APPLICATIONS OF COMPOSITE MATERIALS IN SPACE VEHICLE STRUCTURES

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I. - ABSTRACT

The characteristics of filamentary composite materials are reviewed and compared with the structural design requirements of vehicles used in space operations. Numerous potential applications of filamentary composites in space vehicles are identified but few have been made or planned. Additional applications await solution of basic problems in analysis, design, fabrication, and reliability.

II. - INTRODUCTION

Filamentary composite materials have become the subject of great attention in recent years (1, 2, 3, 4) because lower structural mass or other advantages can accrue from their use in structural applications. Over one hundred million dollars have been expended in research and development on filaments and composites in just the last few years. Only about 10 percent of this effort, however, has been directed toward space vehicle structures and only a few applications have been made. Why have composites been used so little to date and what are the potential uses of these materials in space vehicles? Applications of composites in space vehicle structures will be reviewed in this paper to examine reasons for slow acceptance of composites and those situations in which future utilization appears most promising. Characteristics of composites will be considered first, followed by a discussion of the

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space vehicle design process and several examples of specific applications in which composites appear to have merit.

The term "composite material" can encompass many things, consequently, herein it will be limited to composites composed of long, small-diameter filaments uniformly oriented in an appropriate matrix. In addition, the term "space vehicle" will be used to describe those vehicles, used for operations in space, that can be categorized as launch, space, entry, and landing craft. Within these definitions, there are numerous filamentary composite materials and a large variety of vehicles and space missions that make generalization difficult. Therefore, only a few representative structural applications and composite materials can be considered.

The International System of Units (SI) is used to express all physical quantities in this paper (5).

III. - CHARACTERISTICS OF FILAMENTARY COMPOSITES

The selection of materials for flight vehicle structures is based on numerous properties, parameters, and considerations. For example, the NASA Special Committee on Materials Research for Supersonic Transports (6) used 14 parameters to screen candidate materials. That list has been modified and extended herein to provide a basis for a generalized evaluation of filamentary composites for use in space vehicle structures, figure 1. Properties and factors that influence the selection of typical structural materials for representative space vehicle applications are listed under rating categories of Plus, Minus, and More Data Needed that indicate the relative merits of each characteristic of composites when compared to conventional materials. Some of these items can be established quantitatively, but others are qualitative or subjective. The list is not intended to be exhaustive and many of these ratings are debatable. Certainly, any such general evaluation is controversial and exceptions can be found for every item.

A detailed discussion of each item could fill as many papers, so a few general comments must suffice. Composites have numerous "pluses" that include unique features such as tailored design, but many other important factors are not good or are still in doubt. For example, much more data on the effects of the space environment on composite materials are needed before the place of these materials in space structures can be established. The greatest deficiencies are the result of the relative newness of this technology, limited availability of required design methods, and the cost and complexity of designing functional structures with materials which, in turn, are small-scale structures that require rigorous stress analysis. The relationship of these factors to space vehicle structural applications should become somewhat clearer after specific cases are discussed in the sections to follow.

The plus characteristics of filamentary composites that make them most interesting for use in structures are the high specific strength and stiffness available in filaments. The discussion that follows, therefore, will concentrate on space vehicle components in which strength and stiffness are important. Composites are highly interesting, however, for many space structures because of other unique or outstanding properties; a few such cases will be included, too. The typical composites in most examples cited in this paper will be existing filaments in an existing resin matrix; other matrices, such as metals, may provide additional advantages, but are not given detailed consideration herein because their future development is not expected to alter the conclusions substantially.

Figure 2 shows the ratios of strength and stiffness to density, on logarithmic scales, for a variety of filaments, composites, and metals. The figure also shows the reduction in properties that results from flaws in the filament, from combining filaments with a resin matrix to produce a unidirection reinforcement, and from providing filament orientations that give isotropic properties in the plane of the laminate. These factors, present in practical structures, considerably reduce the outstanding characteristics of filaments, but many composites still exceed significantly the properties of conventional materials. The use of composites to replace sheet metal, where isotropic properties are required, does not give particularly outstanding results, but the gains are substantial in those structural applications in which nearly unidirectional composites can be used. Since many structures require only small amounts of biaxiality, the ability to tailor the orientation of the filaments in each stress field provides a significant design advantage. On the basis of strength or stiffness, then, a composite may have greater material efficiency than most metals. But these two properties alone are not necessarily direct indicators of greater structural efficiency.

Figure 3 considers the structural efficiency of a simple component, a circular cylinder in axial compression (7). Structural density is plotted as a function of the structural index for cylinders of four materials - two metals, aluminum and beryllium, and two composites, glass in epoxy and carbon in epoxy. Note that for each composite, two sets of curves are used; the lower sets are for isotropic laminates with filaments in three directions, 60° apart, whereas the upper sets are for unidirectional composites operating at the yield stress. Other orientations may be used to advantage in the intermediate region. Experiments are needed, however, to determine if composites can achieve these calculated efficiencies since they may experience failure modes not present in ductile metals. The benefits obtainable from composite construction vary significantly with the loading intensity. The calculations indicate that composites are not superior to beryllium metal in stiffness-critical applications but they exceed the metals when advantage can be taken of their high strength in unidirectional applications. Charts such as this provide comparison of the efficiency of materials in simple components under simple loading conditions in which only strength, stiffness, and density are important. In specific applications, strength and stiffness affect the structural mass in more complicated ways. In addition, many other material characteristics must be considered in the selection of practical structural materials.

IV. - SPACE VEHICLE DESIGN CONSIDERATIONS

To determine how materials are selected for space vehicle structures, it is enlightening to review the space vehicle design process outlined on figure 4. An iterative cycle of mission analysis, establishment of design criteria, and selection of appropriate structural configurations and materials is employed (8). Each phase is influenced by the loads and environments that the spacecraft experiences during the mission. Mission analysis considers alternate ways in which the mission objectives might be accomplished to arrive at the optimum approach; it usually identifies one or more mission modes in which state-of-the-art structures and materials technology are acceptable. The selection of mission mode, structural configuration, and materials is guided by three general criteria. The primary consideration for the system is high reliability and maximum assurance that the mission will be performed, as designed, on the first flight. The approach selected must also have acceptable mass and cost; that is, they must be within the limits of the project. Because mass reduction is expensive, the achievement of the lowest cost and the lowest mass is not compatible; thus, the system with the lowest structural mass is not necessarily the optimum one. Tight schedules and the reliability needed to guarantee mission success generally eliminate consideration of materials which are still in the development phase. In addition, the limited data on effects of space environment on bulk and surface properties of composites, and the present lack of methods which reliably predict some types of composite failure have discouraged space vehicle applications (9, 10). Therefore, the opportunities that composites offer for significant reduction in space vehicle structural mass are not likely to be realized until all pertinent composite characteristics are established with high confidence. Applications may be found, however, in which one of the unique characteristics of composites, other than strength or stiffness provides essential capabilities not otherwise available. For example, composites may offer the best solution if a structure must be transparent to radio frequency radiation or if particular thermal expansion characteristics are required (11, 12). The latter would take advantage of the designer's opportunity to tailor composites to the application. This opportunity to tailor materials to the application could be the greatest advantage of the composite if structural designers were more proficient in determining the optimum combination of all material properties required for each structure.

V. - SPACE VEHICLE APPLICATIONS

Some of the potential applications of filamentary composite materials in space vehicle structures are shown in figure 5. Four types of space vehicles are listed on the left and structural components of each vehicle type, in which composites may have application, are listed on the right. Every space vehicle structural element or component is a likely candidate for utilization of filamentary composites, but those listed here are representative possibilities for consideration in the following sections of this paper. Applications in current or planned vehicles, however, are much more limited. Many small structural parts of composite materials (particularly of glass in resin) have been used in all types of space vehicles (10), but only launch vehicles have utilized major structural components of filamentary composites. Plans for future space vehicles do not include much more extensive utilization. Applications must be discussed, therefore, in terms of what may come to pass rather than of what has occurred.

V-A. - Launch Vehicles

Figure 6 shows two types of future launch vehicles. The expendable type takes off vertically and is an extension of current launch vehicle technology. The reusable type, that has been the subject of much study, debate, and planning, probably will have horizontal take-off and landing capabilities. A reusable vehicle could be one stage to orbit (aerospace plane) but the two-stage approach illustrated is more likely. The first stage is a hypersonic airplane with airbreathing propulsion while the second stage is a conventional rocket vehicle. The outlook for major applications of filamentary composites in the reusable, airplane-like vehicle is poor because most of the structural materials must have high efficiency at temperatures above 800° K. This capability is not characteristic of prospective filamentary composites.

The expendable launch vehicle illustrated utilizes a combination of solid and liquid propellants, the solids being clustered around the liquid core. Current space launch vehicles such as Titan III-C and the thrust-augmented Deltas are similar combinations while the Scout uses solid rockets exclusively and the other space launch vehicles use only liquid propellants. Solid rocket motor cases and nozzles are the outstanding example of major space vehicle structural components that now use filamentary composites (13). Solid rockets for current space vehicles, however, use both metal and composite cases, with the latter more prevalent in the smaller sizes, but the prospects for increased future use are good.

Composites also have been used in the payload shrouds on at least two launch vehicles (14). The best known is the Atlas-Agena shroud used to launch a Mariner spacecraft. This shroud, of phenolic-glass honeycomb sandwich construction, failed during launch and was replaced by a ring-stiffened magnesium shroud for launching the successful Mariner IV to Mars (15). The Titan III used shrouds of fiberglass honeycomb sandwich construction on several successful flights, but because of a failure, a replacement of stiffened aluminum was designed (14). In each case, the greater structural efficiency provided by the composite was lost because of design and environmental problems. The Mariner shroud delaminated due to the increased differential pressure in the unvented honeycomb cells resulting from the decreasing external pressure, increasing temperature, and thermal outgassing during launch. A vented honeycomb would not have failed, but this approach creates other problems. Venting to the interior, for example, may significantly contaminate spacecraft surfaces.

Analytical studies (16) have been made of the reductions in structural mass that might accrue from utilizing advanced structures and materials in future, liquid-propellant, launch vehicles. Some results are summarized in figure 7. The sketch at the left indicates the vehicle studied, a 9,140,000-kilogram, two-stage launch vehicle having a payload of 370,000 kilograms. A comprehensive computer analysis was made to determine the loads experienced and the structural mass required. The base line design utilized ring- and stringer-stiffened aluminum-alloy construction typical of present launch vehicles. Honeycomb sandwich provided the lowest mass of the structural configurations examined. Relative structural mass for these two types of structures of several metals and composites is listed. Note that converting to honeycomb construction in aluminum alloy results in a substantial reduction of structural mass. Titanium provides a slight additional reduction when used in sandwich construction and beryllium is even better. Beryllium, however, is about equally efficient in either the integrally stiffened or honeycomb sandwich configurations. The use of filamentary composites in honeycomb sandwich construction saves some additional mass compared to the aluminum sandwich, but this gain is only half as great as that obtained by changing the aluminum structure from stiffened skin to honeycomb sandwich. Moreover, this benefit from composites may not be fully attainable because of practical problems such as propellant compatibility.

All three stages of the Saturn V launch vehicle use stiffened skins of aluminum instead of aluminum honeycomb sandwich with its lower mass but greater complexity and cost. Considering the opportunities to construct more efficient launch vehicle structures of materials that have been available for many years, the prospects appear dim that the designer of the next space launch vehicle will tackle the special problems of an advanced composite sandwich.

V-B. - Spacecraft

Spacecraft have a wide variety of configurations; the one shown in figure 8 is the most complex expected in the near future. This manned laboratory in earth orbit may be used for scientific and engineering research in the NASA Apollo Applications program. The components and appendages of the vehicle offer numerous opportunities for effective use of filamentary composites. Potential application areas include meteoroid shields for the cabin (17); the man-rated pressurized enclosure; the furniture and interior structure of the station; the beams, columns, and trusses used to support the various appendages; the communications antennas; the solar cell arrays that supply power; and the astronomical telescope. However, only two simple structural components, common to most spacecraft, will be discussed.

Spacecraft carry many pressure vessels for storing various fluids. For example, the Apollo space vehicle (Saturn V with Lunar Excursion, Command and Service Modules) contains six main propellant tanks, and 88 other pressure vessels that vary in volume from about 0.02 to over 4 cubic meters. This basic structural component offers an excellent opportunity for introducing composite materials technology into the space vehicles in the near future (18). A precedent also exists since the solid rocket motor case, where filamentary composites have had the greatest use in aerospace vehicles, is primarily a pressure vessel.

Figure 9 shows how pressure vessel mass can be reduced by using the high strength of filamentary composites. Most of the small pressure vessels used in space vehicles are made of titanium because of its high specific strength. Problems have arisen, however, due to stress corrosion attack by various fluids. Both cylindrical and spherical shapes have been used to meet packaging constraints although cylinders have a higher mass per unit volume. If a filamentary composite is used, an isotensoid winding can provide the same specific mass in a wide range of shapes while significantly reducing the specific mass below that for the best metallic sphere. Many combinations of filament and matrix can be used in addition to the three listed, but the least mass will always be provided by the filament with the highest useful strength (glass).

The benefits indicated here may not be achievable, however, because of practical problems such as chemical incompatibility between composite and fluid (which may be a problem for metals, also), minimum gage limitations, and porosity. Filaments in an epoxy matrix may result in a container so porous to the fluid that a liner must be added (19). Other matrices may solve such problems. Therefore, the combination of carbon filaments in a glass matrix is suggested. Methods are not now available for manufacturing this composite but it is an interesting possibility for future development. A glass surface containing the fluid could provide the utility of a soft drink bottle in a structure of the efficiency expected in aerospace applications.

Figure 10 shows a truss structure that has been designed for a space vehicle application in which the design loads arise from vibrations during launch. Design calculations have been made for a variety of materials, all in tubular form, and the relative mass of the resulting structures is shown by the bar graphs. The efficiency of all materials is reduced 20 to 30 percent by the mass of the joints, with the joint mass penalty increasing as the material efficiency increases. Welded joints can be used with aluminum but the tubes of all other materials are much more difficult to connect. Fairly sophisticated connections are required to attain the low joint mass given by these calculations. Again, the advanced composites are only slightly better than beryllium, but substantially better than aluminum or glass in epoxy. The problem of joining components of composite materials will occur in all types of structures and can have a major influence on selection of the best configuration and material. Composites will achieve more of their outstanding potential in those applications where major structural components can be fabricated in a single (filament or tape) winding operation.

V-C. - Entry Vehicles

Ablation materials for thermal protection of entry vehicles are composites but not of the filamentary types used to obtain high strength and stiffness. Figure 11 shows a replaceable heat-shield panel for a lifting-body type, earth-orbital entry vehicle to which a unique combination of properties of filamentary composites has made a significant contribution (20). The ablation material is contained in a honeycomb and supported on a glass-phenolic honeycomb-sandwich panel firmly attached to the underlying vehicle structure at a number of points. Insulation fills the space between the panel and vehicle structure. The composite sandwich provided the best approach in this particular application because it had favorable fabrication and cost characteristics and a combination of load-carrying ability, low thermal stresses, and strain compatibility with the ablator that permitted the panel to be anchored at the support points. Use of this glass-plastic honeycomb core panel on fixed supports permits the use of replaceable panels of any convenient size, whereas the best metal sandwich panel required flexible supports that significantly limit panel size. These larger panels simplify the initial vehicle construction and reduce the time required to refurbish the thermal protection system after each flight.

Figure 12 shows the sequence of events in a representative entry and landing on Mars. Vehicles for landing payloads on Mars have many new and difficult structural design problems (21). Composites may be needed on the first mission, and may make a more substantial contribution to future landings of larger vehicles.

The entry starts with a low-density body that decelerates to supersonic speeds in the very thin atmosphere of Mars. Then, one or more variable-geometry decelerating devices, such as the inflatable afterbody illustrated, are deployed to slow the lander to the speed at which the retrorocket landing system can be activated. The requirement for very low-density vehicles places great emphasis on mass reduction if large payloads are to be landed by a single vehicle. Numerous alternate ways of performing such a mission are currently under investigation but three opportunities for use of advanced composites are evident, one in the structural shell of the entry body (the aeroshell), a second in the variable-geometry decelerator, and a third in the lander. Landing craft will be discussed briefly in the next section.

The inflatable decelerator requires a flexible, impermeable, high-strength membrane that can survive the impact loads and heating of supersonic deployment. These are characteristics that are best obtained by combining several materials in a composite. A laminate of appropriately oriented thin films of high-temperature plastic strengthened by a unidirectional layer of very small-diameter glass filaments may satisfy this requirement. Such membranes could be useful in many other variable-geometry or pressure-stabilized structures of space vehicles.

Figure 13 shows a 120° conical aeroshell for an unmanned Mars entry and the relative structural mass of several combinations of structures and materials for the shell wall. The shell is designed by buckling under an external pressure. In addition to the shell wall, which constitutes 40 percent of the structural mass, large stiffening rings are required at each end and reinforcements are needed because of the discontinuity stresses introduced by the rings. The composites provide a reduction in wall mass, but the difference is not as great as anticipated. This is a very lightly loaded shell and minimum gage limitations affect the structural mass in certain cases; the composite could be used to greater advantage in the larger structure of a manned vehicle. The relative masses shown are for only the wall of the shell. End rings of composites could also be beneficial but the potential gains have not been determined yet. Structures of metals are more competitive, on a mass basis, in this case than in the others examined herein.

V-D. - Landing Craft

The last type of space vehicle to be considered is that which lands on the surface of a planet, or other body, for subsequent operations there. The Lunar Excursion Module (LEM) of the Apollo spacecraft and the Martian lander shown in figure 12 are examples. The structure and landing gear of such vehicles could utilize composites but one of the most likely applications is an expandable shelter. Figure 14 shows a structure designed to extend the lunar exploration time of the Apollo astronauts (22). It is carried to the lunar surface in a small package on the LEM for subsequent deployment and use. The wall construction, figure 15, is a composite that uses combinations of fabrics, plastics, and metal fibers to perform the required functions. Elastic recovery of the flexible foam, compressed in the container, erects and maintains the shape of the shelter without internal pressurization. The foam also provides the primary meteoroid protection but since it is an excellent insulator, copper filaments are required for proper thermal balance between the inner and outer surfaces. Steel wires provide the load-carrying capability for the internal pressure bladder and the fabric outer surface, which provides a meteoroid bumper and container, has a suitable thermal control coating. The filamentary or matrix materials used in this shelter are state of the art and such structures would not necessarily require more advanced materials. However, it is an excellent example of how the unique characteristics of filaments provide capabilities that are not readily attainable with other material forms.

VI. - CONCLUDING REMARKS

A number of potential applications of filamentary composite materials in space vehicles structures have been reviewed and cases identified in which the use of composites instead of conventional materials could significantly reduce the structural mass. The calculated mass reductions, however, are not spectacular when beryllium is the competitor and stiffness is important. Other potential attributes such as high specific strength, foldability, formability into complex shapes, and the opportunity to tailor material properties to structural requirements appear to be of greater interest in space vehicle applications. Filamentary composites have had few such applications but their utilization is expected to increase.

Figure 16 lists several space vehicle structural components wherein composites should find increased or early use, probably in the order listed. Solid rockets already make extensive use of composites and aerodynamic decelerators require combinations of material properties best supplied by composites. Similarly, composites can meet the unique needs of replaceable heat shields and expandable space structures. Pressure vessels benefit from the high specific strength of filaments whereas certain beams, columns, and truss structures can capitalize on their unidirectional properties. Large aeroshells for planetary entry may be the space vehicle application in which minimum structural mass is most important; beryllium appears best but advanced composites may be competive when all factors are considered.

The lack of widespread use of filamentary composite structures is primarily due to the relative newness of this technology and the limited design methods, low reliability and confidence, high cost, and low producibility that are characteristic of an immature engineering material. These are problems to be solved by research and development and do not constitute a physical barrier to extensive future applications.

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PLUS	MORE DATA NEEDED	MINUS
LOW DENSITY	TOUGHNESS	RELIABILITY
HIGH STRENGTH	THERMAL STABILITY	MATURITY
HIGH FABRICATED STRENGTH	FATIGUE RESISTANCE	DESIGN METHODOLOGY
HIGH STIFFNESS	CORROSION RESISTANCE	JOINTS AND CONNECTIONS
LOW THERMAL STRESS	IMPACT RESISTANCE	COST
FORMABILITY	SPACE ENVIRONMENTAL EFFECTS	
TAILORED DESIGN	DAMPING	
	PRODUCIBILITY	
	AVAILABILITY	

Figure 1.- An evaluation of filamentary composite characteristics important in space vehicle structures applications.

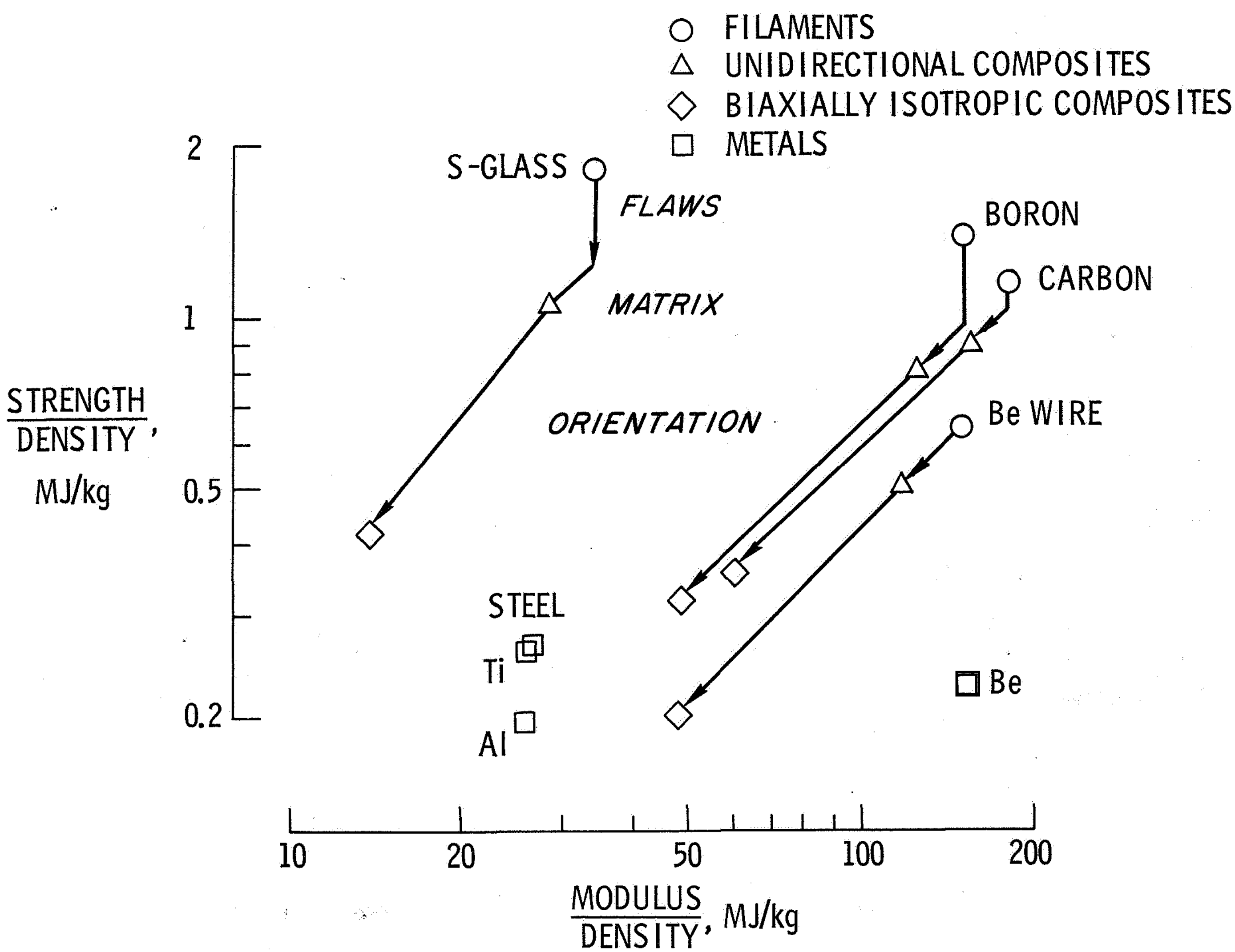


Figure 2.- Specific strength and stiffness of filaments, composites, and metals.

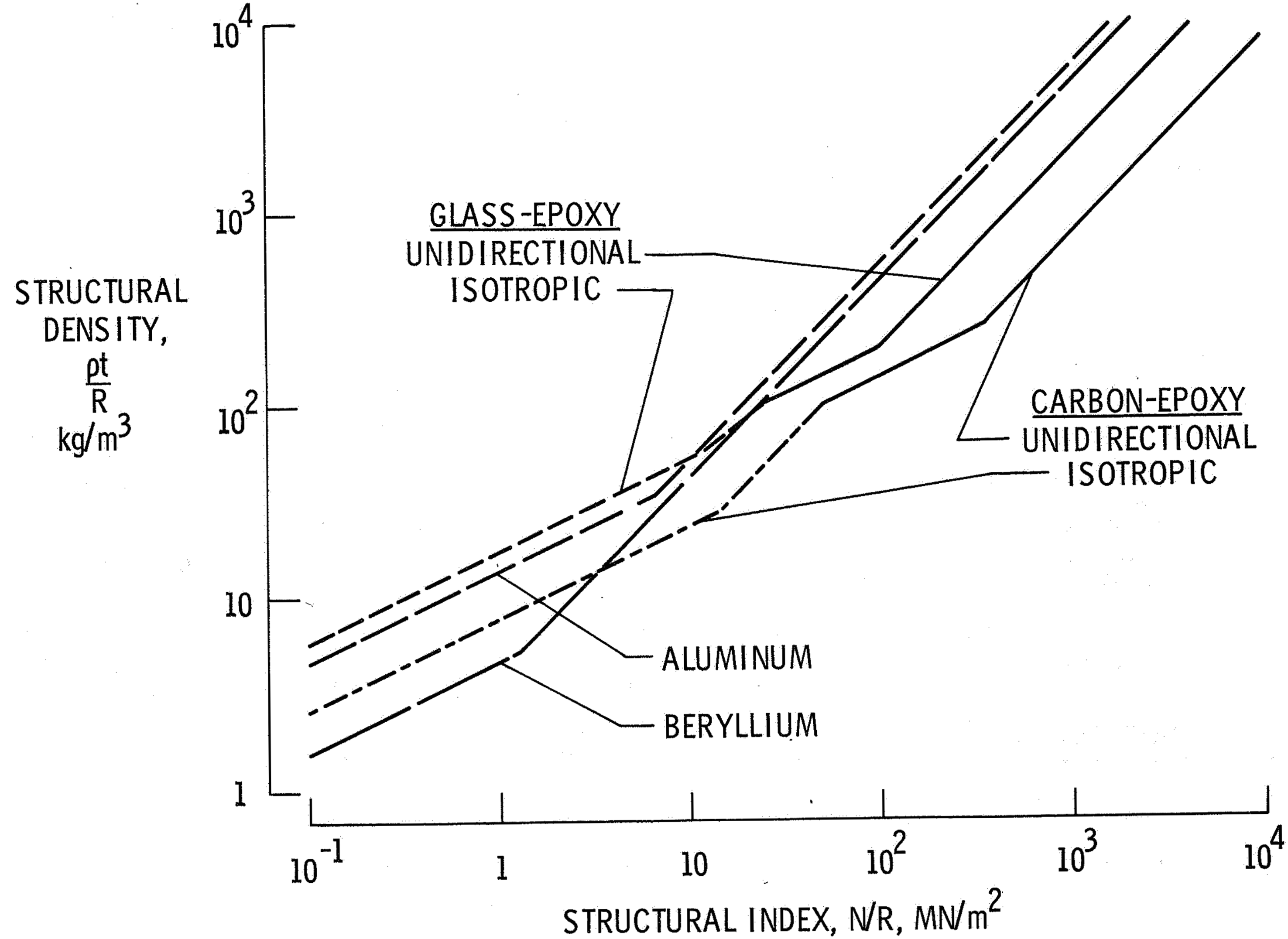


Figure 3.- Structural efficiency of materials for monocoque cylinders under axial compression.

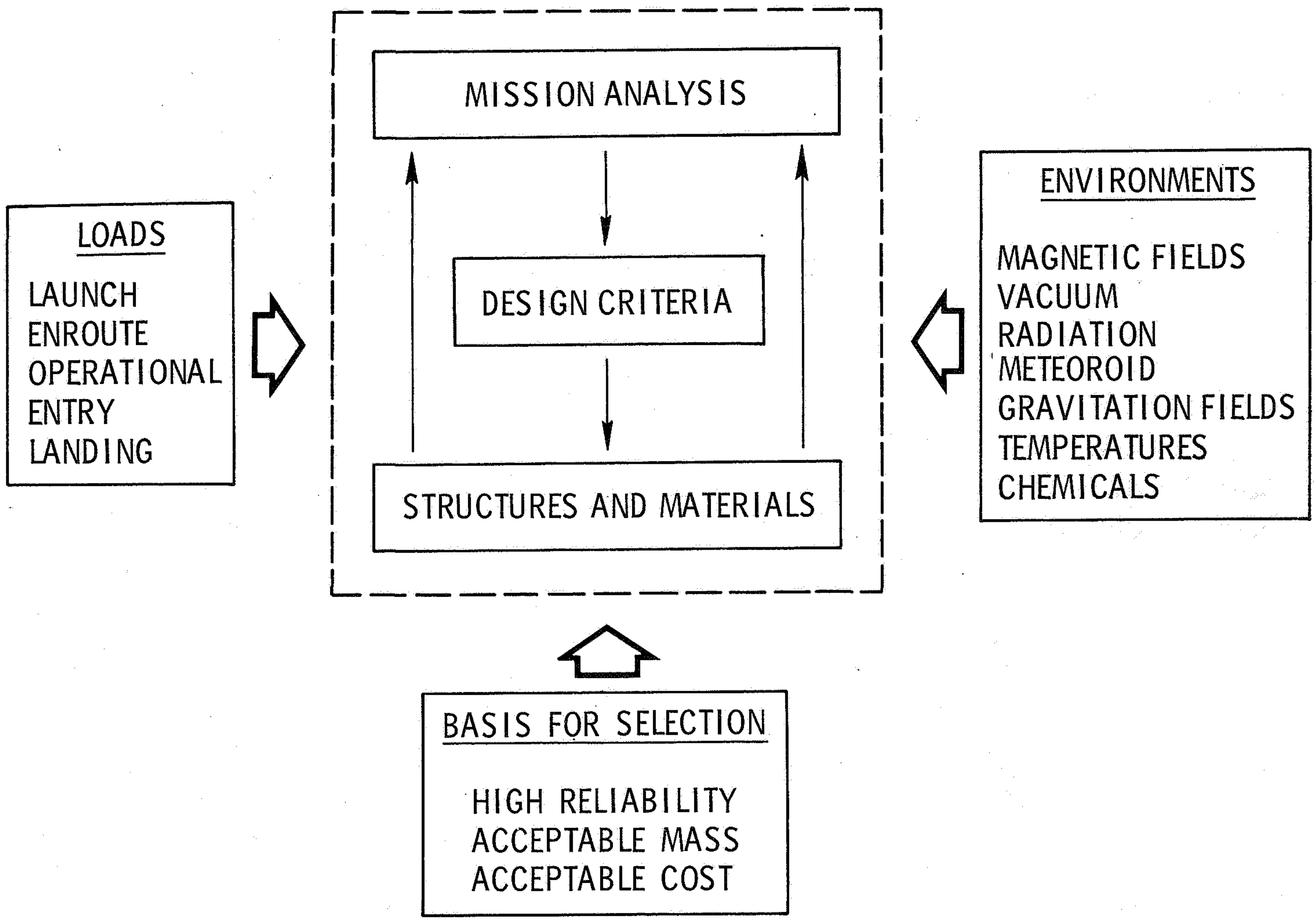


Figure 4.- The space vehicle design process.

VEHICLE	COMPONENT
LAUNCH VEHICLES SOLID, LIQUID, REUSABLE	PROPELLANT TANKS INTERSTAGE STRUCTURES PAYLOAD SHROUDS ROCKET NOZZLES
SPACECRAFT OBSERVATORIES, EXPLORERS MANNED STATIONS	PRESSURE VESSELS ANTENNAS POWER ARRAYS METEOROID SHIELDS TRUSSES
ENTRY VEHICLES BALLISTIC, LIFTING EARTH, MARS, VENUS	THERMAL PROTECTION AEROSHELLS DEPLOYABLE DECELERATORS
LANDING CRAFT LANDERS, SHELTERS, ROVERS EARTH, MOON, MARS	ENERGY ABSORBERS FRAMEWORKS CABIN WALLS

Figure 5.- Potential applications of filamentary composite structures in space vehicles.

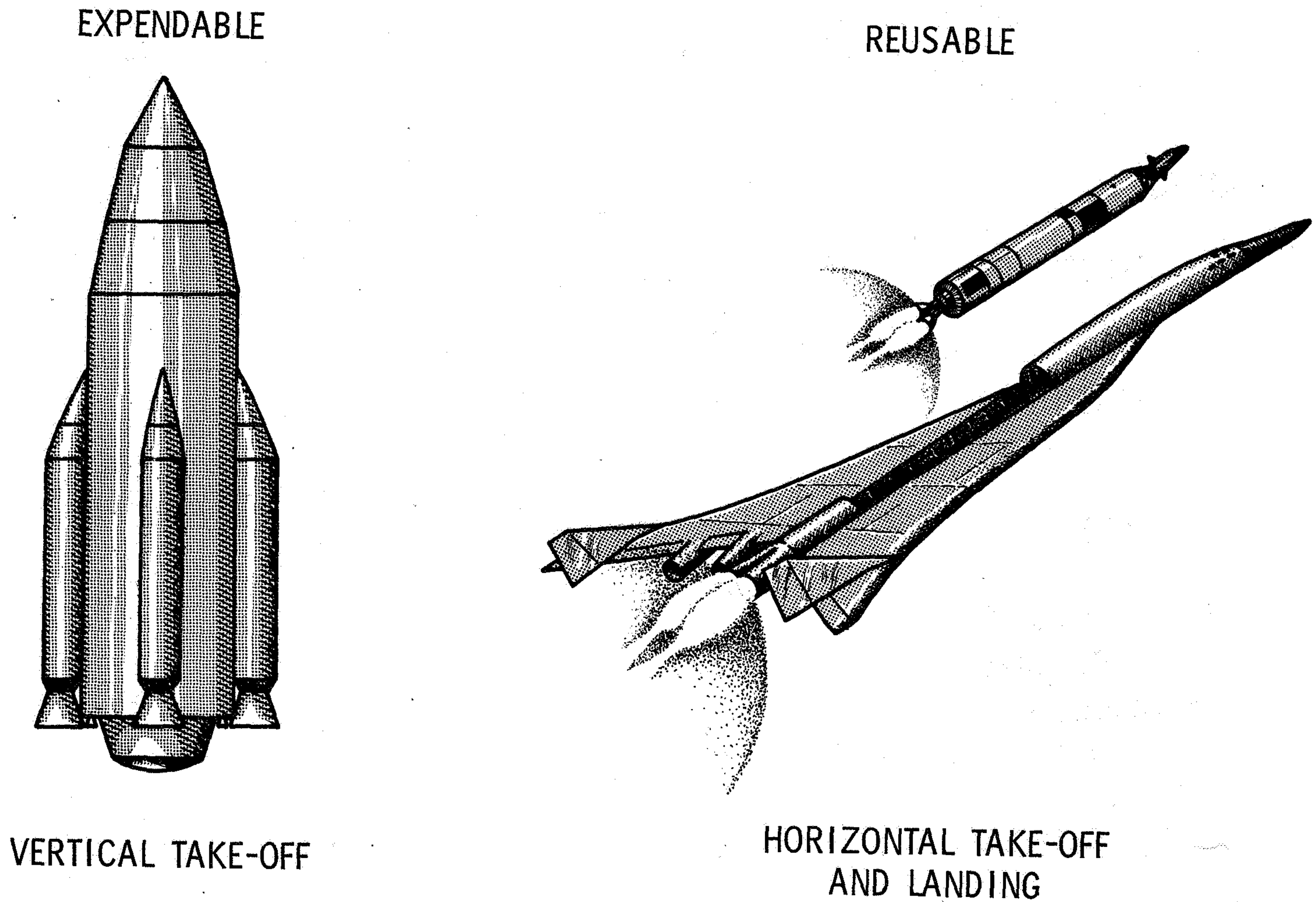
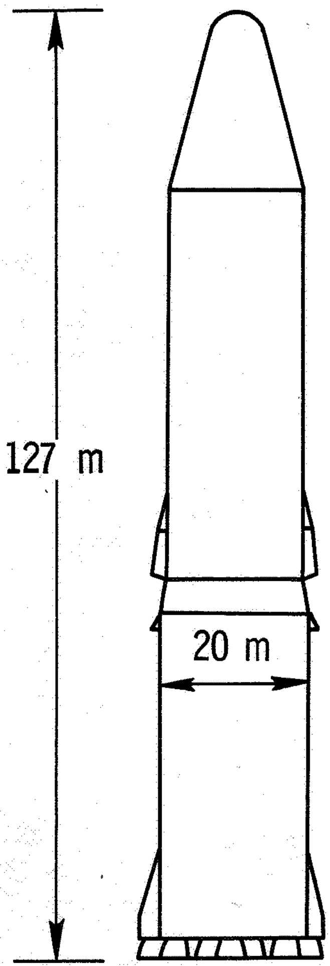


Figure 6.- Types of future space launch vehicles.



TOTAL MASS 9.14 Gg
PAYLOAD MASS 0.37 Gg

INTEGRALLY STIFFENED	
ALUMINUM	1.00
TITANIUM	1.04
BERYLLIUM	.55
HONEYCOMB SANDWICH	
ALUMINUM	0.66
TITANIUM	.61
BERYLLIUM	.53
GLASS IN EPOXY	.67
CARBON IN ALUMINUM	.47

Figure 7.- Relative structural mass of large, liquid-propellant launch vehicles.

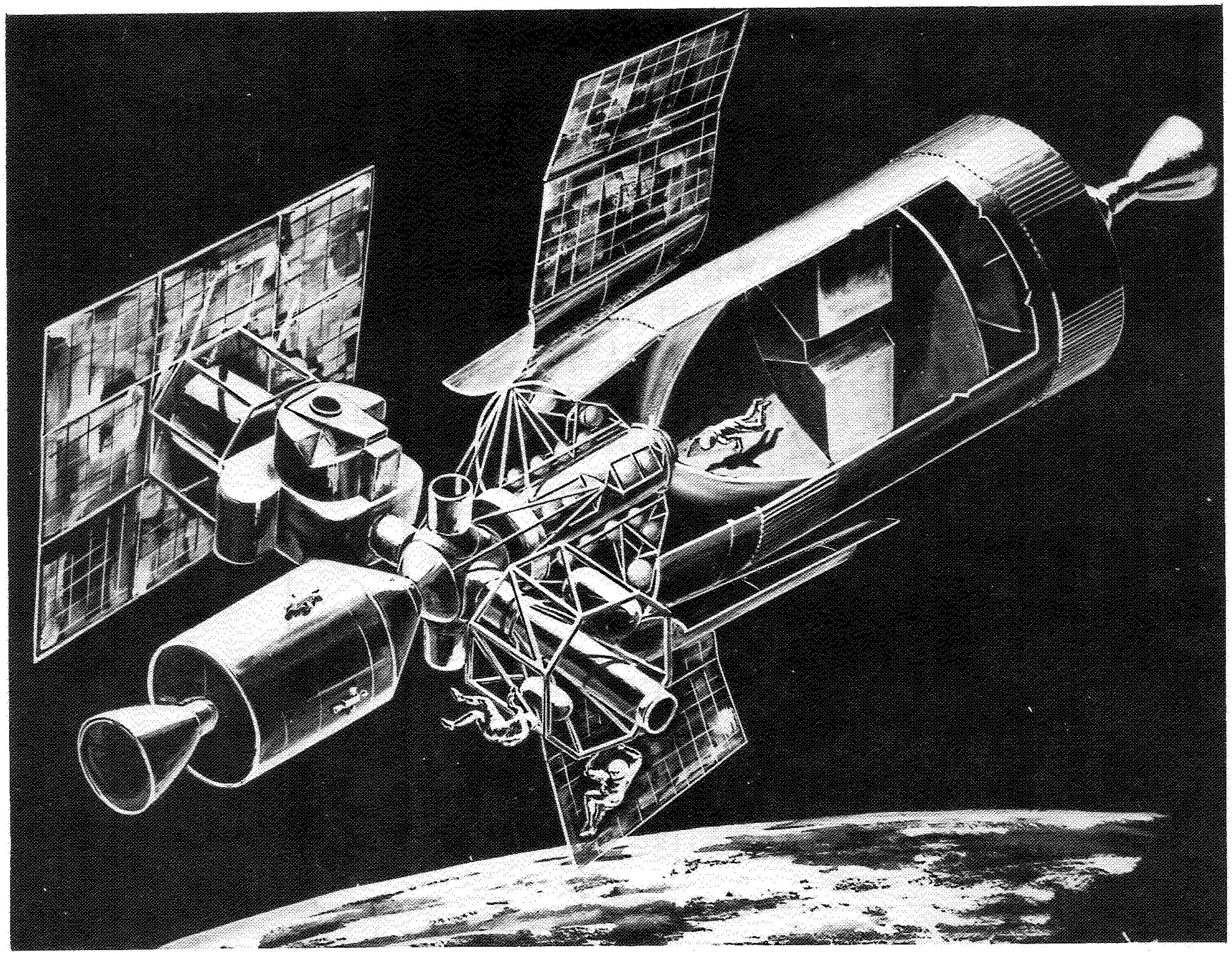
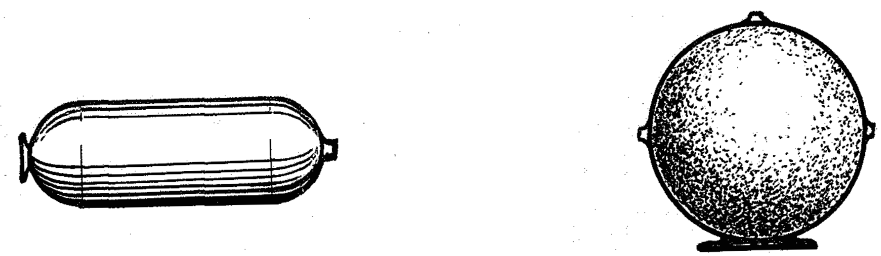


Figure 8.- Future research laboratory in space.

RELATIVE MASS



MATERIAL	CYLINDER L/D = 3		SPHERE
ALUMINUM	1.97		1.57
TITANIUM	1.25		1.00
GLASS IN EPOXY		0.49	
CARBON IN EPOXY		.56	
CARBON IN GLASS		.59	

Figure 9.- Relative mass of pressure vessels.

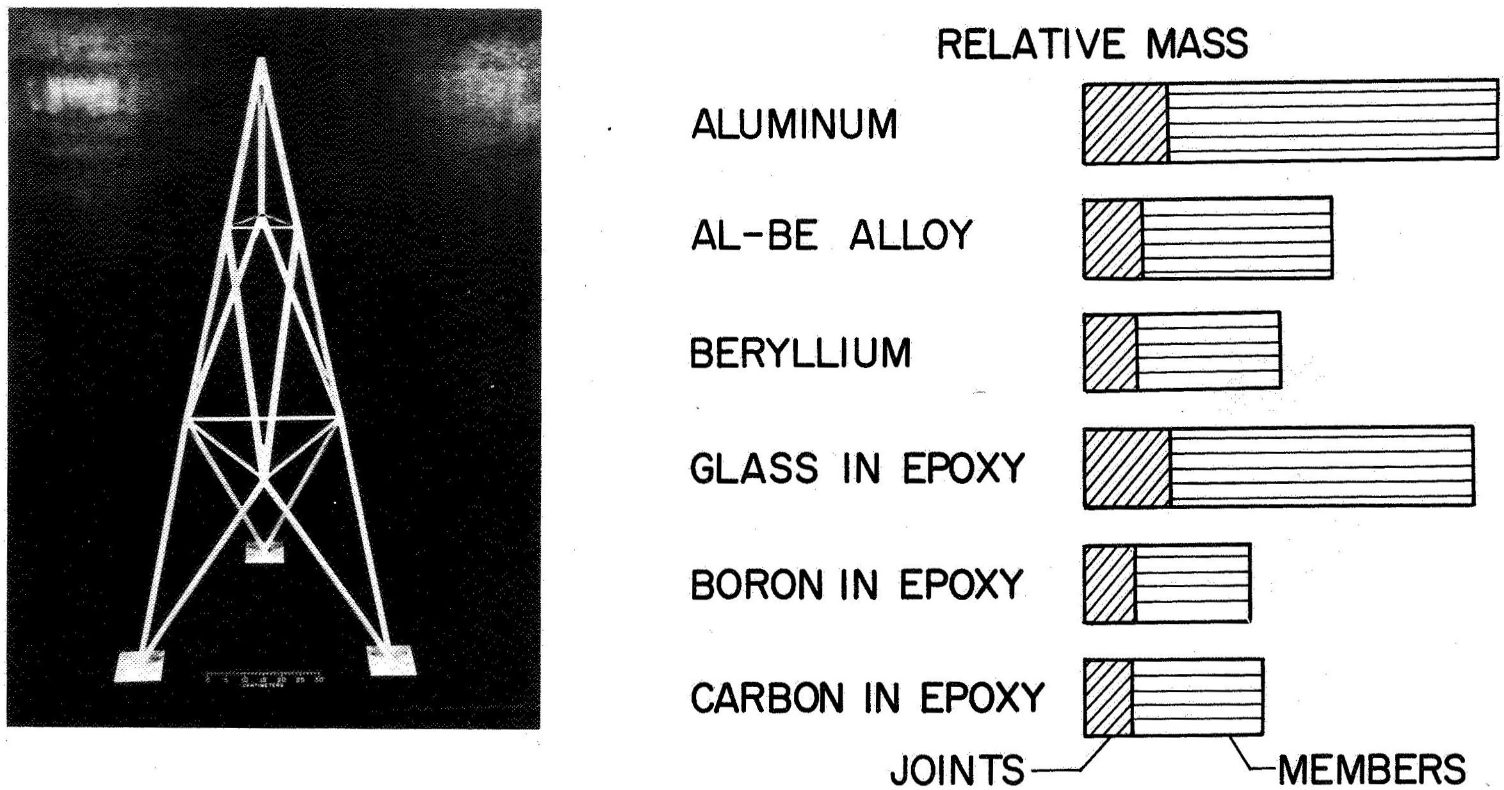


Figure 10.- Relative mass of truss structures.

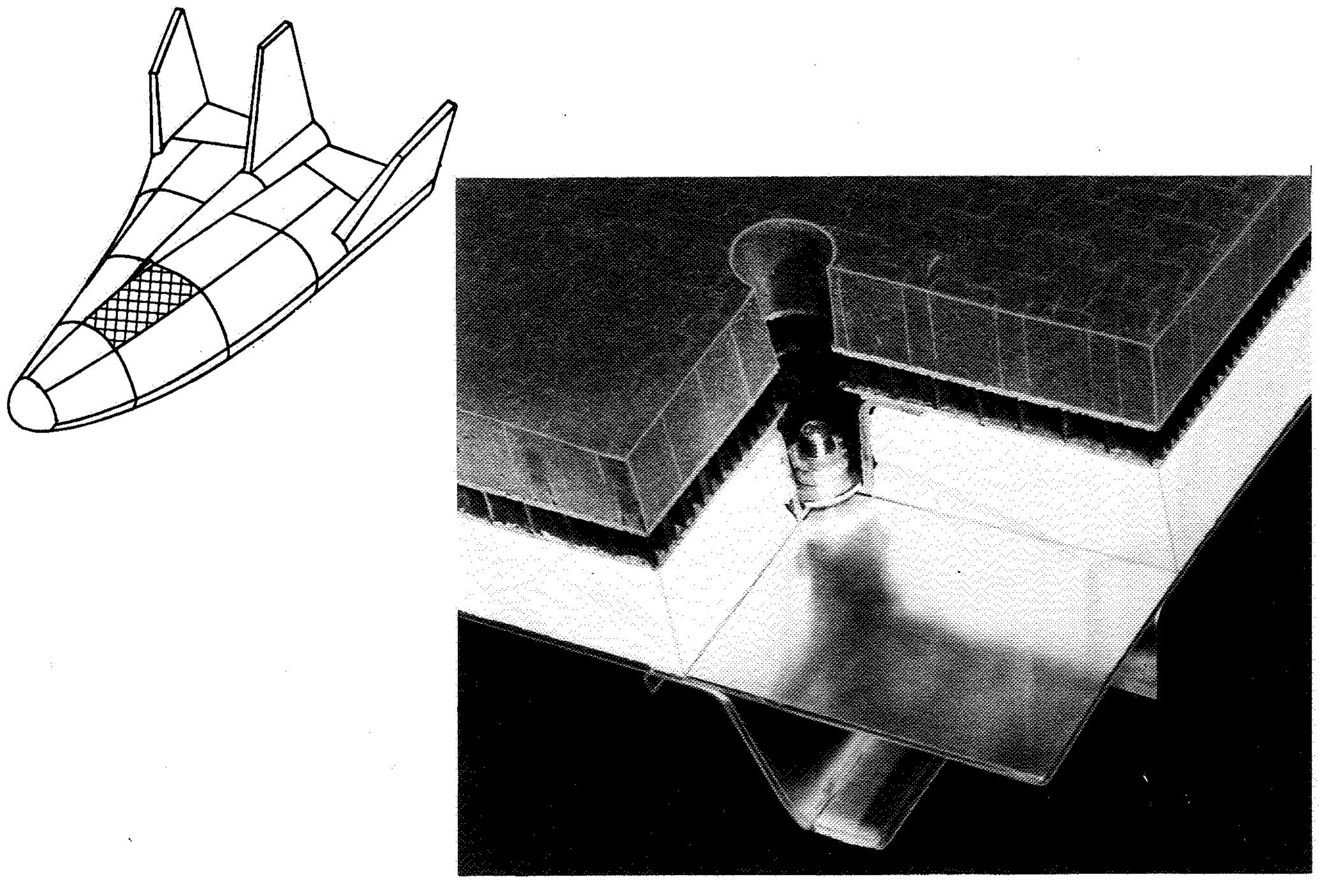


Figure 11.- Replaceable ablation heat shield for a lifting body entering from low earth orbit.

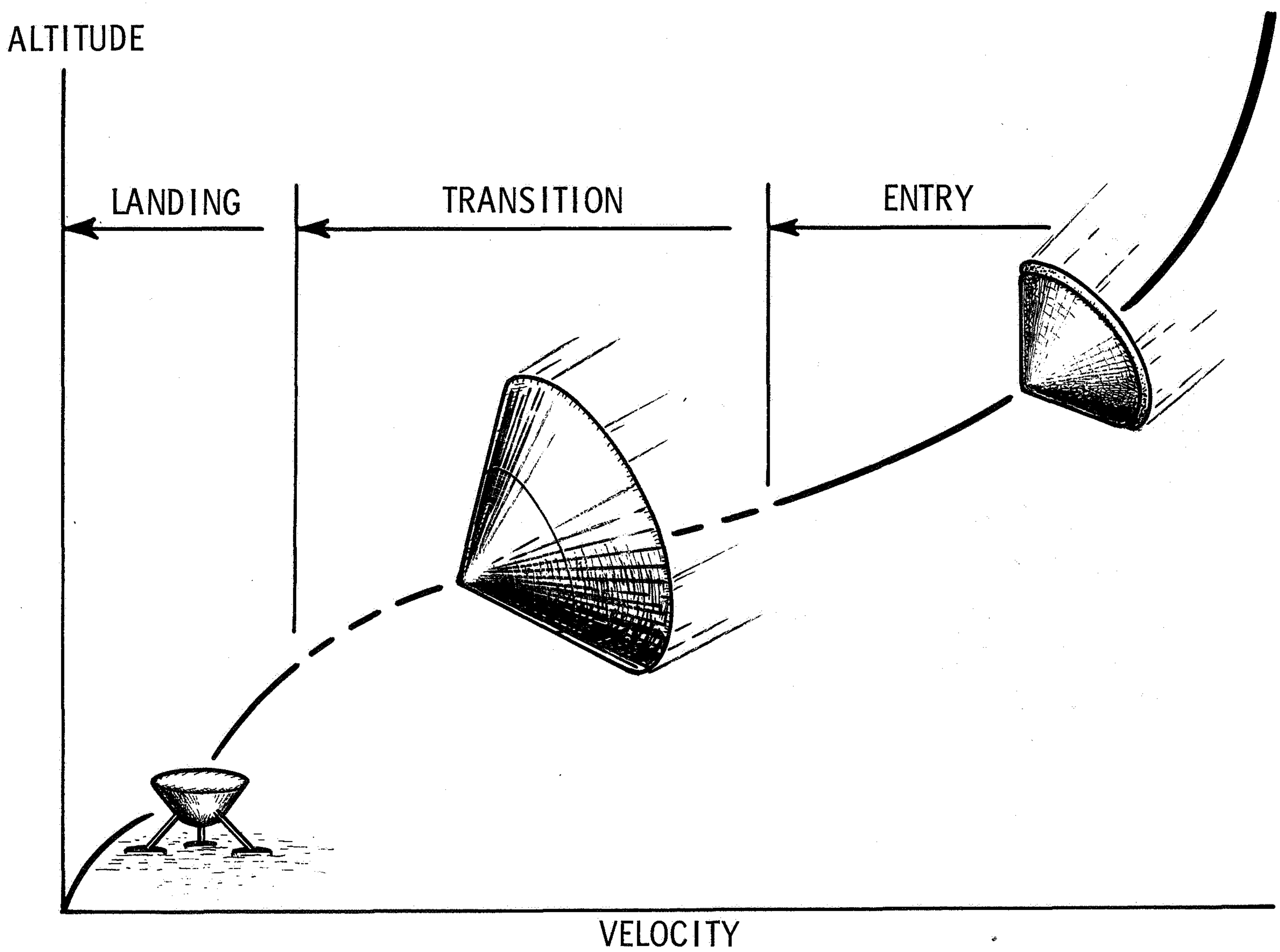
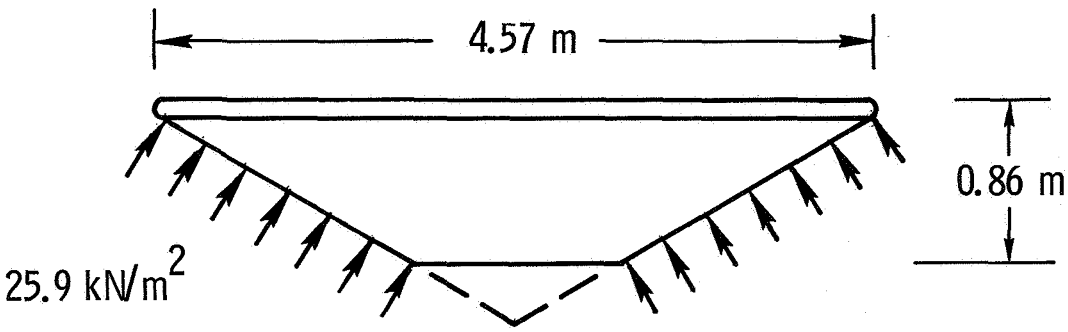


Figure 12.- Atmospheric entry and landing on Mars.



TOTAL MASS = 111 kg $(7.3\ kg/m^2)$

MATERIAL	RELATIVE WALL MASS	
	SANDWICH	RING-STIFFENED
ALUMINUM	1.00*	1.71
MAGNESIUM	1.02	1.32
BERYLLIUM	.57*	.63
GLASS IN EPOXY	1.25	1.92
CARBON IN EPOXY	.90*	.92

*MINIMUM GAGE LIMITATIONS

Figure 13.- Relative mass of low-density aeroshells.

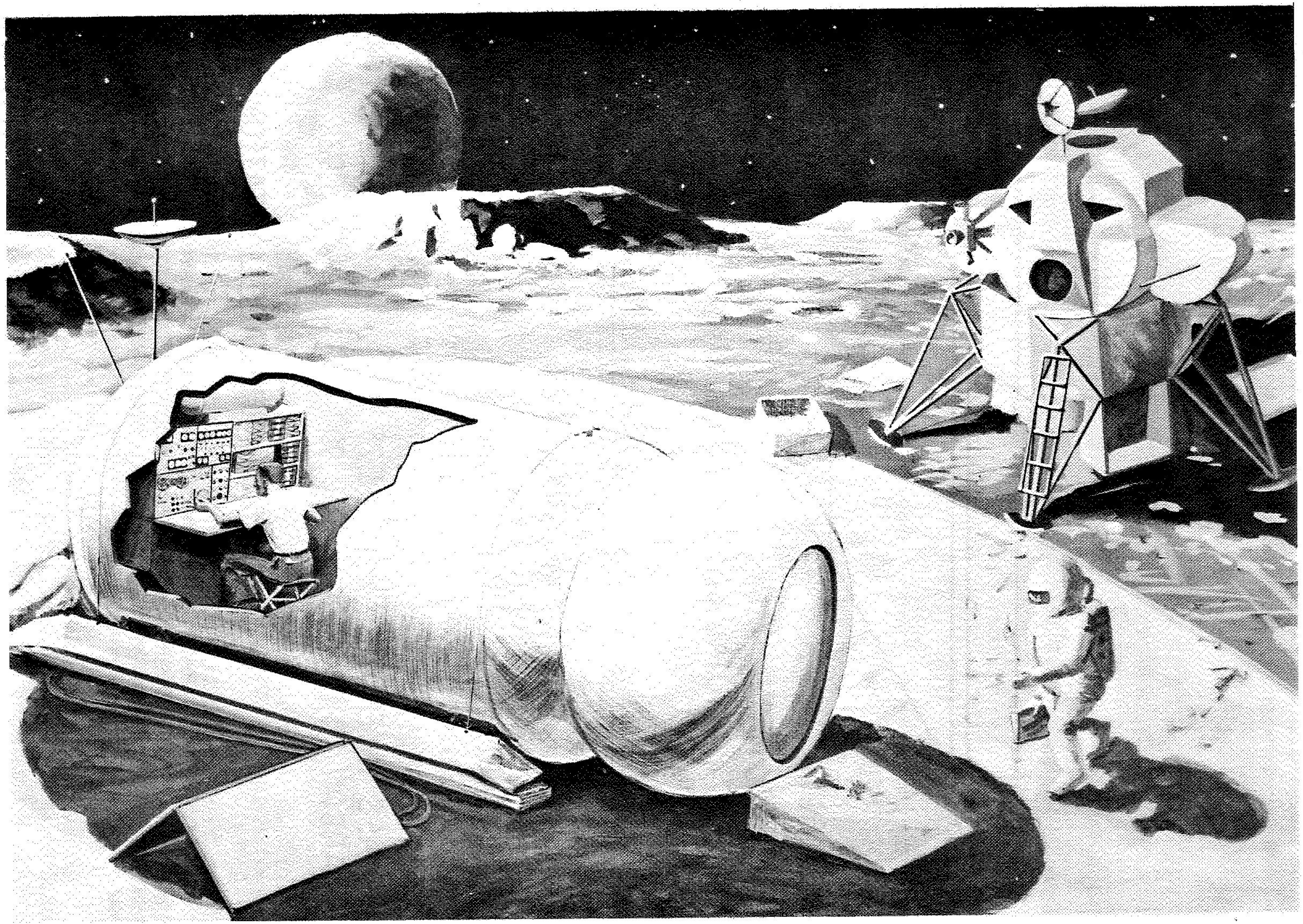
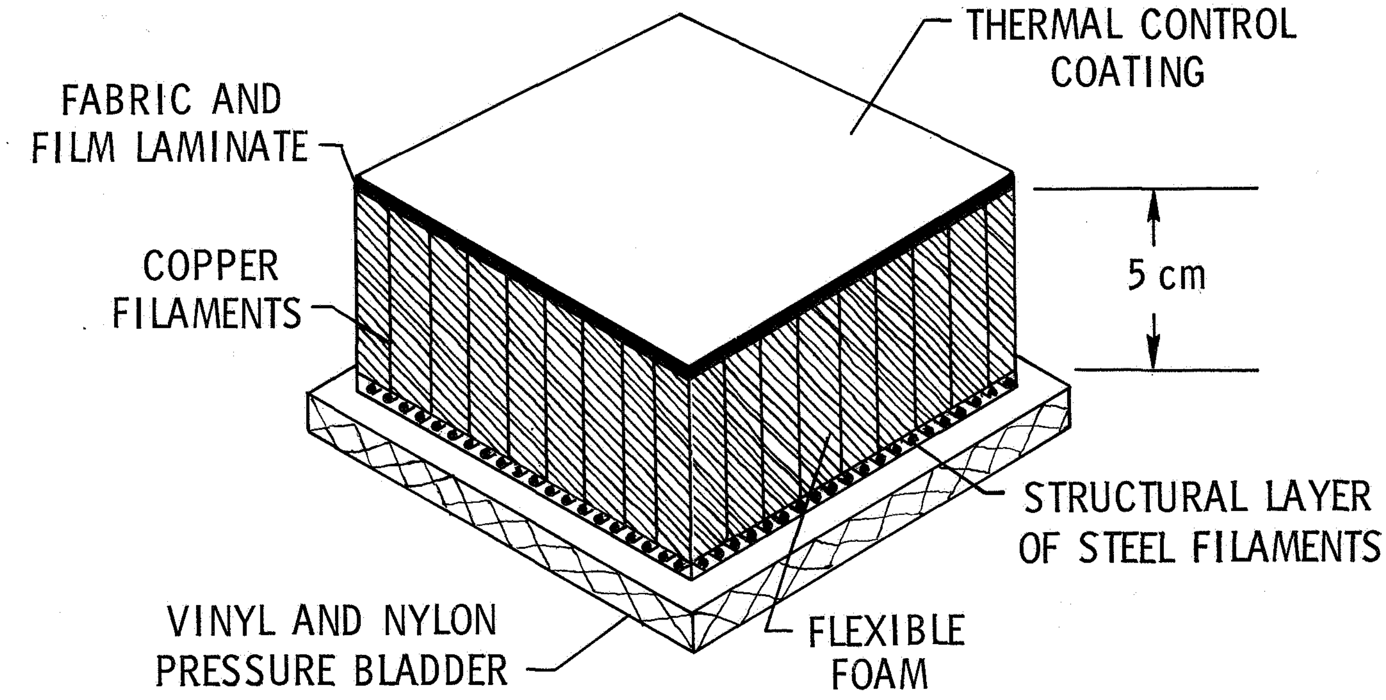


Figure 14.- Expandable lunar shelter.



UNIT MASS = $3.0\ kg/m^2$

Figure 15.- Wall construction of lunar shelter in figure 14.

SOLID ROCKET MOTOR CASES AND NOZZLES

AERODYNAMIC DECELERATORS

REPLACEABLE HEAT SHIELDS

EXPANDABLE SPACE STRUCTURES

PRESSURE VESSELS

BEAMS, COLUMNS, AND TRUSSES

LARGE AEROSHELLS

Figure 16.- Promising future applications of filamentary composites in space vehicle structures.

NASA-Langley, 1967