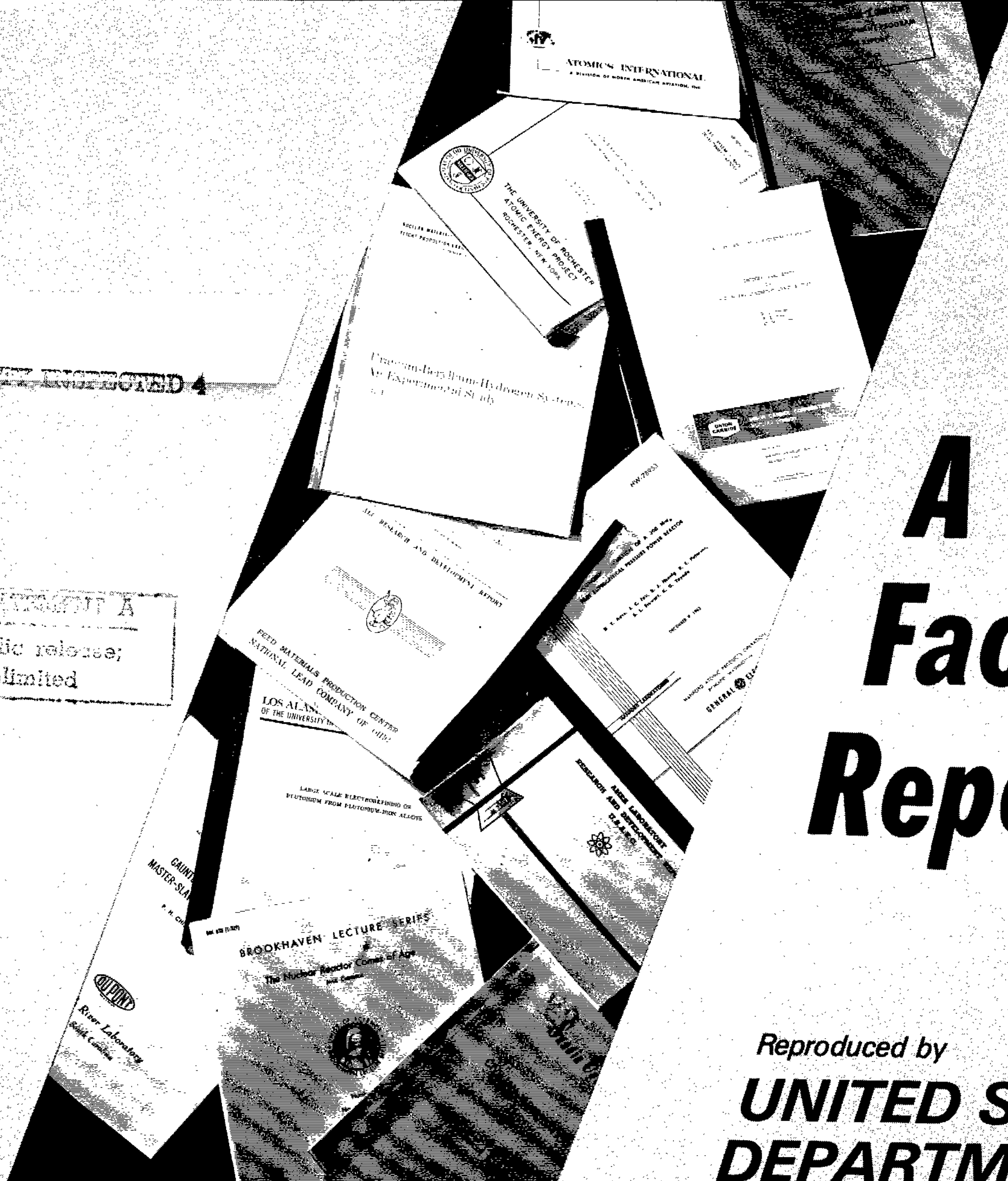

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POTENTIAL FOR ADVANCED THERMOPLASTIC COMPOSITES IN SPACE SYSTEMS

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POTENTIAL FOR ADVANCED THERMOPLASTIC COMPOSITES IN SPACE SYSTEMS

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ABSTRACT

This paper provides rational for incorporating graphite/thermoplastic into future Strategic Defense Initiative space systems. Graphite/PEEK is compared with the best available graphite/epoxy materials, which today are graphite/1962 produced by Amoco and graphite/934 produced by Fiberite. A first-order comparison reveals similar performance between these classes of materials with respect to maximum stiffness, minimum gage, maximum damping, and threat hardness. There are significant differences in the behavior of graphite/polyether ether ketone and graphite/epoxy with respect to the following characteristics: water absorption, condensible-volatile contents, space-environment effects, dimensional stability, weight-savings options, joining alternatives, and production costs. A comparison is also made between organic composites, such as graphite/PEEK, with other spacecraft structural materials, such as aluminum and beryllium (which are commonly used today). The differing requirements for each spacecraft component will determine which of these material options is best suited for the particular structural application.

KEYWORDS: Composites; Advanced Thermoplastic Component; Ultrahigh-Modulus Graphite Fibers, Space Applications; Strategic Defense Initiative; Structures; Polyether Ether Ketone.

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1. INTRODUCTION

The superior toughness, manufacturing options, thermal stability, reprocessibility, and joining characteristics of thermoplastic composites motivated numerous investigations, beginning in 1980, to assesses their potential for use in aeronautical applications. Beginning in 1987, the special requirements anticipated for the Strategic Defense Initiative (SDI), coupled with a continued interest on the part of the National Aeronautics and Space Administration in advanced materials, motivated researchers to evaluate graphite/thermoplastic composites for possible use in space applications. Since 1987, there have been more than 50 technical articles published pertaining to thermoplastics for space, and a variety of prototypical space structures have been targeted for possible construction using graphite thermoplastic composit (1-4). SDI is playing a significant role in developing thermoplastic composites for space applications. This radically different approach to national defense brings with it radically new requirements for space systems.

2. SPACE APPLICATIONS

Four different SDI space applications are being studied for possible incorporation of graphite/thermoplastic composite: interceptor structure, skin-module structure, bus structure, and sunshade. These applications have features that are generic, thereby demonstrating several aspects of technology that are of value to a broad range of space applications (see Table 1). The interceptor shown in the lower right of Figure 1 is a three-stage missile. Graphite/thermoplastic composite is being investigated by W. R. Spencer et al. for use in the terminal stage because of the importance of weight savings in a dimensionally stable structure with maximum stiffness and intrinsic damping. As shown, graphite/thermoplastic composite is used to construct the octagonal center tube, two end flanges, one internal central rib, and one multiflange external central attachment ring (5,6).

Dozens of interceptors may be housed in a single space-based interceptor (SBI) carrier vehicle like that shown in Figure 2, or individual interceptors may be housed in separate "life jackets." In either case, they will be housed in a modular structure. One possible modular-structure concept is the ultralightweight dimple- and fold-stiffened skin module shown in Figure 3. Minimum-gage graphite/thermoplastic materials were demonstrated to provide total surface coverage for these 50- by 100-cm sides. Pitch-based-carbon fiber (PBCF), specifically P75 from Amoco, was combined with the polyether ether ketone (PEEK) matrix to provide local reinforcement along principal load paths (1,4). Induction welding has been demonstrated as an efficient method for joining skins to produce a prototype module.

A graphite/thermoplastic bus structure for orbiting satellites is being investigated by E. M. Silverman et al. (8-19). The space surveillance and tracking system pictured in Figure 4 is targeted as a near-term application for the graphite/thermoplastic bus. The prototype bus will consist of frame members connected with gusset joints and shear panels.

The large sunshade shown in Figure 5 is the fourth protypical application being investigated for possible use of graphite/thermoplastic composite. L. M. Poveromo et al. will develop and construct the blade-stiffened, conical sunshade using graphite/PEEK.

The four demonstration projects were preceded by an evaluation of the producibility of generic space structures using graphite/thermoplastic composite. Figure 6 shows many of these generic structures, including frames, skins, tubes, and joints. Most of these structures include pitch-based-carbon fiber/thermoplastic. These ultrahigh-modulus structures are much more suited for spacecraft than to strength-driven aircraft applications (20-25).

What are the reasons for using graphite/thermoplastic in these and other SDI spacecraft applications? Why not use graphite/epoxy, aluminum, or beryllium materials that are commonly used in spacecraft today? What advantage does graphite/thermoplastic offer that these three three classes of structural materials do not? The next two sections will address these questions.

3. COMPARISON OF THERMOPLASTIC WITH EPOXY COMPONENTS

For the purpose of comparison, PEEK, a semicrystalline thermoplastic matrix that is particularly well suited for space applications, will be compared with either 1962 epoxy (available from Amoco) or with 934 epoxy (available from Fiberite). While newer materials can be proposed, these two space-qualified epoxies represent the best overall performance in thermosetting matrices, which is why they are used in so many space applications today (26).

A first-order comparison will conclude that PEEK and space-qualified epoxies can perform equally well when evaluating density, stiffness, or intrinsic vibration suppression. While differences do exist between the materials on these issues (small, mechanical-property-translation differences, limited availability of thin-gage thermoplastic materials, and slightly better damping in thermoplastic materials), these are not likely to be the points on which a determination to use or not to use PEEK would be based. Nuclear-, laser-, and hypervelocity-pellet-threat performance are also factors that would not clearly separate PEEK from 1962 epoxy (4). Seven important differences between PEEK and space-qualified epoxies include water absorption, condensible volatiles, dimensional stability, space-environmental effects, weight-saving options, jointing characteristics and production costs.

3.1 Water Absorption PEEK has little affinity for water. The graph in Figure 7, by E. M. Silverman, shows that P75/1962 has ten times greater water-weight change than P75/PEEK (9,14,17). This is an important consideration for three reasons. First, when water that was absorbed on the earth is evolved in the space environment, the dimensions of the structure change. benches. Second, the water that is released into space can contaminate cryogenically chilled optics. Finally, the precautions that must be taken to desorb and dessicate moisture while on the ground or to predict final dimensions in space are expensive and might be avoided if PEEK were used in place of epoxy.

3.2 Condensible Volatiles There are many volatile species other than water that tend to evolve from polymers in space. These include unreacted monomers, plastizers, other additives, and solvents. PEEK, which is fully reacted and then processed at >700°F, has one-fifth the contaminating total mass loss as that of 934 epoxy (27).

3.3 Dimensional Stability In addition to coefficient-of-moisture expansion, the dimensional stability of a precise space structure is affected by the tendency of the composite to microcrack. D. E. Bowles and G. F. Sykes have evaluated relative microcracking tendencies of AS4/PEEK compared with T300/934 epoxy by counting the microcracks induced into a thermally cycled laminate (28,29).

The superior toughness of the PAN-fiber/PEEK matrix laminate caused it to have 0.143 as many thermally induced microcracks as the PAN-fiber/934 laminate. The authors caution the reader to not extrapolate these encouraging PAN-fiber-composite results to PBCF composites whose toughness is dominated by the fragile fibers. In the latter case, the higher processing temperature for the PEEK matrix may encourage microcracking in spite of the tough matrix.

3.4 Space Environmental Effects Bowles et al. have also been investigating the effects of simulated space environments on these same materials. In this case, coupons were exposed to electron-beam radiation prior to thermal cycling. The PEEK demonstrated surprisingly good resistance to degradation under radiation exposure (28,29).

There are many other natural space environmental effects that can degrade organic materials. These include atomic oxygen, ultraviolet radiation, proton radiation, micrometeroids, and atomic oxygen. With the exception of atomic oxygen, the author is not aware of studies to compare PEEK with space-qualified epoxy under these exposures. In the case of atomic oxygen, J. A. Barnes reports a slight advantage for PEEK in resistance to atomic-oxygen degradation (30). Nonetheless, one would expect to have the same surface protection required for either of these material systems if exposed for years on the leading edge of a low-earth-orbiting satellite.

3.5 Weight-Savings Options There are a few weight-savings options open to designers using graphite/PEEK composites which are not available with space-qualified epoxy. Although the density and stiffness of graphite/PEEK and graphite/1962 epoxy are quite similar, weight can be saved if differences in (1) joining and attachment methodology or (2) processing approach require less material to perform a given function. L. M. Poveromo report projected 17% weight savings for the graphite/thermoplastic sunshade shown in Figure 5 as compared with a graphite/epoxy design in this case. The superior peel strength and manufacturing and joining features of graphite/PEEK enabled this design alterative to be proposed.

While the design and manufacturing options available with graphite/PEEK may present weight-savings options, the ply thicknesses available may more than offset this advantage. The 125-μm-thick piles, which are well suited for most aeronautical applications, are much too heavy for some space applications. Premium 1962 and 934 epoxy prepregs are commercially available in gages down to 20 μm. The thinnest graphite/thermoplastic preforms available today are specialty products under development to support the growing demand for spacecraft prototype structures—100-μm hot-melt APC2™ prepreg, 50-μm powder-slurry preform, and 45-μm FILMIX™ broadgoods. Material suppliers have shown interest and willingness to produce thinner materials; however, the small and uncertain market for this material has hampered its development (1,20,22).

3.6 Joining Characteristics Weldability is a basic difference between thermosets and thermoplastics. Thermoplastics can be joined using welding methods originally developed for metals. Fusion bonding can be a rapid process resulting in reproducible high-strength joints(7,31-33). Pictured in Figure 8 is a one-twelfth segment of a spacecraft structure designed by S. O. Greenberg of Rockwell International using square tubes and double-cruciform joints. He has shown that thermoplastic welding can save 45% of the labor required to bond a thermoset assembly (23).

3.7 Production Costs Rapid cycle times, reprocessiblity, and thermoformability have led to projections of 30 to 90% costs savings for six aeronautical components—F/A 18 LEX fence, tailplane, equipment bay bracket, refueling probe plugs, aileron farings, and control surfaces (26).

Studies have been initiated recently to generate cost comparisons for spacecraft structures. These are being prepared by E. M. Silverman, W. R. Spencer, and L. M. Poveromo for the SDI bus structure, interceptor structure, and sunshade, respectively. Production-cost projections will be based on cost-tracking data collected in development projects. Preliminary assessments by E. M. Silverman show cost savings consistent with aeronautical applications, even when part count is low (ten parts) (19). The key to achieving cost savings with graphite/thermoplastic composite space structure is to take advantage of out-of-autoclave processes such as diaphragm forming, stamping, fully consolidated tape placement, welding, pultrusion, thermoform shaping, and thermoplastic joining techniques.

4. COMPARISON OF POLYMER MATRIX COMPOSITES WITH ALUMINUM AND BERYLLIUM

Aluminum and beryllium are the two most commonly used spacecraft structural materials. Table 2 provides a comparison of properties of the best polymer-matrix composites (either thermoplastic or thermoset) with aluminum and beryllium. Each row on the table is discussed briefly in the following sections.

4.1 Density and Stiffness Density, independent of stiffness, is important for gage-limited portions of the space structure. Stiffness per unit density, or specific stiffness, is also very important in weight savings because most space structures are optimized for stiffness rather than for strength. It is apparent from the table that beryllium and selected polymer-matrix composites have similar densities and may have similar stiffnesses as well. Aluminum, on the other hand, is considerably more dense and considerably less stiff than the other two.

4.2 Minimum Gage Although either aluminum or beryllium may be produced in thin-gage-foil stock, this form is not commonly used in structure. The minimum practical gage shown for these metals is 750 μm, based on standard machining practice. Composites, on the other hand, are fabricated by material placement rather than material removal. Six-ply composite space structures have been produced in gages down to 125 μm (34).

4.3 Damping The intrinsic damping of polymer matrix composite is one of three decades greater than aluminum or beryllium alloys. While this intrinsic damping may be insufficient to remove all undesirable vibrations, it can help to reduce the weight penalty for add-on damping treatments (35).

4.4 Water Absorption, Other Volatiles, and Space Environmental Degradation All polymers exhibit some outgassing, while aluminum and beryllium do not. Metals are also insensitive to space-environment degradation (radiation and thermal cycling) that may damage exposed polymers.

4.5 Coefficient of Thermal Expansion The minimum achievable coefficients of thermal expansion (CTEs) for aluminum or beryllium are 23 and 11 μm/m K, respectively. Polymer-matrix composites can be designed to have near-zero CTE or may be tailored to have a particular CTE that matches other materials. This parameter was the primary justification for incorporating the first graphite/epoxy composite into spacecraft.

4.6 Part Cost In most cases, aluminum parts are the least expensive, polymer-composite parts are more expensive, and beryllium is the highest-cost alternative. The cost of beryllium can be very high, and delivery can take a year or more due to the highly toxic metal chips.

4.7 Potential for Weight Savings If aluminum is taken as the baseline, then either polymer-matrix composites or beryllium can typically be produced with 30 to 80% weight savings. This is directly related to the difference in specific stiffness. M. Miller and M. Aswani have studied representative space structures and found practically equivalent weight-savings potential among several advanced structural materials, including polymer-matrix composites and beryllium, when compared with aluminum (4). Nonetheless, the minimum gage and joining options available to polymer-matrix composites may represent special weight-savings options.

4.8 Threat Survivability The very low atomic number and high thermal capacity of beryllium make it an excellent performer in the presence of a nuclear or laser threat. The relatively low atomic number of polymer-matrix composites makes them fairly survivable in a nuclear environment, but low degradation temperatures (<500°C) make them poor survivors of laser threats. Compared with polymer-matrix composites or beryllium, aluminum has a higher atomic number and therefore is more likely to be damaged by nuclear threats. The optical reflectance and melting point of aluminum make it much more survivable than polymer composite in the presence of a laser threat (2).

Hypervelocity impact from pellets orbiting through space at 7- to 15-km/s relative velocity is capable of destroying almost any component. Secondary damage should be investigated in order to make an effective comparison between polymer matrix composites, aluminum, and beryllium.

5. CONCLUSIONS

Graphite/thermoplastic composites are being evaluated for selected SDI space applications. Graphite/PEEK has been compared with space-qualified graphite/epoxies, aluminum, and beryllium. It is apparent that graphite/thermoplastic composites merit consideration for space applications requiring the following characteristics: low water absorption, negligible volatiles,dimensional stability, radiation stability, low cost, complex joining, minimum weight, and nuclear hardness. Graphite/thermoplastic composites are not well suited for space applications requiring these two characteristics: laser hardness and hypervelocity pellet hardness.

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TABLE 1. GENERIC APPLICABILITY OF SELECTED STRUCTURES

	SDI Space Applications: • Surveillance • Interceptor • Beam devices • Launch			
	SUNSHADE	INTERCEPTOR	BUS STRUCTURE	SKIN MODULE
Function	• Optical	• Kinetic kill vehicle	• Platform	• Packaging
Size	• Very large	• Small	• Intermediate	• Intermediate
Configuration	• Conical skin	• Octagonal box	• Truss with panels	• Dimple- and fold-stiffened skins
Production Rate	• Low	• High	• Intermediate	
Special Features	• Blade stiffened	• Ultrahigh-modulus fibers	• Joints	• Local reinforcement and welding

TABLE 2. COMPARISON OF PROPERTIES BETWEEN POLYMER MATRIX COMPOSITE, ALUMINUM, AND BERYLLIUM

	Polymer Matrix Composite	Aluminum	Beryllium
Density, mg/m^3	1.7	2.7	1.7
Stiffness, GPa	350[a]	70	290
Minimum Gage, μm	125[b]	750	750
Damping, %	10^{-1} to 10^{0}[c]	10^{-2}	10^{-2}
Minimum Water Absorption, %	0.1[d]	0.0	0.0
Minimum Total Mass Loss, %	0.03[d]	0.00	0.00
Space Environmental Degradation	Some	None	None
Minimum CTE, μm/m K	0.1	23	11
Part Cost	Low to Medium	Low	High
Potential Weight Savings, %	30 to 80	None	30 to 80
Nuclear Survivability	Fair	Poor	Best
Laser Survivability	Poor	Good	Best

[a]Stiffness value is for a $[+30^\circ, -30^\circ, 0^\circ, 0^\circ, 0^\circ, 0^\circ]_s$ laminate that is directionally stiffened for beam and tube applications.

[b]Minimum polymer matrix composite gage is for six plies of graphite/1962 epoxy.

[c]Range of damping results from measuring responses at oblique angles or parallel with reinforcing fibers.

[d]Water absorption and total mass loss valves for graphite/PEEK.

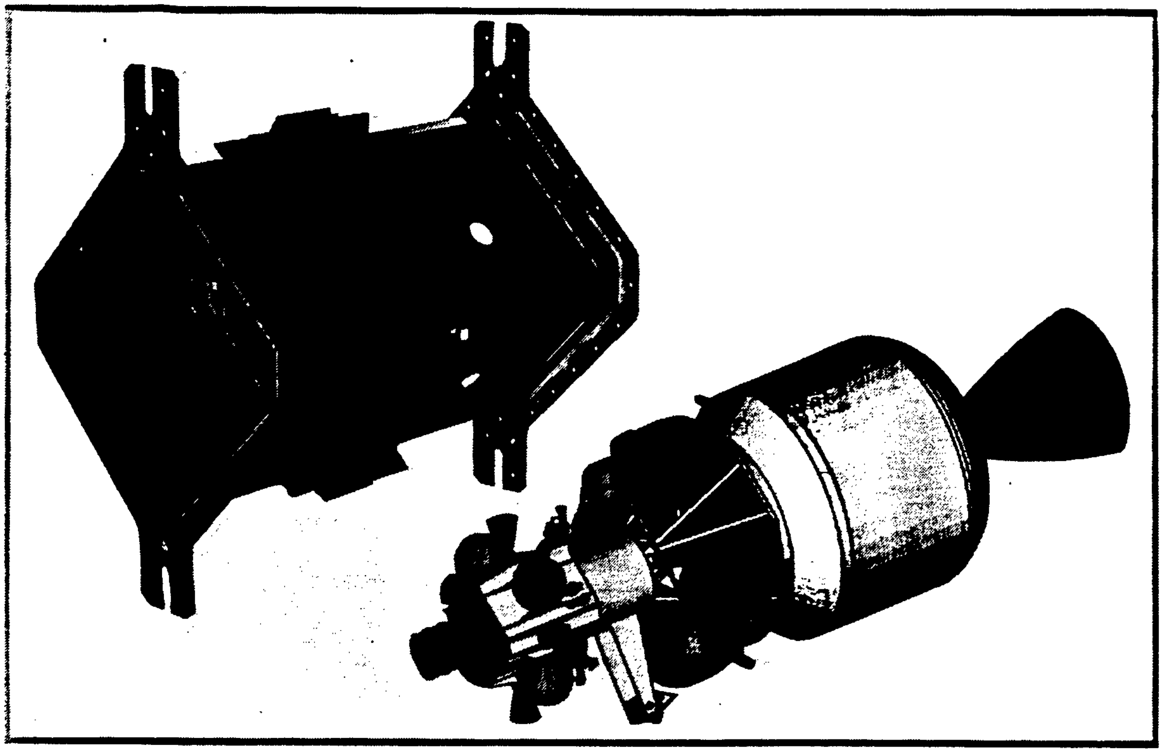


FIGURE 1. Graphite/thermoplastic structure for terminal stage of SDI interceptor.

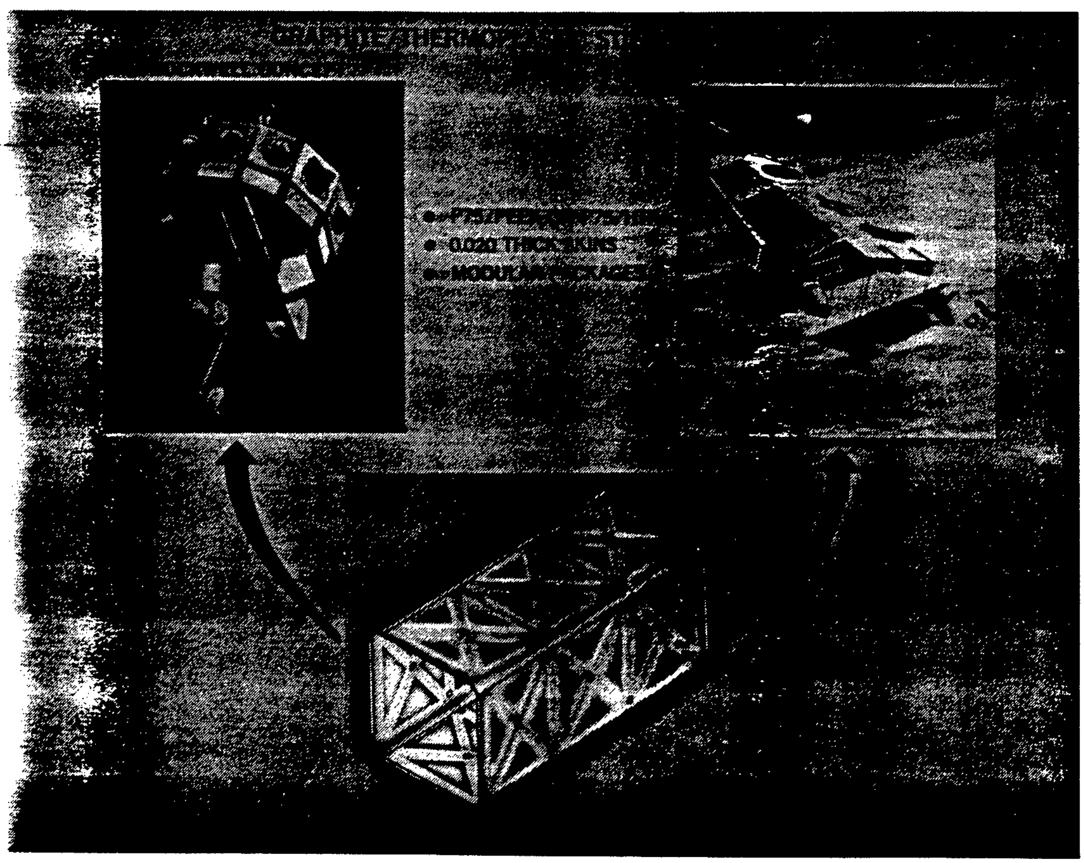


FIGURE 2. Graphite/thermoplastic modular structure carrier vehicle or other ultralightweight packaged structures.

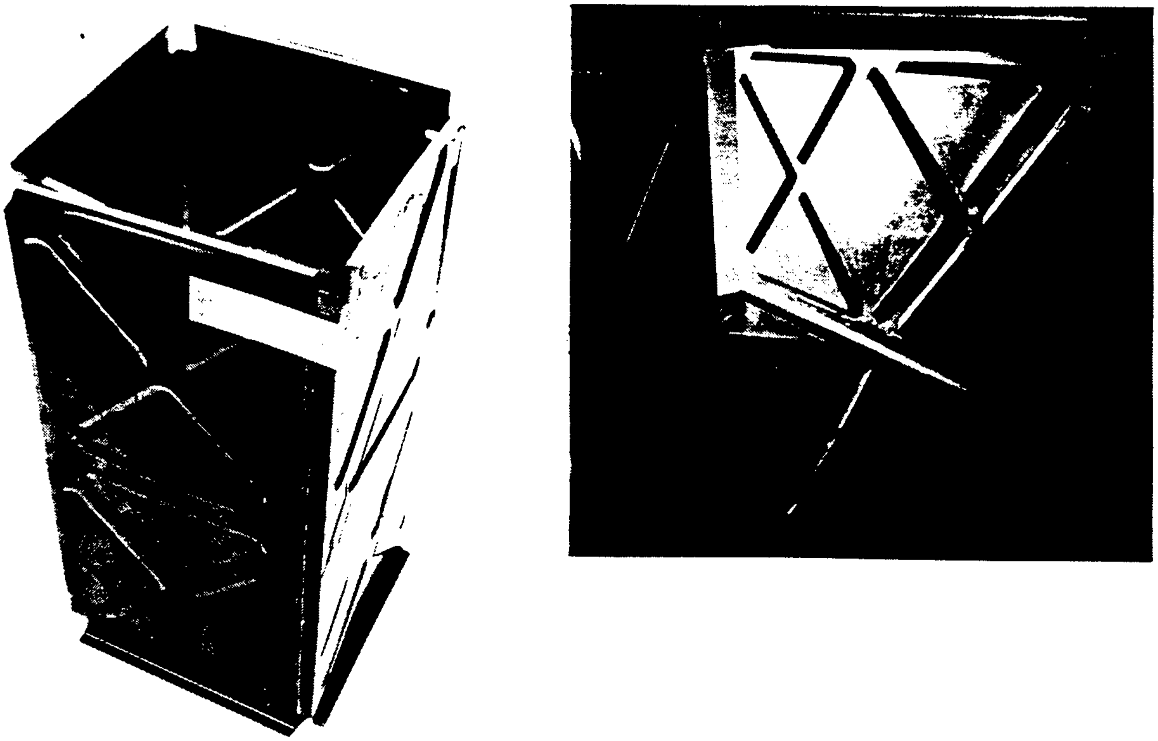


FIGURE 3. Dimple- and fold-stiffened skin modules.

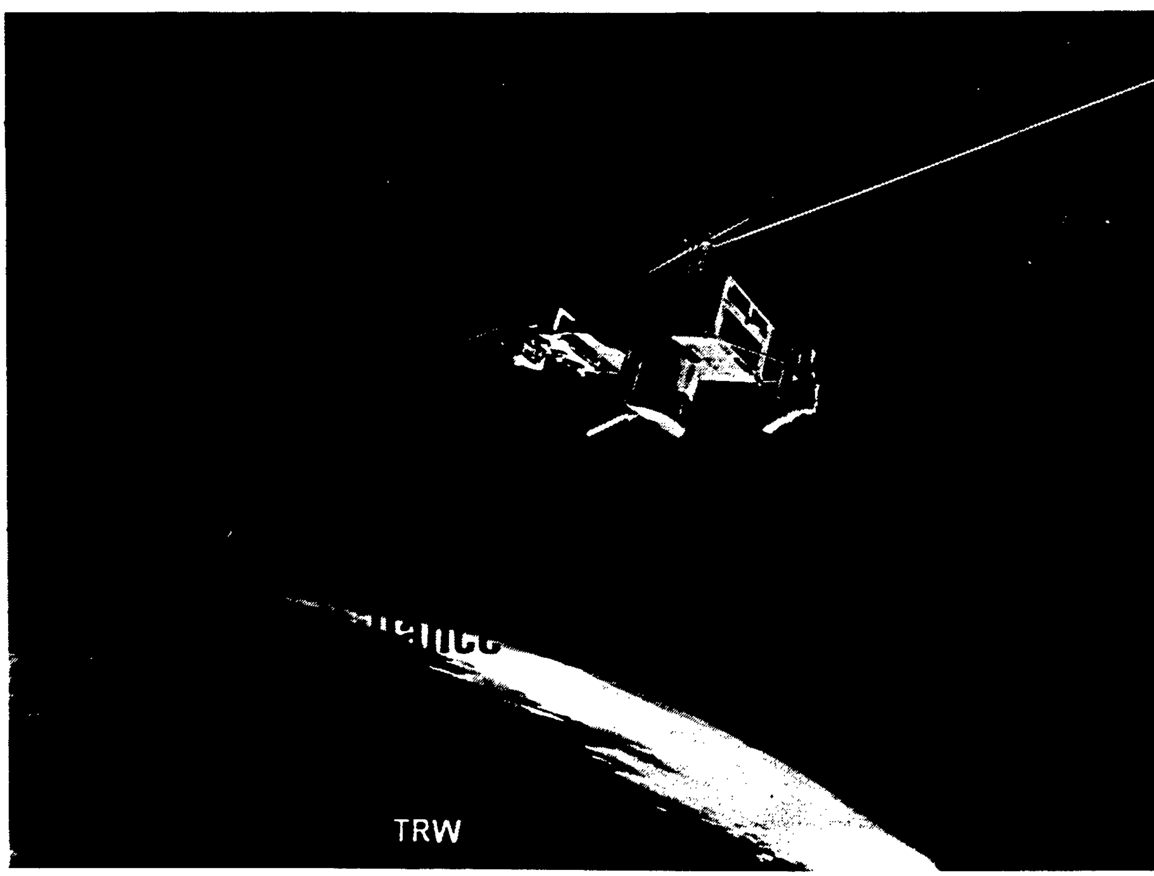


FIGURE 4. One version of Space Surveillance and Tracking System (SSTS).

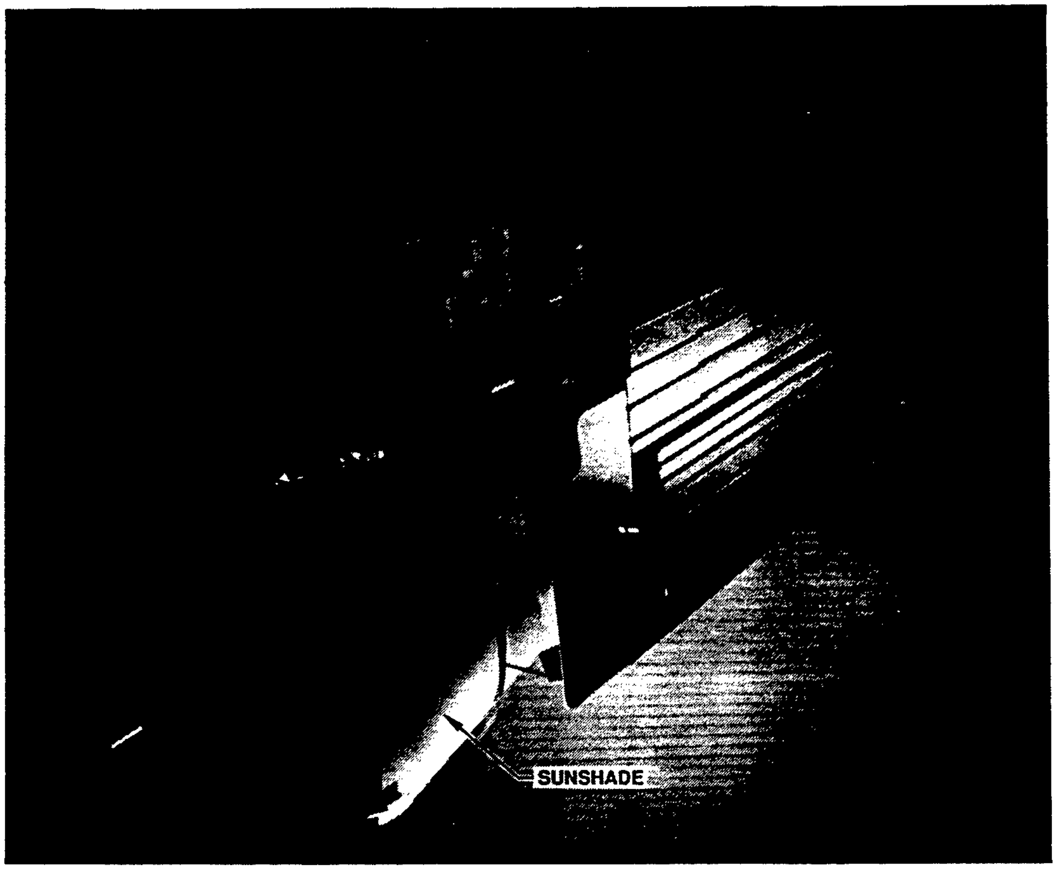
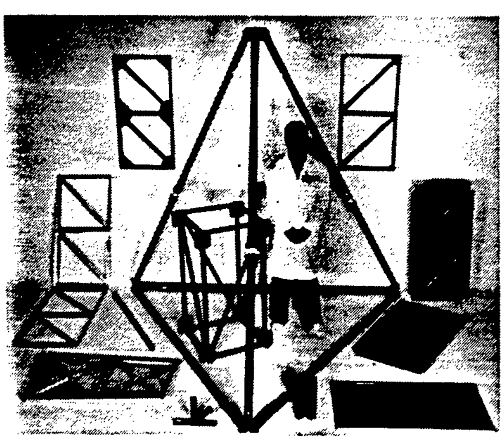


FIGURE 5. Large sunshade for high-altitude surveillance satellite.



Upper right	–	PBCF/Tp L and T frame with fusion-welded joints fabricated by Westland.
Upper left	–	PBCF/Tp L and T frame with six different joints fabricated by TRW.
Center left	–	aluminum frame fabricated by ORNL for baseline comparison.
Center left	–	PBCF/Tp L and T frame with six different joints f abricated by Courtaulds.
Center left	–	PBCF/Tp square tube fabricated by Westland.
Lower left	–	aluminum dimple- and fold-stiffened skill fabricated by ORNL for baseline comparison.
Lower center	–	one-step-fabricated PBCF/Tp L and T joint fabricated by TRW.
Lower center	–	two-piece cruciform joint fabricated by TRW.
Lower right	–	PBCF/Tp dimple- and fold-stiffened skin fabricated by TRW.
Center right	–	PBCF/Tp dimple- and fold-stiffened skin fabricated by Courtaulds.
Center right	–	PAN-fiber/Tp dimple- and fold-stiffened skin fabricated by Westland.
Center	–	PAN-fiber/Tp tubular truss fabricated by Westland.
Center	–	PBCF/Tp square-tube truss fabricated by Westland.

FIGURE 6. Generic structural shapes including graphite/thermoplastic.

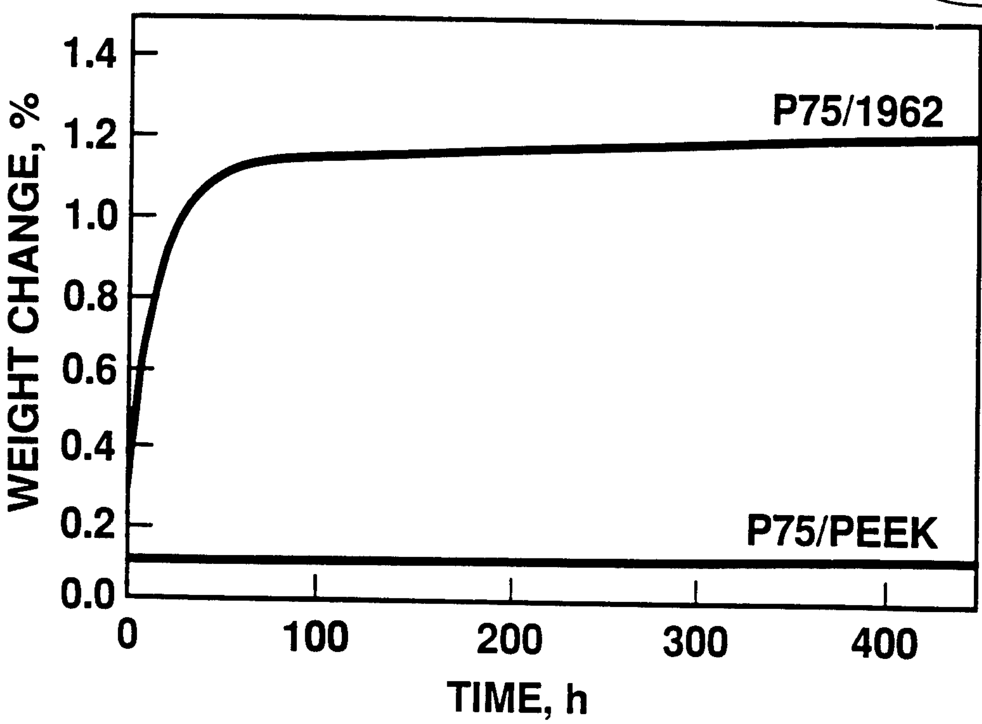


FIGURE 7. Water absorption for P75/PEEK compared with P75/1962 epoxy.

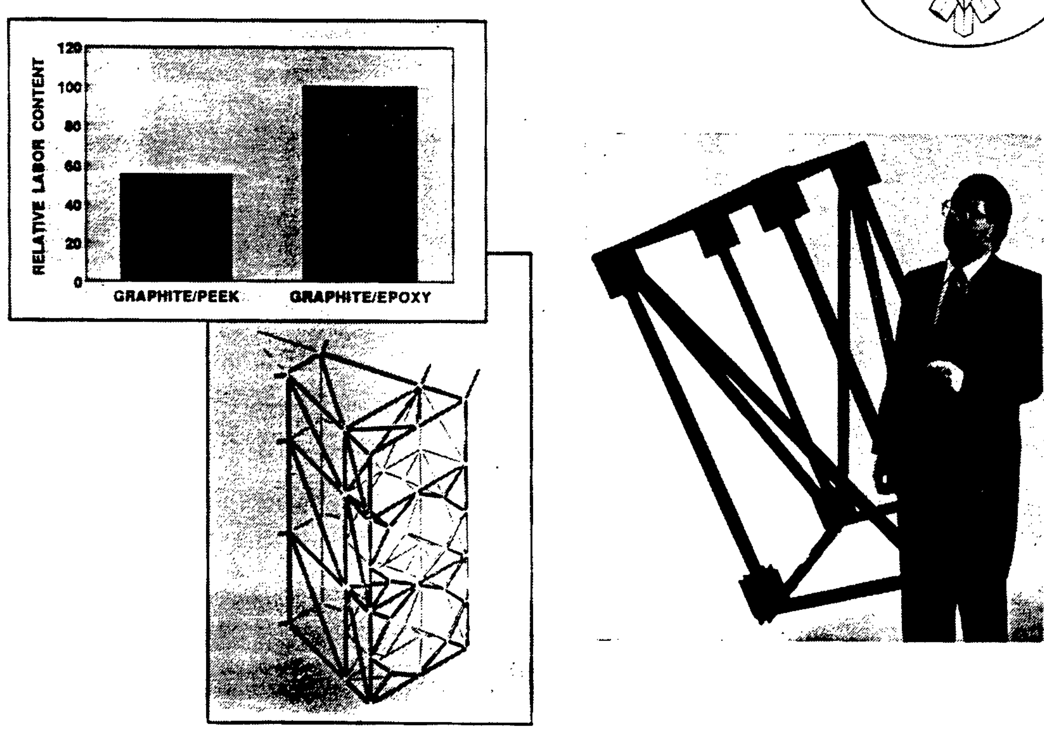


FIGURE 8. Joining, assembly, and rework of graphite/PEEK compared with graphite/epoxy.