced Aluminum. Paper presented at Applications of Composite Materials Seminar, Pennsylvania State University (College Park, Pa.), Sept. 9-12, 1968.

61. Clark, E. D.: Application of Composites to Structural Members. Paper presented at the ASM Meeting (Philadelphia, Pennsylvania), Oct. 16, 1969.

62. Anon.: Explosive Bonded TZM-Wire-Reinforced C129Y Columbium Composites, NASA Tech Brief 71-10356, Sept. 1971.

63. Reece, O. Y.: TZM Wire Reinforced Columbium Composites. Paper presented at 17th Refractory Composites Working Group Meeting, June 1970.

64. Leonhard, K. E.; and Hyde, E. H.: Multilayer Insulation Materials for Reusable Space Vehicles. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

65. Gille, John P.; Buskirk, David L.; and McGrew, Jay L.: Material Development for a Shuttle Hydrogen Tank Internal Gas Layer Insulation. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

66. Nies, George E.; and Niendorf, Lynn R.: Self Evacuating Multilayer Insulation (SEMI) for Space Shuttle Orbiter Cryogenic Tanks. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

67. Middleton, Robert L.; Schell, John T.; and Stuckey, James M.: Cryogenic Thermal Insulation. U.S. Patent 3,365,897, Jan. 30, 1968.

68. Perkins, Porter J., Jr.: Cryogenic Insulation System. U.S. Patent 3,379,330, Apr. 23, 1968.

69. Keller, C. W.: Thermal Performance of Multilayer Insulations. NAS 3-12025, Apr. 20, 1971.

70. Krause, D.R.; Fredrickson, G.O.; and Klevatt, P.L.: Effects of Cyclical Environments on High-Performance Multi-Layer Insulation Materials. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

71. Krause, D. R.: Development of Lightweight Material Composites to Insulate Cryogenic Tanks. NAS 8-26006, Sept.-Oct. 1971.

72. Islamoff, I.: Cryogenic Insulation Development in Connection with Saturn I and V Vehicles. Tech. Utilization Report. Technical Engineering, Hayes International Corp., Missile & Space Support Division, Huntsville, Alabama, pp. 1-44.

73. Glaser, Peter E.; Black, Igor A.; Lindstrom, Richard S.; Ruccia, Frank E.; and Wechsler, Alfred E.: Thermal Insulation Systems, A Survey. NASA SP-5027, 1967.

74. Anon.: The Low-Cost Cryostat, NASA Tech Brief 70-10592, Oct. 1970.

75. Carlson, L. W.: Improved Insulating Materials Effective at Extremely High Temperatures. NASA Tech Brief 71-10289, Aug. 1971.

76. Fuchs, C. E.: Inexpensive Cryogenic Insulation Replaces Vacuum Jacketed Line. NASA Tech Brief 67-10264, July 1967.

77. Sweeney, George A.: Development and Production of High-Altitude Decelerator, Lightweight Low Permeability Brace Material. NASA CR-111964, 1971.

78. Niccum, R. J.: Comparison of Polyester, Film-Yarn Composite, Balloon Materials Subjected to Shear and Biaxial Loading. NAS 1-10750, Oct. 1971.

79. Withers, J. W.: Space Structure Rigidization. NAS 1-847, Sept. 1961.

80. Meiners, K. E.: Mechanical Properties and LOX Compatibility of Stainless Steel-Clad Titanium Prepared by Explosive Welding and Vacuum Deposition. NAS 3-12007, Dec. 31, 1969.

81. Buckman, R. W., Jr.; and Goodspeed, R. C.: Evaluation of Refractory/Austenitic Bimetal Combinations. NAS 3-7634, Apr. 1970.

82. Lalacona, Felix P.: Diffusion Bond Method of Joining Steel and a TFE-Bronze Composite. NASA Tech Brief 69-10237, July 1969.

83. LaLacona, Felix P.; and Schwinghamer, R.: Method for Joining Teflon-Bronze Composite to Steel, U. S. Patent 3,602,979. Sept. 7, 1971.

84. Vaughan, R. W.; Jones, R. J.; Creedon, J. F.; and Goodman, J. W.: The Development of Thermally Stable Adhesives for Titanium Alloy and Boron Composite Structures. NASA CR-1824, 1971.

85. Anon.: Bonding and Joining Technology. NASA SP-5925(01) and (02), 1971.

86. Crawford, R. F.: Efficiency of Boron- and Carbon-Polymer Laminated Film Composites for Stability-Designed Structures. Paper presented in AIAA/ASME 12th Structures, Structural Dynamics and Materials Conference (Anaheim, California), Apr. 19-21, 1971.

87. Talboom, Frank P.; and Elam, Richard C.: Evaluation of Advanced Superalloy Protection Systems. NAS 3-12415. Paper presented at National SAMPE Technical Conference (Anaheim, California), Apr. 21-23, 1971.

88. Carpenter, H. W.: Protective Coating System for a Regeneratively Cooled Thrust Chamber. NASA CR-72855, 1970.

89. Vogel, C. E.; Ferris, J. R.; Patterson, R. L.; and Steffen, R. J.: Refractory Coating Protects Intricate Graphite Elements from High Temperature Hydrogen. NASA Tech Brief 66-10084, March 1966.

90. Anon.: Improved High-Temperature Silicide Coatings. NASA Tech Brief 69-10266, Aug. 1969.

91. Radnofsky, Matthew, I.: Developments in Fire-Retardant Materials and Coatings. Paper presented at the 16th Annual Ohio Fire Prevention Seminar (Columbus, Ohio), Oct. 21-23, 1970.

92. Radnofsky, M. I.: History and Development of Nonflammable Material for Apollo Spacecraft. Aerospace Medicine, vol. 40, no. 11, Nov. 1969, pp. 1181-1185.

93. Radnofsky, M. I.: New Materials for Manned Spacecraft, Aircraft, and Other Applications. Paper presented at the NASA Conference on Materials for Fire Safety (Houston, Texas), May 6-7, 1970.

94. Radnofsky, M. I.; and Gauldin, E. W.: Materials That Won't Burn. A Product of Space Research with Nonspace Applications. NASA, Manned Spacecraft Center. Houston, Texas.

95. Radnofsky, M. I.: Protective Firefighters Clothing. NASA, Manned Spacecraft Center. Houston, Texas.

96. Radnofsky, M. I.: Improvement of Fire Safety in Commercial Aircraft. Paper presented at the Flight Safety Foundation (Washington, D. C.), Oct. 26-30, 1970.

97. Tyner, J. D.: Sauers, D. G.; and Powell, J. E.: Test Procedure Simulated-Housing Module Flammability Testing. NASA, Manned Spacecraft Center. Houston, Texas.

98. Kramer, B. E.; and Potter, D. Y.: Development of High Strength, Brazed Aluminum, Honeycomb Sandwich Composites Adaptable for Both Elevated and Cryogenic Temperature Applications. NAS 8-5445, Sept. 30, 1966.

99. Grant, L. A.: Development of Beryllium Honeycomb Sandwich Composite for Structural and Other Related Applications. NAS 8-21215. 1968.

100. Schnitzer, Emmanuel: Method of Making Inflatable Honeycomb. U. S. Patent 3,342,653, Sept. 19, 1967.

101. Carmody, Robert J.: Honeycomb Panel and Method of Making Same. U. S. Patent 3,346,442, Oct. 10, 1967.

102. Pattee, H. E.; Evans, R. M.; and Monroe, R. E.: Joining Ceramics and Graphite to Other Materials. NASA SP-5052, 1968.

103. Parker, J. A.; Riccitiello, S. R.; Gilwee, W. J.; and Fish, R.: Fire Retardant Foams Developed to Suppress Fuel Fire. NASA Tech Brief 68-10358, Sept. 1968.

104. Fish, Richard H.: The Performance of Lightweight Plastic Foams Developed for Fire Safety. NASA, Manned Spacecraft Symposium. Houston, Texas. June 1970.

105. Parker, J. A.; Fohlen, G. M.; Sawko, P. M.; and Fish, R. H.: Intumescent Coatings as Fire Retardants. NASA Tech Brief 70-10450, May 15, 1970.

106. Fohlen, G. M.; Parker, J. A.: Riccitiello, S. R.; and Sawko, P. M.: Intumescence: An In Situ Approach to Thermal Protection. NASA, Ames Research Center. Moffett Field, California.

107. Neel, Carr B.; and Fish, Richard H.: Protection of Aircraft in Ground Crash Fuel Fires. NASA, Ames Research Center. Moffett Field, California.

108. Karre, Lowell E.; and Kelliher, Warren C.: Processing of Pyrrone Foams. Paper presented at National SAMPE Technical Conference (Anaheim, California), Apr. 21-23, 1971.

109. Marks, Burton S.; Shoff, Lester E.; and Watsey Gazel W.: Study and Production of Polybenzimidazole Billets, Laminates, and Cylinders. NASA CR-1723, 1971.

110. Look, George F.: Organic Reactants Rapidly Produce Plastic Foam. NASA Tech Brief 65-10288, Sept. 1965.

111. Chase, Vance A.; and Van Auken, Richard L.: Chemceram Foam - A Low-Cost Approach to the Space Shuttle External Insulation Problem.

Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

112. Paine, T. O.; Kaznoff, Alexis I.; and Marlow, Mickey O.: Method of Making a Cermet. U.S. Patent 3,579,390, May 18, 1971.

113. Jech, R. W.; Weeton, J. W.; and Signorelli, R. A.: Preparation of Fibered Ceramics by Mechanical Deformation. NASA TN D-5736, 1970.

114. Weeton, John W.; Quatinetz, Max.; and Jech, Robert W.: Method for Producing Fiber Reinforced Metallic Composites. U.S. Patent 3,337,337, Aug. 22, 1967.

115. Haggerty, J.S.; and Menashi, W.P.: Production of Oxide Fibers by a Float-Zone Fiber Drawing Technique. NASA CR-72811, 1971.

116. Quatinetz, Max.; Weeton, John W.; and Herbell, Thomas P.: Method of Producing Refractory Composites Containing Tantalum Carbide and Hafnium Boride. U.S. Patent 3,472,709, Oct. 14, 1969.

117. Harada, Y.: Graphite-Metal Composites. NASA CR-77114. 1966.

118. Sliney, Harold E.: An Investigation of Oxidation-Resistant Solid Lubricants Materials. Paper presented at International Conference on Solid Lubricants sponsored by the American Society of Lubrication Engineers (Denver, Colorado), Aug. 24-27, 1971.

119. Campbell, M.E.; Loser, John B.; and Sneegas, Eldon: Solid Lubricants, NASA SP-5059, 1966.

120. Weeton, J.: Interview. NASA, Lewis Research Center. Jan. 1972.

121. Grant, Nicholas J.; Siegel, Howard J.; and Hall, Robert W.: Oxide Dispersion Strengthened Alloys. NASA SP-143, 1967.

122. Anon.: TD Nickel, an Also-Ran at 70°F is Unbeatable at Over 1800°F. Product Engineering, vol. 37, No. 18, Aug. 29, 1966, pp. 42-43.

123. Kraft, R. W.: Controlled Eutectics. J. of Metals, vol. 18, no. 2, Feb. 1966, pp. 192-200.

124. Hertzberg, Richard W.: Composite Materials Formed by the Directional Soldification of Eutectic Alloys. Modern Composite Materials, L. J. Broutman & R. H. Krock, ed., Addison-Wesley Publishing Company, 1967.

125. Johnson, P. C.; Berkowitz, J.; and Wechsler, A. E.: Research Study on Composite Castings. NAS 8-25709, May 26, 1971.

126. Wechsler, A. E.; Mattuck, J. B.; Griffiths, L.; Johnson, P. C.; and Carroll, R. J.: Sphere Forming and Composite Casting in Zero-G. NASA CR-61317, 1970.

127. Kraft, R. W.; and Hertzberg, R. W.: Investigation of Solidification, Structure, and Properties of Eutectic Alloys Including Consideration of Properties Control. NASA-CR-106838, 1969.

128. Darwish, F. A. I.: The Effect of Temperature and Fiber Orientation on the Strength and Deformation Characteristics of Fiber Composites. NASA NSG-622, 1969.

129. George, F. D.: Development of High Temperature Fasteners Using Directionally Solidified Eutectic Alloys. NAS 8-27358, Oct. 22, 1971.

130. Milewski, John V.; Shyne, James J.; and Shaver, Robert C.: Whiskers and their Composites. Handbook of Fiberglass and Advanced Plastics Composites, G. Lubin, ed., Van Nostrand Reinhold Company, 1969.

131. Alexander, John A.; Withers, J. C.; and Macklin, B. A.: Investigation of Three Classes of Composite Materials for Space Vehicle Application. NASA CR-785, 1967.

132. Alexander, J. A.; Shaver, R. G.; and Withers, J. C.: A Study of Low Density, High Strength High Modulus Filaments and Composites. NASA CR-523, 1966.

133. Shaffer, Peter T. B.: Whiskers - Their Growth and Properties. Modern Composite Materials, L. J. Brontman & R. H. Krock, ed., Addison-Wesley Publishing Company, 1967.

134. Sutton, Willard H.: Principles & Methods for Fabricating Whisker-Reinforced Composites. Whisker Technology, A. P. Levitt, ed. Wiley-Interscience, 1970, pp. 310.

135. Kirkpatrick, M. E.; Staudhammer, K. P.; Reger, J. L.; and Toy, A.: A Continuous Process for the Production of Whisker Reinforced Composites. J. of Composite Materials, vol. 3, Apr. 1969, pp. 322-336.

136. Gilbu Agnar.: The Drostholm Continuous Filament Winding Process. Paper presented at 26th Annual Technical Conference, 1971 Reinforced Plastics/Composites Division, the Society of the Plastics Industry, Inc. (Washington, D. C.), 1971. Section 16-D, pp. 1-6.

137. Anon.: Plastic Enclosures Step Toward Reality. Product Engineering, vol. 42, no. 14, Sept. 1971, pp. 16.

138. Anon.: Air Buildings: No Longer Just Castles in the Sky. Modern Plastics, Mar. 1972, pp. 46-48.

139. White, E.; and Mathews, F.: NASA-Tricot: A Lightweight, Radar Reflective, Knitted Fabric. NASA Tech Brief 71-10342, Sept. 1971.

140. White, E.; and Mathews, F.: NASA-Tricot: A Lightweight, Radar Reflective, Knitted Fabric. Technical Support Package for NASA Tech Brief 71-10342, Sept. 1971.

141. Anon.: Hercules Builds Graphite Composite Satellite Support Truss. Hercules, Inc., Nov. 22, 1971.

142. MacFadden, J. A.: Tethered Balloons: Their Uses in Industrial Applications. Paper presented at 12th National SAMPE Technical Conference (Anaheim, California), Oct. 10-12, 1967.

143. Anon.: Giant Balloon Aids Rough Country Logging. Australian Plastics and Rubber J., vol. 22, no. 261, Apr. 1967, pp. 23.

144. Anon.: Balloon Logging. Compressed Air Mag., vol. 69, no. 11, Nov. 1964, pp. 12-13.

145. Joseph, J.: Diesels "Fly" New Logging Balloons. Diesel and Gas Engine Progress, vol. 31, no. 3, Mar. 1965, pp. 50.

146. Dow, Norris F.: Materials and Engineering Problems. Paper presented in Mechanics of Composite Materials; Office of Naval Research, 5th Symposium on Naval Structural Mechanics. (Philadelphia, Pennsylvania), May 8-10, 1967.

147. Gerard, George.; and Lakshmikantham, C.: Structural Design Synthesis Approach to Filamentary Composites. NASA CR-964, 1967.

148. Tsai, Stephen W.: Structural Behavior of Composite Materials. NAS 7-215. 1964.

149. Alexander, John A.: Shaver, Robert G.; and Withers, James C.: Critical Analysis of Accumulated Experimental Data on Filament-Reinforced Metal Matrix Composites. NASw-1779, June 1969.

150. Scheck, W. G.: Development of Design Data for Graphite Reinforced Epoxy and Polyimide Composites. NAS 8-26198, May 1970.

151. Alexander, John A.; and Davies, Lawrence G.: Continuous Casting as a Composite Fabrication Process. Paper presented at the 15th National SAMPE Symposium and Exhibition (Los Angeles, California), Apr. 29, 30, and May 1, 1969.

152. Davis, John G., Jr.: Compressive Instability and Strength of Uniaxial Filament-Reinforced Epoxy Tubes. NASA TN D-5697, 1970.

153. Dexter, H. Benson: Compressive and Column Strengths of Aluminum Tubing with Various Amounts of Unidirectional Boron/Epoxy Reinforcement. NASA TN D-5938, 1970.

154. McDanels, David L.; Jech, Robert W.; Weeton, John W.; and Petrasek, Donald W.: Reinforced Metallic Composites. U.S. Patent 3,084,421, Apr. 9, 1963.

155. McDanels, David L.: Electrical Resistivity and Conductivity of Tungsten-Fiber-Reinforced Copper Composites. NASA TN D-3590, 1966.

156. Morris, E. E.: Glass-Fiber-Reinforced Metallic Tanks for Cryogenic Service. NAS 3-6292, June 1967.

157. Gleich, David: Cryogenically Formed Prestressed Composite Fiber-Metal Structures for O_2/N_2 High Pressure Gas Tanks. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

158. Sumida, P. T.; Hart-Smith, L. J.; Pride, R. A.; and Illg, W.: Filamentary Composite Reinforcement of Metal Structures. Paper presented at Society of the Plastics Industry, 28th Annual Western Conference (Coronado, California), May 5-7, 1971.

159. Stuckey, J. M.: Development of Advanced Materials Composites for Use as Internal Insulation for Liquid Hydrogen (SUB 2) Tanks. NAS 8-25873, 1971.

160. Anon.: NASA Space Shuttle Technology Conference, Volume 2: Structures and Materials. NASA TM-X-2273, Apr. 1971, pp. 626.

161. Kelsey, R. H.; and Raynes, B. C.: Filamentized Ceramic Radome Techniques. ASD TDR 62-721, Aug. 1962. (Available from D DC as AD 28345-1).

162. Musikant, S.; Magin, F. P., III; Gebhardt, J. J.: The Development of REI Mullite (Reusable External Insulation). Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

163. Sliney, H. E.; White Graphite Solid Lubricant. Interview at NASA, Lewis Research Center. Jan. 1972.

164. Demorest, K. E.: Materials (Lubricants Development). NAS 8-26619, Dec. 31, 1970.

165. Perkins, R. B.; and Glarum, S. N.: Adhesives, Sealants, and Gaskets. NASA SP-5066, 1967.

166. Van Auken, R. L.; and Chase, V. A.: Composite Seals for Liquid Hydrogen and Nuclear Radiation Environments. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

167. Wisander, D. W.; & Johnson, R. L.: Filled Polymers for Bearings and Seals Used in Liquid Hydrogen. NASA Tech Brief 70-10573, Oct. 1970.

168. Desan, P. O.; & Emmons, W. F.: Low-Temperature Radiation-Resistant Material for Ball-Bearing Retainers. NASA Tech Brief 70-10576, Nov. 1970.

169. Bilow, N.; Landis, A. L.; and Miller, L. J.: New Hyperthermal Thermosetting Heterocyclig Polymers. NASA Tech Brief 70-10403, Aug. 1970.

170. Hughes, C. T.: Preparation and Characterization of Low DP End-Capped Pyrrone Moldings. NASA CR-1633, 1970.

171. Hughes, Charles T.; and Price, Howard L.: Preparation and Compression Molding of a Low DP End-Capped Pyrrone (BTDA-DAB). Paper presented at the Fourth Annual Symposium on High Performance Composites, Washington University (St. Louis, Missouri), Apr. 8-9, 1969.

172. Morgan, P. E. D.; and Scott, H.: Simultaneous Polymerization and Molding of Pyrrone Polymers. NASA CR-1737, 1971.

173. Price, Howard L.; and Bell, Vernon L.: Preparation and Compression Molding of Salt-Like Intermediate Pyrrone (BTDA-EG-DAB). Paper presented at the 27th Annual Technical Conference of the Society of Plastic Engineers (Chicago, Illinois), May 5-9, 1969.

174. Price, Howard L.; and Bell, Vernon, L.: Radiation Stability of Unfilled Pyrrone Moldings. Paper presented at the 15th National SAMPE Symposium (Los Angeles, California), Apr. 29-May 1, 1969.

175. Vaughan, R. W.; Jones, R. J.; Sheppard, C. H.; and Burns, E. A.: Development of a Low Void Polyimide Resin for Autoclave Processing of Glass and Graphite Reinforced Composites. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

176. Serafini, T. T.; Delvigs, P.; and Lightsey, G. R.: Thermally Stable Polyimides from Solutions of Monomeric Reactants. NASA Tech Brief 71-10442, Nov. 1971.

177. Doyle, H. M.: Adhesive for Cryogenic Temperature Applications. NASA Tech Brief 69-10074, Mar. 1969.

178. Soffer, Louis M.; and Molho, Ralph: Cryogenic Resins for Glass-Filament-Wound Composites. NAS 3-6287, Jan. 1967.

179. Paine, T. O.; and Welling, C. E.: Thermally Activated Foaming Composites. U. S. Patent 3,481,887, Dec. 2, 1969.

180. Hall, Eric; and Marshall, K. T.: The Quest for Lightness. Yachting, vol. 128, Sept. 1970, pp. 52, 54, 110, 112, 114, 116, 118.

181. Ward, John: Interview at NASA Langley Research Center, Nov. 1971.

182. Holcomb, W. N.: Design and Development of a Boron-Glass-Epoxy Lightweight Composite Gear Case. Paper 71-GT-85 presented, under auspices of ASME, at the Gas Turbine Conference and Products Show (Houston, Texas), Mar. 28-Apr. 1, 1971.

183. Demorest, K. E.: Self-Lubricating Gear. NASA Tech Brief 69-10408, Sept. 1969.

184. Lander, L. L.: Time and Temperature Dependent Modulus of Pyrrone and Polyimide Moldings. NAS 1-8495. July 1971.

185. Korb, L. J.; and Nadler, M. A.: Space Shuttle Oriented Polyimide Matrix Composite Studies. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

186. Anon.: Epoxy/Graphite Golf Club is Computer-Designed. Modern Plastics, vol. 48, no. 11, Nov. 1971, pp. 30.

187. Anon.: Graphite Puts Oomph! in Sports Gear. Design News, vol. 27, no. 6, Mar. 20, 1972, pp. 8-9.

188. Anon.: Plastics in the News. SPE Journal, vol. 28, Jan 1972, pp. 6.

189. Anon.: Foreign Science, Soaring Magazine, vol. 36, no. 1, Jan. 1972, pp. 20.

190. Kramer, B. E.; Potter, D. Y.; and La Iacona, F. P.: Development of High Strength, Brazed Aluminum, Honeycomb Sandwich Composites Adaptable for Both Elevated and Cryogenic Temperature Applications. NAS 8-5445, Sept. 30, 1966.

191. Burns, E.; Jones, J.; and Lubowitz, H.: Polyimide Polymers Provide Improved Ablative Materials. NASA Tech Brief 70-10300, July 1970.

192. Rocci, S. A.: The 210-Ft. Parabolic Fully Steerable Tracking Antenna for a Deep Space Instrumentation Facility (JPL).

Ch. 4 in Deep Space and Missile Tracking Antennas. The American Society of Mechanical Engineers, Aviation and Space Division, 1966, pp. 50-70.

193. Anon.: Medical Benefits from Space Research-Biomedical Application Team, Southwest Research Institute, NASA Contributions in the Field of Rehabilitations.

194. Williams, D. F.: The Properties and Medical Uses of Materials. Part Four: New Materials. Biom. Eng., vol. 6, no. 6, June 1971, pp. 260-264.

195. Benson, James: Carbon Offers Advantages as Implant Material in Human Body. NASA Tech Brief 69-10087, Apr. 1969.

196. Ring, N. D.; and Benford, J. M.: Carbon Fibre-Based Harness for Artificial Arms. Biomed. Eng., vol. 6, no. 1, Jan. 1971, pp. 17-21.

197. Hill, James T.; Eaton, James C., Jr.; Mouhot, Henry G.; and Leonard, Fred: Porous Plastic Prostheses. J. Biomed. Mater. Res., vol. 1, 1967, pp. 253-361.

198. Lee, Henry; and Neville, Kris: Handbook of Biomedical Plastics. Pasadena Technology Press, 1971.

199. Kay, Hector, W.: Clinical Evaluation of the Engen Plastic Hand Orthosis. Artificial Limbs, vol. 13, no. 1, Spring 1969, pp. 13-26.

200. Grover, Horace, J.: Some Engineering Aspects of Metallic Orthopedic Implants. Battelle Tech. Rev., vol. 17, no. 4, Apr. 1968, pp. 17-22.

201. Homsy, Charles, A.: Biocompatibility in Selection of Materials for Implantation. J. Biomed. Mater. Res., vol. 4, 1970, pp. 341-356.

202. Musikant, S.: Quartz and Graphite Filament Reinforced Polymer Composites for Orthopedic Surgical Application. J. Biomed. Mater. Res. Symp., vol. 1, 1971, pp. 225-235.

203. Hulbert, S. F.; Young, F. A.; Mathews, R. S.; Klawitter, J. J.; Talbert, C. D.; and Stelling, F. H.: Potential of Ceramic Materials as Permanently Implantable Skeletal Protheses. J. Biomed. Mater. Res., vol. 4, 1970, pp. 433-456.

204. Fryer, Thomas B.: Implantable Biotelemetry Systems. NASA SP-5094, 1970.

205. Mears, D. C.: The Limitations of Available Prosthetic Metals. J. of Metals, vol. 16, Mar. 1964, pp. 229-231.

206. Crimmins, David S.: The Selection and Use of Materials for Surgical Implants. J. of Metals, vol. 21, Jan. 1969, pp. 38-42.

207. Ludwigson, D. C.: Today's Prosthetic Metals. Are they Satisfactory for Surgical Use? J. of Metals, vol. 16, Mar. 1964, pp. 226-229.

208. Radnofsky, Matthew, I.: New Materials for Manned Spacecraft, Aircraft, and Other Applications. Proc. of the NASA Conference on Materials for Improved Fire Safety, pp. 10-1 - 10-15. Houston, Texas, May 6-7, 1970.

209. McIntyre, Ruluff D.: High-Strength Tantalum Composite by Thermomechanical Working. NASA TN D-5640, 1970.

210. Talboom, F. P.; Elam, R. C.; and Wilson, L. W.: Evaluation of Advanced Superalloy Protection Systems. NASA CR-72813, 1970.

211. Blankenship, C. P.: Oxide Deformation and Fiber Reinforcement in Tungsten-Metal-Oxide-Composite. NASA TN D-4475, 1968.

212. Kalke, B. R.: Hemodynamic Features of a Double-Leaflet Prosthetic Heart Valve of a New Design. Trans. Am. Soc. of Artificial Internal Organs, vol. 13, 1967, pp. 105-110.

213. Anon.: Organic Reactants Rapidly Produce Plastic Foam. NASA Tech Brief 65-10288, Sept. 1965.

214. Jones, William, J.; and Simpson, Wyatt C.: Cardiovascular Monitoring. NASA SP-5041, 1966.

215. Johnson, Leonard, N.: Composite Resins as a Dental Restorative Material. J. Biomed. Mater. Res. Symp., vol. 1, 1971, pp. 207-223.

216. Brown, R. L.: Dental Filling Material Comprising Vinyl Silicon Treated Fused Silica and Binder Consisting of the Reacton Product of Bisphenol A and Glycidyl Acrylate. U.S. Patent No. 3,066,112, Nov. 27, 1962.

217. Lee, H.: Advances in the Synthesis of Epoxy Resins for Adhesion to Dry and Wet Tooth Structure. Adhesive Restorative Dental Materials, II. Proc. from the Second Workshop sponsored by the Biomaterials Research Advisory Committee, National Institute of Dental Research, 1965, pp. 232.

218. Von Fraunhofer, J.A.; L'Estrange, P.R.; and Marck, A.O.: Materials Science in Dental Implantation and a Promising New Material: Vitreous Carbon. Biomed. Eng., vol. 6, no. 3, Mar. 1971, pp. 114-118.

219. Cowlard, F.C.; and Lewis, J.C.: Vitreous Carbon - A New Form of Carbon. J. of Materials Science, vol. 2, 1967, pp. 507-512.

220. Dawn, Frederick, S.: Nonmetallic-Materials Development for Spacecraft Applications. Proc. of the NASA Conference on Materials for Improved Fire Safety, pp. 6-1 - 6-19. Houston, Texas, May 6-7, 1970.

221. Fish, Richard H.: The Performance of Lightweight Plastic Foams Developed for Fire Safety. Proc. of the NASA Conference on Materials for Improved Fire Safety, pp. 11-1 - 11-20. Houston, Texas, May 6-7, 1970.

222. Barnett, J.H. Jr.: NASA Firesuit Development Plan. NASA Manned Spacecraft Center, Houston, Texas, Dec. 9, 1970.

223. Sauers, Dale G.: Development and Application of Flame-Resistant Polymers and Composites. Proc. of the NASA Conference on Materials for Improved Fire Safety, pp. 8-1 - 8-31. Houston, Texas. May 6-7, 1970.

224. Paul, H.: Power Transmission of The Future - Microwaves or Superconductors? Electronics and Power, vol. 16, May 1970, pp. 171-175.

225. Buxton, R. W.; Hanson, R. N.; and Fernandez, D.: Design Improvements in Liners for Glass-Fiber Filament-Wound Tanks to Contain Cryogenic Fluids. NAS 3-4189, Jan. 20, 1966.

226. Anon.: Multilayer Insulation Takes 4000°F. Materials Eng., vol. 74, no. 5. Oct. 1971, pp. 33.

227. Anon.: MIT Builds Superconducting Electric Power Generator. Research/Development, vol. 23, Mar. 1972, pp. 6.

228. Garwin, R. L.; and Matisoo, J.: Superconducting Lines for the Transmission of Large Amounts of Electrical Power Over Great Distances. IEEE Proc., vol. 55, no. 4, Apr. 1967, pp. 538-548.

229. Nored, Donald L.; and Laurence, James C.: Cryogenics and Superconductivity. Selected Technology for the Electric Power Inductor. NASA SD-5057. Lewis Research Center, Cleveland, Ohio, Sept. 11-12, 1968.

230. Burck, Gilbert: Transportation's Troubled Abundance. Fortune, vol. 84, no. 1, July, 1971, pp. 59-62, 137-139.

231. Anon.: Plastics Face Critical Tests as Automotive Standards Tighten. Product Engineering, vol. 43, no. 3, Mar. 1972, pp. 18-21.

232. San Diego Aircraft Engineering, Inc.: Potential Structural Materials and Design Concepts for Light Aircraft. NASA CR-1285, 1969.

233. Sumida, P. T.: A Demonstration Program Plan Utilizing Composite Reinforced Metals for the DC-8 Horizontal Stabilizer Structure. NAS 1-9953, June 1971.

234. Roy, Paul A.; McElman, John A.; and Henshaw, Jim: Boron Epoxy Reinforced Structural Sections. Paper presented at the National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

235. Karre, L. E.; Keller, L. B.; and Miller, L. J.: Development and Processing of Pyrrone Polymers. NASA CR-1310, 1969.

236. Kimmel, B.G.; and Karre, L. E.: Preparation and Characterization of the Pyrrones as Thermal Structural Materials. NAS 1-7381, 1971.

237. Grant, L. A.: Development of Beryllium Honeycomb Sandwich Composite for Structural and Other Related Applications. NAS 8-21215, Nov. 1, 1968-Jan. 30, 1969.

238. Watson, H. A., Jr.: Structural and Environmental Studies of Duct-Lining Acoustical Materials. Paper presented at the Noise Abatement Symposium of the 1969 Southern Metal Conference, NASA and MDC (West End, Grand Bahama Island), Apr. 20-24, 1969, pp. 24.

239. Anon.: Composite Recast. An AF/NASA Long Range Planning Study, Feb. 20, 1972.

240. Kong, S. J.; Fisher, G. H.; and Freeman, V. L.: Evaluation of Metal Landing Gear Door Assembly Selectively Reinforced with Filamentary Composite for Space Shuttle Application. NAS 1-10785, Mar. 1972.

241. Wennhold, William F.: Evaluation of a Metal Fuselage Panel Selectively Reinforced with Filamentary Composites for Space Shuttle Application. NAS 1-10766, Nov. 1970.

242. Oken, S.; and June, R. R.: Analytical and Experimental Investigation of Aircraft Metal Structures Reinforced with Filamentary Composites. NAS 1-8858, Nov. 1971.

243. Parker, J. A.; Fohlen, G. M.; Sawko, P. M.; and Fish, R. H.: Intumescent Coatings as Fire Retardants. NASA Tech Brief 70-10450, Sept. 1970.

244. Radnofsky, Matthew, I.: Improvement of Fire Safety in Aircraft. NASA, Manned Spacecraft Center, Houston, Texas.

245. Neel, Carr B.; and Fish, Richard H.: Study of Protection of Passengers in Aircraft Crash Fires. NASA, Ames Research Center, Moffett Field, California.

246. Radnofsky, Matthew, I.: Interview at NASA Manned Spacecraft Center, Nov. 1971.

247. Welge, R. T.: Application of Boron/Epoxy Reinforced Aluminum Stringers for the CH-54B Helicopter Tail Cone. Phase I: Design, Analysis, Fabrication and Test, NAS 1-10459, July 1971.

248. Hieronymus, William S.: Wide Use of Composites Planned for HLH. Aviation Week and Space Technology, vol. 95, no. 9, Aug. 30, 1971, pp. 43.

249. Hackman, Lloyd E.; Dukes, Wilfred H.; and Krivetsky, Alexander: Future of V/STOL Aircraft May Depend on Composites. SAE Journal, vol. 77, Oct. 1969, pp. 64-68.

250. Howell, J.P.: Interview at NASA Langley Research Center. Oct. 1971.

251. Tillian, D.J.: Interview at NASA Manned Spacecraft Center. Oct. 1971.

252. Toth, L.W.; and Bolier, T.J.: Manufacturing Concepts in Application of Molded Advanced Composites to Aerospace Components. Paper presented at National SAMPE Technical Conference (Seattle, Washington). Sept. 9-11, 1969.

253. Anon.: New Materials. Polyimide Stands Out in High-Temperature Applications. Plastics World, Sept. 1971, pp. 261.

254. Fisher, Jim; and Ericksen, Arnold: Investigation of the Properties of Fiber Metal Acoustical Materials. NASA CR-66643, 1968.

255. Stuckey, James; and Salmassy, O.K.: Development of Advanced Materials Composites for Use as Insulations for Liquid Hydrogen Tanks. NAS 8-25973, 1971.

256. Stuckey, J.M.; and Scheck, W.G.: Development of Graphite/Polyimide Composites. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama). Oct. 5-7, 1971.

257. Miller, Michael F.; and Christian, Jack L.: Design, Manufacture, Development, Test, and Evaluation of Boron/Aluminum Structural Components for Space Shuttle. NAS 8-27738, July 1971-Sept. 1971.

258. Clary, Robert R.: Vibration Characteristics of Unidirectional Filamentary Composite Material Panels. Paper presented at the Second ASTM Conference on Composite Materials: Testing and Design (Anaheim, California), Apr. 20-22, 1971.

259. Anon.: RP: Fishing for the Fleet. Modern Plastics, vol. 46, no. 10, Oct. 1969, pp. 69-71.

260. Boulden, Larry L.: Moving Solids Like Liquids. The New Way to Transport Solid Substances Through Pipes. Machine Design, vol. 44, no. 5, Feb. 24, 1972, pp. 87-91.

261. Yaffee, Michael L.: Air Cushion Cargo Craft Tested in Canada. Aviation Week & Space Technology, vol. 95, no. 25, Dec. 20, 1971, pp. 58-60.

APPENDIX A

BIBLIOGRAPHY

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Anon.: Compact Assembly Generates Plastic Foam, Inflates Flotation Bag. NASA Tech Brief 65-10090, Apr. 1965.

Anon.: Testing Filamentary Composites. NASA Tech Brief 70-10004, May 1970.

Anon.: High Temperature Rare Earth Solid Lubricants. NASA Tech Brief 70-10175, June 1970.

Anon.: Tungsten Fiber-Reinforced Nickel Superalloy with Greatly Increased Strength at 2000°F. NASA Tech Brief 70-10183, June 1970.

Anon.: Grinding as an Approach to the Production of High-Strength, Dispersion-Strengthened Nickel-Base Alloys. NASA Tech Brief 70-10185, Apr. 1970.

Anon.: Flame-Resistant Thin Panels of Glass Fabric-Polyimide Resin Laminates. NASA Tech Brief 70-10490, Nov. 1970.

Anon.: Apollo Flame-Resistant Substitute Materials Program. NASA, Manned Spacecraft Center, Houston, Texas, 1967.

Anon.: Aircraft Lands on Lightweight Epoxy Laminate Floats. Mater. Eng., vol. 73, no. 6, June 1971, pp. 33.

Anon.: Consider Composites for Cryogenic Conditions. Mater. Eng., vol. 66, no. 6, Nov. 1967, pp. 68-70.

Anon.: Four-Inch Glass-Fiber Pipe Plowed-In. Pipeline & Gas J., vol. 198, Jan. 1971, pp. 44.

Anon.: GRP: Pipe of the Future? Petroleum Rev., vol. 24, Aug. 1970, pp. 259.

Anon.: High Strength Fibers Boost Strength of Lightweight Metals. Product Eng., vol. 42, no. 11, June 1971, pp. 24-25.

Anon.: NASA Nonmetallic Nonflammable Materials. NASA, Manned Spacecraft Center, Houston, Texas.

Anon.: Air-Supported Buildings Move into New Applications. Modern Plastics, vol. 47, no. 3, Mar. 1970, pp. 162.

Anon.: Study of Technology Requirements for Structures of Large Launch Vehicles. vol. 1, NASA CR-73343, July 1, 1969.

Anon.: Study of Technology Requirements for Structures of Large Launch Vehicles. vol. 2, NASA CR-73344, July 1, 1969.

Anon.: Study of Technology Requirements for Structures of Large Launch Vehicles. vol. 3, NASA CR-73345, July 1, 1969.

Anon.: Tape Comes to Tape Laying. Am. Machinist, vol. 113, no. 26, Dec. 29, 1969, pp. 56-58.

Alexander, J.A.; Shaver, R.G.; and Withers, J.C.: A Study of Low Density, High Strength High Modulus Filaments and Composites. NASW-1020, July 23, 1965.

Allinikov, Sidney; Ziegenhagen, John A.; and Morton, William H.: Foam-in-Place Form Fitting Helmet Liners. AFML-TR-70-21, Apr. 1970.

Bales, Thomas T.; and Cain, Ronald, L.: An Evaluation of the Slurry Compaction Process for the Fabrication of Metal-Matrix Composites. NASA TN D-6107, 1971.

Berg, K.R.: Should we Bury Boron Composites? SAMPE Quarterly, vol. 2, no. 1, Oct. 1970, pp. 36-40.

Beuyukian, C.S.: Brazing of Refractory, Superalloy and Composite Materials for Space Shuttle Applications. Welding J., vol. 50, July 1971, pp. 491-499.

Blasingame, W.; Thomas, E.V.; and DiTaranto, R.A.: Development of Damped Machinery Foundations. The Shock and Vibration Bull., Jan. 1967, pp. 81-94.

Bliton, J.L.; Christian, W.; Harada, Y.; and Rechter, H.: Refractory Composite and Coating Work Conducted at IIT Research Institute - Part I. Paper presented at the ASD-NASA 8th Meeting of the Refractory Composites Group (Fort Worth, Texas), Jan. 14-16, 1964.

Burns, E.A.; Jones, J.F.; and Lubowitz, H.R.: Polyimide Polymers Provide Higher Char Yield for Graphitic Structures. NASA Tech Brief 70-10330, Aug. 1970.

Chamis, Christos C.: Design Properties of Randomly Reinforced Fiber Composites. NASA TN D-6696, Mar. 1972.

Chamis, C.: Analysis of Multilayered Fiber Composites. NASA Tech Brief 71-10372, Oct. 1971.

Chamis, C.: Buckling of Boron/Aluminum and Graphite Resin Fiber Composite Anisotropic Panels. NASA TM X-67880, 1971.

Chamis, Christos, C.; Hanson, Morgan P.; and Serafini, Tito T.: Designing for Impact Resistance with Unidirectional Fiber Composites. NASA TN D-6463, Aug. 1971.

Christian, J.L.; Forest, J.D.; and Weisinger, M.D.: Metal Progress, vol. 97, May 1970, pp. 113-126.

Christian, J. L.: Evaluation of Advanced Metal Matrix Composite Materials. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

Cimerol, J. J.; Erickson, A. R.; and Fisher, J. I.: Investigation of the Properties of Fiber Metal Acoustical Materials. NASA CR-66643, 1968.

Cobb, Boughton, Jr.: New Fiberglass Spars. Yachting, vol. 122, no. 4, Oct. 1967, pp. 41, 80-82.

Corse, F. E.; and Kausen, R. C.: Syntactic Foam Prepregs: A New Composite Construction Material. Paper presented at 15th National SAMPE Symposium and Exhibition (Los Angeles, California), Apr. 29-May 1, 1969.

Coulbert, C. D.; Wough, J. S.; and Campbell, J. G.: Refractory Composite Materials for Spacecraft Thrust Chambers. NASA CR-118321, 1971.

Crawford, R. F.: An Evaluation of Boron-Polymer Film Layer Composites. NASA CR-1114, 1968.

Dally, J. W.; and Broutman, L. J.: Frequency Effects on the Fatigue of Glass Reinforced Plastics. J. Composite Mater., vol. 1, 1967, pp. 424-443.

Davis, John G., Jr.; and Zender, George W.: Compressive Behavior of Plates Fabricated from Glass Filaments and Epoxy Resin. NASA TN D-3918, 1967.

Dial, D. D.; and Howeth, M. S.: Advanced Composite Cost Comparison. Paper presented at National SAMPE Technical Conference (Anaheim, California), Apr. 21-23, 1971.

Dietz, Albert G.H.: Fibrous Composite Materials. International Sci. and Tech., no. 32, Aug. 1964, pp. 58-62.

Dolowy, J.F.; and Webb, B.A.: Al-B Composites Strengthening and Internal Mechanisms. SAMPE Quarterly, vol. 2, no. 1, Oct. 1970, pp. 62-67.

Dow, N.F.; and Rosen, B.W.: Evaluation of Filament - Reinforced Composites for Aerospace Structural Applications. NASW-817, Sept. 1964.

Dow, N.F.; and Rosen, B.W.: A Concept for Improving the Dimensional Stability of Filamentary Composites in One Direction. NASA Tech Brief 71-10061, Apr. 1971.

Epremian, E.: Thornel, A New Graphite Reinforcement. Applied Polymer Symp., no. 15, 1970, pp. 139-154.

Fleck, James N.; Goldstein, Mas; Jablonowski, Edward J.; and Niesz, Dale E.: Metal-Containing Filamentary. Battelle Tech. Rev., vol. 17, no. 8, Aug. 1968, pp. 16-23.

Forest, J.D.; and Christian, J.L.: Development and Application of High Matrix Strength Aluminum-Boron. Metals Eng. Quarterly, vol. 10, Feb. 1970, pp. 1-6.

Gillin, L.M.: The Engineering Potential of Fibre-Reinforced Composite Materials. J. of the Institution of Eng., Australia, July-Aug. 1969, pp. 124-134.

Greszczuk, L.B.; Miller, R.J.; and Netter, W.C.: Development of a System for Biaxial Prestressing Brittle Materials. NAS 8-21083, Sept. 1968.

Gunston, W.T.: Carbon Fibres. Sci. J., vol. 5, no. 2, Feb. 1969, pp. 39-49.

Hackworth, J. V.: Evaluation of Techniques to Fabricate Seams in High Strength Graphite Fabrics. NASA CR-111826, 1970.

Hale, D. V.; Sims, W. H.; and Lane, J. H.: A Study of Thermal Conductivity Requirements. NASA CR-61442, 1967.

Hanby, K. R.: Fiber-Reinforced Metal-Matrix Composites--1968. DMIC Report S-27. July 1, 1969.

Hanby, K. R.: Fiber-Reinforced Metal-Matrix Composites--1967. DMIC Report S-21. June 1, 1968.

Hasemeyer, Earl A.: Composites Casting Development (Part of M-512 Space Experiment). Manufacturing Development Memorandum MDM-S&E-ME-M-5-70, Mar. 24, 1970.

Hepper, Richard H.: Boron-Aluminum Structural Component for Shuttle. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

Hill, P. W.; and LeFevre, K. G.: Protective Coatings: Industrial Repairs and Maintenance with Reinforced Fiber Glass. Chemical Eng. Progress, vol. 66, no. 8, Aug. 1970, pp. 52-53.

Hood, J. C.: Glass Fiber Reinforced Plastic Tires for the Marginal Terrain Vehicle. Owens-Corning Fiberglass Corp., Granville, Ohio. pp. 1-9. (Available from DDC as AD 689 503).

Huffman, J. W.: Development of High Strength, Low Density Composite Materials for Saturn Applications. NAS 8-11108, Oct. 1965.

Jech, R. W.: A Study of the Required Critical Aspect Ratio of Fibers in Composites Intended for Stress Rupture Applications. NASA TM X-52993, 1971.

Johnson, R. P.: Research on Steel-Concrete Composite Beams. J. of the Structural Division, Proc. of the Am. Soc. of Civil Eng., vol. 96, no. ST3, Mar. 1970, pp. 445-459.

Kennedy, A. J.: The Prospects for Materials. The Aeronautical J. of the Royal Aeronautical Soc., vol. 73, no. 697, Jan. 1969, pp. 1-8.

LaChance, M.; Thompson, B.: Todd, H.; and Kuskevics, G.: Development of Composite Ionizer Materials. NASA CR-54188, 1965.

Lager, John R.; and June Reid R.: Compressive Strength of Boron-Epoxy Composites. J. Composite Mater., vol. 3, Jan. 1969, pp. 48-56.

Langley, Marcus: Carbon Fibres - The First Five Years. Flight International, vol. 100, Sept. 9, 1971, pp. 406-408.

Lankard, David R.; and Sheets, Herbert D.: Use of Steel Wire Fibers in Refractory Castables. Ceramic Bull., vol. 50, no. 5, 1971, pp. 497-500.

London, G. J.; Taylor, W.; and Herman, M.: Co-Extruded Beryllium/ Titanium Alloy Composites for Light Weight Structures. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

Lowry, D. W.; and Ciardullo, W.: CH-54B Boron/Epoxy Reinforced Tail Cone Detailed Structural Substantiation. NASA CR-111930, 1971.

Lurie, Robert M.: 3-Dimensional Reinforcements. Applied Polymer Symp., no. 15, 1970, pp. 103-111.

Manning, Charles R. Jr.; and Lineback, Lynn D.: Development of High Temperature Materials for Solid Propellant Rocket Nozzle Applications. Ninth Quarterly Progress Report, NGR-34-002-108, Oct. 1971.

Manning, Charles R. Jr.; and Lineback, Lynn D.: Development of High Temperature Materials for Solid Propellant Rocket Nozzle Applications. Seventh Quarterly Progress Report, NGR-34-002-108, May 1971.

Manning, Charles R. Jr.; and Lineback, Lynn D.: Development of High Temperature Materials for Solid Propellant Rocket Nozzle Applications. Eighth Quarterly Progress Report, NGR-34-002-108, Sept. 1971.

Mark, R. E.; Adams, S. F.; and Maiti, M.: Design of Composite Pole Laminate. Forest Products J., vol. 18, no. 4, Apr. 1968, pp. 23-28.

May, Luke C.; and Hertz, Julius: Quartz-Polyimide Processing for Advanced Randomes. SAMPE Quarterly, vol. 1, no. 3, Apr. 1970, pp. 15-25.

Mayer, Norman J.: Structural Applications for Advanced Composite Materials. NASA TM X-54860, 1964.

Meredith, O. D.; Seiferth, R. W.; and Rummel, W. D.: A Graphite/Epoxy Compression Panel for the Space Shuttle. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

Miller, M. F.; and Schaeter, W. H.: Metal Matrix Fabrication Processes. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

Morris, E. E.; and Landis, R. E.: Cryogenic Glass-Filament-Wound Tank Evaluation. NASA CR-72948, 1971.

Muir, Hugh M.: Improved Oxidation-Resistant Carbon and Graphite Materials. NASA CR-1970, 1972.

Parker, J.A.; Riccitiello, S.R.; Gilwee, W.J.; and Fish, R.: Development of Polyurethane for Controlling Fuel Fires in Aircraft Structures. SAMPE J., Apr./May 1969, pp. 41-47.

Pazmany, L.; Prentice, H.; Waterman, C.; and Tietge, F.: Potential Structural Materials and Design Concepts for Light Airplanes. NASA CR-73258, 1968.

Pazmany, L.; Prentice, H.; Waterman, C.; and Tietge, F.: Potential Structural Materials and Design Concepts for Light Airplanes. NASA CR-73257, 1968.

Petker, Ira: High-Strength Composites. Modern Plastics Encyclopedia, 1970-1971, pp. 261-262.

Petit, P.H.: An Application Study of Advanced Composite Materials to the C-130 Center Wing Box. NASA CR-66979, 1970.

Plunkett, Jerry D.: NASA Contributions to the Technology or Inorganic Coatings. NASA SP-5014, 1964.

Radar, Charles A.; and Schwartz, Anthony M.: Colloidal Asbestos Fibrils as Reinforcements for Polymeric Structures. NASA CR-893, 1967.

Reece, O.Y.: Molybdenum Wire Reinforced FS-85 Columbium. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

Reece, O.Y.: Explosive Bonding Potential for Shuttle Applications. Paper presented at National SAMPE Technical Conference (Seattle, Washington), Sept. 1969.

Reddy, V.M.; and Hendry, A.W.: An Experimental Study of the Ultimate Load Behavior of Composite Steel-Concrete Bridge Deck Structures. Build. Sci., vol. 4, Dec. 1969, pp. 119-132.

Riegner, E. I.; and Scotese, A. E.: Use of Reinforced Epoxy Models to Design and Analyze Aircraft Structures. Paper presented in AIAA/ASME 11th Structures, Structural Dynamics and Materials Conference (Denver, Colorado), Apr. 22-24, 1970.

Rogers, Charles W.: Advanced Composite Material Application to Aircraft Structures. Paper presented in AIAA/ASME 8th Structures, Structural Dynamics and Materials Conference (Palm Springs, California), Mar. 29-31, 1967.

Rogers, D. T.; and Munday, J. C.: A Modern Building Material from Asphalt and Soil. Ind. and Eng. Chemistry, vol. 8, no. 3, Sept. 1969, pp. 241-255.

Rolston, J. A.: Reinforced Plastics for Rotating Structures. SPE J., Apr. 1963, pp. 387-391.

Rosen, B. W.; and Dow, N. F.: Influence of Constituent Properties Upon the Structural Efficiency of Fibrous Composite Shells. Paper presented at AIAA/ASME 6th Structures, Structural Dynamics and Materials Conference (Palm Springs, California), Apr. 6, 1965.

Ross, J. H.: Fiber Reinforcements for Structural Composites. Mater. and Res. Standards, vol. 11, no. 5, May 1971, pp. 11-15.

Schjelderup, J. P.; and Purdy, D. M.: Advanced Composites -- The Aircraft Material of the Future. Paper presented at AIAA 3rd Aircraft Design and Operations Meeting (Seattle, Washington), July 12-14, 1971.

Schulte, E. H.; and Clifford, D. W.: Experimental Evaluation of Lightning Protective Coatings for Boron/Epoxy Composites. Paper presented at National SAMPE Technical Conference (Huntsville, Alabama), Oct. 5-7, 1971.

Shuler, W. T.: How to Get There from Here with New Materials . . . A Designer's Viewpoint. SAMPE Quarterly, vol. 2, 1971, pp. 12-14.

Singleton, R. W.: Advanced Engineering Composites from High Modulus Graphite. Paper presented at 26th Annual Technical Conference, Reinforced Plastics/Composites Division, The Society of the Plastics Industry, Inc. (Washington, D.C.), Feb. 9-12, 1971.

Smith, Ronald H.; and Caseldine, H.: Lightweight, High-Strength, Reinforced Plastic Tube-Franging Die. NASA Tech Brief 70-10273, May 1970.

Soffer, L. M.; and Molho, R.: Improved Epoxy Resin for Constructing Cryogenic Filament-Wound Pressure Vessels. NASA Tech Brief 71-10261, July 1971.

Sohl, J. D.: Development of Low-Cost Ablative Nozzles for Large Solid Propellant Rocket Motors. NASA CR-72973, 1971.

Soldatos, A. C.; Burhans, A. S.; Eckstein, B. H.; and Spence, G. B.: High-Performance Epoxy/Graphite Fiber Composites. Modern Plastics, vol. 48, no. 12, Dec. 1971, pp. 62-64.

Thornton, J. S.; Yenawine, D. L.; and Thomas, A. D. Jr.: Flexural Properties of Aluminum-Aluminum Oxide Sandwich Composites. J. Composite Mater., vol. 3, Jan. 1969, pp. 182-185.

Wall, L. B. Jr.; and Card, Michael F.: Torsional Shear Strength of Filament-Wound Glass-Epoxy Tubes. NASA TN D-6140, 1971.

Weisinger, M. D.: Forming and Machining Aluminum-Boron Composites. Metals Eng. Quarterly, vol. 11, Aug. 1971, pp. 17-25.

Williams, J. G.; and Goodman, G. P.: Structural and Materials Investigation of a 1/8-Scale-Model Space Structure of Toroidal Configuration and Filamentary Construction. NASA TN D-2652. Feb. 1965.

Williams, M. L.: Cost-Property Index for Comparing Load Bearing Materials. J. Composite Mater., vol. 4, Apr. 1970, pp. 172-177.

Winny, H. F.: Development of Fibre Composites for Structural Components of Helicopters. Textile Inst. and Ind., vol. 7, no. 12, Dec. 1969, pp. 333-336.

Winter, Jerry M.; and Peterson, Donald A.: Development of Improved Throat Inserts for Ablative Rocket Engines. NASA TN D-4964, 1969.

Wise, D. C.; and Trask, R. B.: Graphite Composites for Use as Hot Pressing Dies. Paper presented at the 73rd Annual American Ceramic Society Symposium on Advanced Materials, Apr. 28, 1971.

Yaffee, Michael L.: Carbon Strands Surge as Reinforcements. Aviation Week and Space Technology, vol. 88, May 27, 1968, pp. 61-70.

Zecca, A. R.; and Hay, D. R.: Elastic Properties of Metal-Matrix Composites. J. Composite Mater., vol. 4, Oct. 1970, pp. 556-561.

Zweben, C.; and Rosen, B. W.: A Statistical Theory of Material Strength with Application to Composite Materials. J. Mech. Phys. Solids, vol. 18, 1970, pp. 189-206.

APPENDIX B

ORGANIZATIONS AND PERSONS CONTACTED

APPENDIX B: ORGANIZATIONS AND PERSONS CONTACTED

I. NASA Langley Research Center, Hampton, Virginia 23365.
Telephone (703) 827-1110

Name and Organization	Field of Interest	Phone No.
W.M. Haraway, Materials Processing, FAB	Honeycombs, adhesive bonding, sealing, foams, etc.	827-2781
J.B. Hall, Materials Processing, SSD	High temperature insulation, rocket nozzles, graphite parts	827-2366
J.M. Cawthorn, Acoustics Branch, LD	Acoustics of materials	827-2395
R.A. Jones, Reentry Vehicles, HVD	Entry vehicle configurations. Heat transfer problems	827-2488
J.F. Ward, Flight Research Branch, LSAD	Helicopter rotor blades and rotor attachment methods	827-3621
N. Johnston, Polymer Section, MD	High heat resistant polymers (pyrrones)	827-3041
N. Kelliher, Viking Project Office	High temperature resistant polymers (pyrrones)	827-3781
A.D. McHatton, Structural Systems Division, SED	High altitude balloons	827-2635
E.C. White, Aerospace Equipment Section, SED	Decelerators (ribbon parachutes)	827-2681
F.R. Mathews, Pliant Model Dev. Section, FAB	Inflatable structures	827-3358
C. Hall, Pliant Model Dev. Section, FAB	Inflatable structures	827-3358
J.V. Boyle, Pliant Model Dev. Section, FAB	Inflatable structures	827-3358
W.C. Thompson, Impact Dynamics Section, CD	Micrometeoroid detection techniques	827-2594
W. Kinard, Meteoroid Section, SRD	SRD-Meteoroid section, sandwich structures for meteor detection	827-3704

Name and Organization	Field of Interest	Phone No.
C. P. Shore, Aerothermoelasticity Section, SD	Thermal insulation systems	827-3421
R. M. Baucom, Manufacturing Technology Section, MD	Adhesives, spotwelding, sandwich structures, etc.	827-3940
R. Pride, Composites Section, MD	Graphite and boron composite structures	827-2869
E. Mathauser, Materials Applications Branch, MD	Composite structures	827-2036
J. G. Davis, Jr., Composites Section, MD	Composite structures	827-2848
G. W. Zender, Composites Section, MD	Composite structures	827-3870
B. Dexter, Composites Section, MD	Composites structures	827-3401
T. T. Bales, Manufacturing Technology Section, MD	Metallurgy	827-3940
C. J. Shoemaker, Technology Utilization Office	Technology utilization	
P. J. Kurbjon, Technology Utilization Office	Technology utilization	

II. NASA Space Nuclear Propulsion Office, Washington, D. C. 20545 (Germantown, Maryland). Telephone (301) 973-1000

S. Snyder	Technology utilization	973-3182
N. Gerstein	Small nuclear engines	973-4567
I. Helms	Stress analysis	973-4567
H. Hessing	Metallurgical materials	973-4547

III. NASA Headquarters, Washington, D.C. 20546.
Telephone (202) 963-7101

Name and Organization	Field of Interest	Phone No.
L. Ault, Technology Utilization Office	Technology Utilization	755-3793
E.N. Case, Technology Utilization Office	Technology Utilization	755-3793
B.G. Achhammer, Office of Advanced Research and Technology	Polymeric Materials	755-3793
Norman Mayer, Office of Advanced Research and Technology	Fibrous reinforced materials	755-3280
Jim Gangler, Office of Advanced Research and Technology	High modulus fiber-glass	755-3280
Joe Maltz, Office of Advanced Research and Technology	Oxide dispersioned strengthen alloys	755-3280

IV. NASA Marshall Space Flight Center, Huntsville, Alabama 35812.
Telephone (205) 453-2121

Juan Bizarra, Technology Utilization Office	Technology utilization	453-2223
Floyd Bulette, Technology Utilization Office	Technology Utilization	453-2223
Henry Martin, Technology Utilization Office	Technology utilization	453-2226
J.W. Wiggins, Technology Utilization Office	Technology utilization	
F.P. Lalacona, Astronautics Lab., Materials Division	Fiber/metal matrix composites Metal composite fabrication methods	
L.M. Thompson, Astro. Lab., Materials Division	Fiber/polymer matrix composites Insulation systems	

Name and Organization	Field of Interest	Phone No.
Hill M. Walker, Product Technology and Process Eng. Lab., Materials Division	Fiber/polymer matrix composite processing	
Wayne Morgan Astro. Lab., Materials Division	Fiber/metal matrix comp.	
E.A. Hasemeyer, PT & PE Lab., Materials Division	Aligned eutectics, casting in space	
Keith Demorest	Lubrication	
H.M. King	Fiber reinforced ceramics	
E. Brown, PT & PE Lab., Materials Division	Fiber/metal matrix composite fabrication methods	
D.B. Franklin, PT & PE Lab., Materials Division	Aligned eutectic alloys	

V. NASA Goddard Space Flight Center, Greenbelt, Maryland 20771.
Telephone (301) 982-5042

A. Fisher, Special Materials Office	Non-metallics such as rubber and plastics, foams, etc.	982-5322

VI. NASA Manned Spacecraft Center, Houston, Texas 77058.
Telephone (713) 483-3111

John Wheeler, Technology Utilization Office	Technology utilization	483-3809
Glen Ecord, Eng. and Devel., Structures and Mechanics Division	Materials technology systems, boron fiber/aluminum radiator panels	
I.K. Spiker, Eng. & Devel., Structures and Mechanics Division	Materials technology systems, high temperature polymers, high temperature thermal protection material, adhesives for high temperature use	
J. Pavlosky, Eng. & Devel., Structures and Mechanics Division	Thermal protection systems, carbon-carbon composites	

Name and Organization	Field of Interest	Phone No.
D. J. Tillian, Eng. & Devel., Structures and Mechanics Division	High temperature thermal protection systems	
Dr. Matthew Radnofsky, Eng. & Devel., Crew Systems Division	Flame retardant materials and composites for spacecraft, aircraft, housing, and personnel	
Dr. Fred Dawn, Eng. & Devel., Structures and Mechanics Division	Flame retardant fabrics systems	
Jack Naimer, Eng. & Devel., Structures and Mechanics Division	Flame retardant fabrics and elastomers	
Dale Sauers, Eng. & Devel., Structures and Mechanics Division	Flame proof asbestos fabric and multilayered flame proof composites	

VII. NASA Ames Research Center, Moffett Field, California 94035.
Telephone (415) 961-1111

Name and Organization	Field of Interest	Phone No.
Brad Evans, Technology Utilization Office	Technology utilization	961-1111
A.V. Karpen, Technology Utilization Office	Technology utilization	961-1111
Horace Emerson, Technology Utilization Office	Technology utilization	961-1111
Dr. John Parker, Chemical Research Projects Office	Flame retardant foams	
Carr Neel, Chemical Research Projects Office	Flame retardant coatings	
Howard Goldstein, Thermal Protection Branch	High temperature thermal protection materials	
Charles Kubokawa, Bio-Technology Division	Composite materials in aircraft seating, conforming foam for seating	

VIII. NASA Lewis Research Center, Cleveland, Ohio 44135.
Telephone (216) 433-4000

Name and Organization	Field of Interest	Phone No.
P.E. Foster, Technology Utilization Office	Technology utilization	433-4000
Harrison Allen, Technology Utilization Office	Technology utilization	433-4000
H.E. Sliney, Fluid Systems and Components	Solid lubricants, graphite fiber composite aircraft brakes	
Charles Zalabak, Chemical Rockets	Thermal protective coatings for liquid propellant rocket motor combustion chambers	
John Weeton, Composite Material Branch	Dispersion strengthened alloys	
Jerry Winters, Chemical Rockets	Ablative insulation in oxidizing environmental and erosion resistant coatings for rocket nozzles	
R.A. Signorelli, Composite Material Branch	Fiber reinforced metal matrix composites	
Richard Kemp, Structural Mechanics and Polymers Branch	Fiber reinforced polymer matrix, composite structures, filament wound pressure vessels	
Christos Chamis, Structural Mechanics and Polymers Branch	Structural analysis of fiber reinforced polymer matrix composites	

APPENDIX C

GLOSSARY

APPENDIX C: GLOSSARY

Aligned Eutectic: See the definition for directionally solidified eutectic alloys.

Annular: Ring-shaped.

Borsic: Silicon carbide coated boron fibers. (United Aircraft Co. proprietary treatment.)

Brazing: A process which joins metals and involves the use of a filler material having a melting point higher than 800°F but lower than the metals to be joined.

Cermet: A composite which consists of ceramic particles embedded in a metal.

CNR: Carboxy nitroso rubber - a flame resistant elastomer.

Collimated: Unidirectional arrangement of fibers.

Compatibility: The property of two or more substances to combine with each other to form a homogeneous composition.

Composite: A material made up of several identifiable phases, combined in an ordered fashion, to provide specific properties, different from or superior to those of the individual materials.

Core: The central part of a sandwich construction, to which the facings of the sandwich are attached.

Cryostat: Insulated container used to store fluids at cryogenic temperatures.

Cure: Process of polymerization of a resin, usually by heat and/or catalytic action, with or without pressure.

CTOL: Conventional take-off and landing aircraft.

Diffusion Bonding: Method of joining metals by forming a bond between two similar or dissimilar surfaces, without the presence of a liquid phase at the interface, by means of pressure and heat.

Dimensional Stability: Property of a material or part to show minimum change in shape and/or size throughout a temperature range.

Directionally Solidified Eutectic Alloys: Using a selected alloy composition, particles of high strength and/or special physical properties are produced, aligned and bound to the matrix in one process. A controlled temperature gradient causes directional solidification of the alloy and a directional heat flow pattern is developed. The controlled cooling causes directionality in the two phases.

Dispersion: Distributing a particulate reinforcement through a matrix material.

Drostholm Process: Filament winding process to produce continuous lengths of glass fiber reinforced polyester or epoxy pipes, tubing, tankage, plating, etc.

Electroless: Catalytic deposition from solution in which the deposited material catalyzes the reaction so that deposition is continuous.

Electron-Beam Vapor Deposition: An electron beam is used to vaporize material for purpose of deposition.

Electron-Beam Welding: A high power electron gun generates a narrow stream of high velocity electrons which produce a narrow zone of molten metal. This fuses the parts together.

Eutectic: Intimately mixed solids, frequently two, formed upon cooling from a liquid solution, the number of solids being the same as the number of components in the system. The eutectic melting point frequently has the lowest melting point in the material system.

Fibers: Relatively short lengths of various very small cross section materials. Prepared by chopping longer filaments, or made as such originally.

Fiber Composites: Continuous or discontinuous fibers dispersed in a matrix to serve as a reinforcement.

Fibrils: Very fine, inorganic fibers.

Filament: Individual fibers of any length.

Filament Winding: Strands, impregnated with resin, are wound tightly on a mandrel (cylinder) in a prescribed pattern that varies with the type of revolution of the cylinder or the winding, or both.

Fillets: A rounded filling of the internal angle between two surfaces of a part.

Flake Composites: These consist of thin, two-dimensional particles, oriented in a planar relationship and dispersed in a matrix or held together by an interface binder.

Floc: Very short fibers, usually cellulose or wool.

Foamed Plastics Resins in a flexible or rigid cellular form, with interconnected or closed cells.

Fusion Joining: A welding process in which the materials in the parts to be joined are heated until they melt together.

GRP: Glass fiber-reinforced plastics.

Hand: Touch or feel and drape characteristics, particularly of a fabric.

Hat Section: The cross section of a thin-walled structure that has the shape of a hat (_∩_).

Honeycomb: Resin-impregnated sheet material of paper, glass fabric, etc., or sheet metal formed into connected hexagonally shaped cells and used as core stock in honeycomb sandwiches.

Hybrid Composites: A material formed of a composite and a monolithic structure; e.g., a hollow aluminum extrusion filled with epoxy-impregnated boron fibers.

Impregnate: Saturation of the reinforcement with a resin in reinforced plastics.

Infiltration: Process of permeation of a skeletal matrix by the reinforcing material, or permeation of reinforcement fibers by the matrix.

Interface: The surface between two different materials.

Interfacial Bonding: Similar to diffusion bonding but not necessarily in metals.

Intumescence: This phenomenon is caused by the presence of a gas-liberating agent in a composite. When heated, the material foams and has a tremendous volume change. In the form of a paint film, heat causes swelling, and a fine textured, low density foam is formed with good insulating properties and good resistance to ignition. The gases evolved may also serve as flame quenchers.

Laminar Composites: Two or more layers of material bonded together.

Lay-up: In reinforced plastics, the reinforcing material is placed in position on the mold by hand, rather than by machine injection or by press action.

Lenticular: Lens-shaped.

LOX: Liquid oxygen.

MAGLEV: Magnetically levitated vehicles.

Mandrel: The core around which paper-, fabric-, or resin-impregnated glass is wound to form pipes or tubes.

Mat: A fibrous material of randomly oriented filaments, used to reinforce plastics.

Matrix: The material used to bind together the reinforcement material, to transfer the load from fiber to fiber or from particle to particle. The matrix determines the shape and form of the composite.

MHD, Magnetohydrodynamics: The interaction between an electrically conductive liquid and the electric and magnetic field. The fluid may be an ionized gas or a conductive liquid.

MLI: Multilayer Insulation System.

Modulus of Elasticity: The ratio of the stress or load applied to the strain or deformation produced in a material that is elastically deformed. (Young's Modulus.)

Modulus, Shear: The ratio of the shear stress to the strain in the material, over the range for which this value is constant.

Modulus, Tensile: The ratio of the tensile stress to the strain in the material over the range for which this value is constant.

Monolithic: Single phase, bulk material.

Neuromuscular: Pertaining jointly to nerves and muscles.

Omniweave: ® Three-dimensional weaving. Fabrics are produced with multidirectional fibers and the interlocking fibers are woven in three dimensions so that there are no discrete layers.

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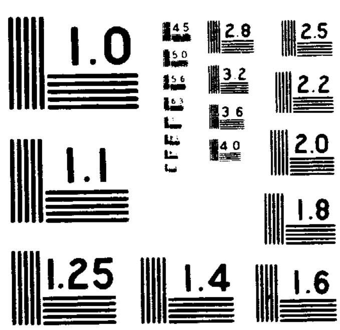

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963

Opponens: Any of the several muscles of the hands or feet which allows movement of fingers or toes toward each other.

Orthopedic: Correction of deformities of the skeletal system, either bones or muscles.

Orthosis: The straightening of a deformity.

Particulate Composites: Particles of varying size and of regular or irregular shape, embedded in a matrix.

PBI: Polybenzimidazole.

Phase: Homogeneous, physically distinct and mechanically separable portion of a mixture.

Plasma Spraying: Material heated until ionized before spraying.

Prepregs: Catalyzed ready-to-mold material in sheet form, comprising cloth, mat, or paper which is impregnated with resin and stored for use.

Prosthetic: An artificial substitute for a missing part of the human body.

psia: psi, absolute

Pultrusion: Manufacture of rods, tubes, and structural shapes by pulling thermoset resin-impregnated fiber bundles through a die and a heat-curing zone.

Pyrolysis: Chemical decomposition by heat.

Radiopacity: Opaque to x-rays.

Reinforcement: The structural component of a composite, which may be in the form of fibers, flakes, particles, or laminae. They may be held or embedded in the matrix and determine largely the physical properties of the composite.

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Rovings: A collection of bundles of continuous filaments, either untwisted strands or twisted yarns. They may be lightly twisted, but for filament winding they are generally wound as bands or tapes with as little twist as possible. Glass rovings are used predominantly in filament winding.

Sandwich Construction: Panels composed of a lightweight core material, honeycomb or foamed plastic, etc., to which two relatively thin, dense, high-strength facings or skins adhere.

Scrim: A low-cost, non-woven, or very open-weave reinforcing fabric.

SEMI: Self Evacuating Multilayer Insulation.

Sizing: Application of a material to a surface, in order to fill the surface pores and irregularities and reduce absorption of the adhesive or coating which is then applied. Sizing also may be used to improve adhesion. The material used for this purpose is also called a primer.

Skeletal Composites: These are composed mainly of a three-dimensional, continuous network constituent, into which is introduced a second constituent. An open-celled foam filled with resin and a filled honeycomb are examples.

Slurry: A thin, watery mixture of clay or other finely divided material and water or other liquid.

STOL: Short take-off and landing aircraft.

Superconductors: Materials whose electrical resistivity becomes zero at a temperature near absolute zero.

Syntactic Foam: A cellular plastic formed by incorporating very small hollow spheres or micro-balloons in a resin matrix.

Tack Welds: Tack welds are used in part assembly and consist of a series of short welds at convenient distances along the unit.

TACV: Tracked air cushion vehicles.

Teflon, TFE: Polytetrafluoroethylene.

Teflon, FEP: Fluorinated ethylene-propylene copolymer.

Tows: Graphite fibers made from rayon precursor, are prepared in bundles of 1000 to 10,000 collimated filaments, either twisted or untwisted.

Unidirectional Laminate: A reinforced plastic laminate in which most of the fibers are oriented in the same direction.

Velcro: This fastener is a composite utilizing a fabric pile and nylon or other plastic hooks.

Vitallium: 30% chromium-5% molybdenum-65% cobalt. A metal used for internal prostheses.

VTOL: Vertical take-off and landing aircraft.

Wetting: Ease with which a liquid will spread or flow over a given surface.

Whiskers: Elongated crystals ranging in size from submicron, i.e., less than 0.0004 in., to over 0.001 in. in diameter.

APPENDIX D

SUBJECT INDEX

APPENDIX D: SUBJECT INDEX

END

DATE

FILMED

MAR 12 1973