JPL PUBLICATION 79-51

Applications in the Automotive Industry for the Electric and Hybrid Vehicle

Annual Report, November 1978

J. L. Bauer

July 15, 1979

Prepared for

U.S. Department of Energy
Assistant Secretary for Conservation
and Solar Applications
Office of Transportation Programs

Through an agreement with
National Aeronautics and Space Administration

by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL PUBLICATION 79-51

N79-28233

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NOTICE

Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

The JPL Electric and Hybrid Vehicle System Research and Development Project* is sponsored by the U.S. Department of Energy, Transportation Energy Conservation Division.

*This work was performed by the JPL Applied Mechanics Division.

ABSTRACT

A comprehensive review is made of the state-of-the-art in
regard to the use of composite materials for reducing the struc-
tural mass of automobiles. Reduction of mass will provide, in
addition to other engineering improvements, increased performance/
range advantages that are particularly needed in the electric and
hybrid vehicle field. Problems to be overcome include the attain-
ment of mass production techniques and the prevention of environ-
mental hazards.

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SUMMARY

This document reports on efforts to reduce the mass of the electric and hybrid vehicle, thereby increasing performance/range targets. Mass reduction is to be accomplished through the application of composite materials to primary and secondary structural members of the vehicle. Precedence for the effort will be to develop manufacturing processes for cost effective hardware in high volume production.

Composite materials potentially have the properties to improve vehicle performance and reduce cost because:

(1) High specific strength and stiffness permit load carrying ability at reduced weight.

(2) Anisotropy and the absence of structural yield permit more efficient component design.

(3) Fatigue, creep, and corrosion resistance permit long life hardware.

(4) Vibration and noise dampening characteristics permit quieter operation and improved performance.

(5) Consolidation of components and reduced energy demands reduce cost.

To realize the advantages of these materials, certain problems must be overcome, including;

(1) The current cost of composite raw material is considerably higher than steel.

(2) The supply of certain reinforcements is not yet available in required quantities.

(3) A potential electrical hazard exists if graphite fibers are accidentally released into the atmosphere.

(4) Technology must be developed to mass manufacture composites from process-compatible materials capable of resisting the performance environment in a cost effective fashion.

Subsequent portions of the review describe feasibility and demonstration programs illustrating some of the above advantages. These include the Ford lightweight vehicle program to fabricate an all graphite/epoxy vehicle and Garrett's all fiberglass/polyester electric car. Both programs demonstrated significant structural weight reduction and subsequent performance improvements.

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The major impediment to the large scale introduction of composites is the current raw material cost and the lack of sophisticated manufacturing methods for high volume production. Current prices on composite raw materials range from approximately five times that of carbon steel for fiberglass to over an order of magnitude for some types of graphite fibers. Production methods developed by the aerospace industry yield high reliability hardware using low capital investment, but they employ labor intensive processes and time consuming fabrication techniques.

Composite hardware can be fabricated cost-effectively and in high volume if appropriate developmental programs are performed with a subsequent investment in capital facilities. In addition to performance advantages and cost-effective hardware, composites can also achieve meaningful energy savings during fabrication and while in service.

The predominant composite cost savings can be achieved through the manufacture of hardware and through anticipcated raw materials price reductions through volume usage. Manufacturing cost savings can be achieved through the ability to consolidate composite subassemblies into one production operation thereby eliminating many secondary joining and assembly processes. A significant labor saving is thereby obtained.

Further cost and energy savings are achieved through reduced processing parameters such as pressure and temperature, and reductions in the inventory because of fewer types of manufactured subassemblies and individual components.

Composites, as a result of corrosion and fatigue resistance, are more durable and are therefore expected to last for the life of the vehicle. This achieves a reduction in replacement cost as well as the energy required to fabricate replacement hardware.

Operation of composites for the vehicle lifetime achieves further energy savings as a result of reduced component weight; or for the same energy expenditure, improves payload, range, or performance.

A preliminary review of current composite usage in the automotive industry is presented along with a discussion of programs to fully demonstrate composite feasibility. There are more than 350 fiberglass reinforced plastic parts in the 1978 model U.S. cars including front end panels, head lamp and tail lamp housings, air condition housings and others.

The predominant raw material used in the fabrication of automotive components is sheet molding compound (SMC). Sheet molding compound consists of chopped fiberglass, randomly distributed impregnated with an uncured polyester resin and sandwiched between two plies of removable polyethylene liner. Application of heat and pressure is required to cure the polyester into a rigid structure while it is contained in contoured tooling to impart the desired shape.

Several limited production items for 1978 vehicles are discussed including automotive front and rear end assemblies, grill panels, and truck cabs. Each application has shown reduced weight as diminished cost and improved performance.

A review is also presented for the current industry demonstration programs. Most publicized of these is the Ford "all-graphite" passenger car. Plans are to reduce the vehicle's weight from 4,000 to 2,750 pounds thereby increasing fuel economy to 23 miles per gallon from 17 miles per gallon.

Applications of composites to electric vehicles include AiResearch's all fiberglass vehicle and Exxon Enterprises' electric. Exxon fabricated an all-graphite frame and a glass/graphite hybrid body for a total weight reduction of 200 pounds. Budd Company, under subcontract to AiResearch, achieved a significant reduction of parts using glass reinforced polyester.

A newly organized automotive manufacturer, the De Lorean Motor Company, plans to use 600 pounds of plastic per vehicle in primary load bearing applications. The automobile, the DMC-12, will be produced at a rate of 20,000 vehicles per year in Belfast, Ireland. The DMC-12 will utilize a sandwich structure of urethane foam and glass reinforced thermoset resin for the structure. The sandwich will be fabricated in a one-step operation named elastic reservoir molding (ERM).

A review of representative efforts to design and fabricate other demonstration components is also presented, including leaf springs, drive shafts, door intrusion beams, doors, hoods, deck lids, wheels, gears, brackets, and support beams. Also discussed are internal combustion components such as push rods, connecting rods, and rocker arms.

The information necessary to conduct an effective cost analysis is presented and the potential source of and availability of raw materials is reviewed. Resins and fiberglass reinforcement is shown to be a mature industry that is subject to intelligent forecasting. Graphite fiber reinforcement is shown to be a relatively infant industry. Reductions in graphite fiber price can be expected as a result of economics of scale, a result of technological advances, and as a result of the "learning curve" phenomenon.

The cost associated with possible adverse environmental health and safety impacts as a result of increased production are addressed and shown to be covered by existing industry practices and previously implemented legislation.

Increases in demand for plastics as a result of a wide range of composites in automotive components is expected to increase the demand on petroleum feedstocks. The entire plastics industry currently consumes only 2% of the total petroleum and natural gas expended in the U.S. thereby sustaining an industry which is adding significant value to these feedstocks in the production of durable goods and making a distinguished contribution to the GNP.

SECTION I

INTRODUCTION

This report presents work carried out for the Electric and Hybrid Vehicle System Research and Development Project of the Jet Propulsion Laboratory (JPL) during fiscal year 1978.* Within this work element of the project, the effort has specifically been to assess the potential of, and develop a program for reducing the mass of, the electric and hybrid vehicle (EHV) through extensive use of composite materials in primary and secondary structural applications as well as in rotating and other dynamic system components.

Although the automotive industry has been making limited but increasing use of composite materials in such applications in recent years, it was felt that a comprehensive review of the industrial applications of composite materials from the viewpoint of applicability to electric and hybrid vehicles was indicated since the requirements of the EHV, while often similar to the conventional automobile, may sometimes require unique solutions to cost/benefit trade-off problems in the materials areas. An assessment of the technology has been conducted through review of technical literature, attendance at technical society and trade show meetings and visits to selected companies in the automotive and composites industries. Results in this assessment are presented here.

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*Public Law 94-413, as amended by Public Law 94-238, authorizes the development and demonstration of electric and hybrid vehicles under the direction of the Department of Energy (DOE). As an element of that program, the Electric and Hybrid Vehicle System Research and Development Project has been assigned to JPL.

SECTION II

OBJECTIVE

The objective of this activity is to investigate means of reducing the cost of composite materials in application to the EHV through the use of designs, techniques, and materials more suitable for mass production than is currently the case. In this manner, the proven capability of composite materials to reduce mass in automotive applications can be made increasingly feasible economically, particularly in applications to the EHV.

During FY'78, the objective has been to develop an in-depth application of the state-of-the-art of composite technology in automotive applications. What are the problems and what is the promise? The approach to this objective has been described in the introductory section. This report, as the first output of the work element, summarizes the information gained to date.

In subsequent years, the overall objective will be attained by contracting for: (1) the development of high-volume, low-cost manufacturing techniques for composites and (2) the selection, evaluation, and modification of composite materials to facilitate high-volume manufacture while achieving structural requirements. These efforts will be brought into focus through the development and fabrication of demonstration components which will be evaluated on the Vehicle Technology Test Bed or other appropriate vehicle to demonstrate cost-effective, reduced weight vehicle structures.

SECTION III

BACKGROUND

The highest priority objective of the mass reduction work element will be to develop manufacturing processes through materials modification, and new processing techniques to produce cost-effective hardware in high volume. Thus, in contrast to the AiResearch fiberglass body program or the Ford light-weight vehicle program, this work is not devoted to demonstrating the feasibility of a composite component, but to determining the cost effectiveness of demonstration hardware.

This work investigates "quick-cure" resin systems similar to those used in high-volume manufacturing operations that are analogous to processes such as pultrusion, injection molding, and heat forming. Sample hardware could be fabricated during this program to demonstrate the different methods of manufacturing various composite forms corresponding to structural shapes (beams), aerodynamic shapes (fenders), or complex shapes (connecting rods, etc.), if appropriate.

Automotive acceptance and usage of composites is required to reduce prices of selected raw materials and to fully develop the technology. The volume usage of raw materials associated with automotive manufacturing is necessary to establish a competitive price structure for graphite and aramid reinforcements. The existing data base for composite materials is generally available in high-performance resin systems such as epoxies and polyimides. These systems generally have a higher cost than polyesters and thermoplastics, but more importantly they require extensive processing times to rigidize composite structures. Accordingly, a data base must be developed in resin systems more compatible with high-volume manufacturing. In addition, more design data is essential on hybrid systems of specific interest to the potential applications. The detailed materials systems must be more precisely defined in order to permit aggressive developmental efforts.

These topics are not severe deterrents to automotive acceptance of composites, requiring only management direction and developmental funding to surmount. A more insurmountable barrier to automotive utilization of the material is the industry's ability to achieve mandated fuel economy through other technologies such as improved engine performance or engine downsizing.

The electric vehicle, on the other hand, requires as much assistance as possible to improve performance and increase range. Albeit the most significant improvements can be made in the battery. Reductions in structural weight, however, will permit reduced demands on the battery, allow incorporation of additional power sources and increased response in acceleration and hill climb efforts. In addition, through the use of durable composites, the electric vehicle will gain a reputation as a long-life automobile.

A 20% reduction in weight for a baseline vehicle (Reference 3-1) has been shown to improve the energy economy from 2.75 to 3.37 mi/kWh on a SAE J227 schedule C. The subsequent range was increased from 73 to 90 mi and the time to accelerate from 0 to 50 mph was reduced from 37 to 30 seconds. Support of composite programs, as defined in the next section, is required for timely availability of composite components for the electric and hybrid vehicle.

Although a clear definition of the required technologies has not yet been succinctly stated, most industry executives (References 3-2 through 3-9) agree that they fall into several categories, including:

(1)   Materials development and property determinations.

(2)   High-volume fiber production and composite manufacture.

(3)   Surface finish.

(4)   Joining.

(5)   "Drive-away" hardware cost (always an overriding consideration).

Composite materials are receiving extensive attention as a potential structural constituent of automotive components. The interest is justifiable from a review of composite properties and advantages including:

(1)   High specific strength and stiffness.

(2)   Anisotropic properties and absence of structural yield.

(3)   Fatigue and creep resistance.

(4)   Corrosion resistance and chemical stability.

(5)   Vibration and noise dampening characteristics.

(6)   Low coefficient of friction and extended wear.

(7)   Excellent thermal stability.

(8)   Thermal and electrical properties may be designed to requirements.

(9)   Cost effective fabricated hardware through consolidation of subassemblies.

(10) Energy-efficient raw material and manufacturing processes.

(11) Processable into more sharply defined contours than stamped metals.

A factor limiting composite applications is the lack of a sufficient data base on composite design. Testing or prototype composite has indicated that the modes of failure differ from those experienced by conventional steel parts. Due to isotropic strength and stiffness properties of steel, steel parts are designed to support the principal static and dynamic loads. Because the strength of composite materials is very direction-sensitive, it is necessary to know the magnitudes, directions, and frequency of the minor loads as well as those of the principal ones since the former may be the source of component failure in the composite part. The industry does not have an adequate data base on these minor loads; it will need to develop this base prior to the use of composite parts in load-bearing applications. This knowledge of requirements will determine the composite system needed, thereby assisting in defining the reinforcement/resin.

Emphasis will be restricted to fiberous graphite glass and aramid reinforcements as the most efficient structural materials as yet available; i.e., promising to yield cost efficient systems. Similarly, quick cure thermoset or thermoplastic resin systems will receive primary attention.

SECTION IV

BENEFITS AND HANDICAPS OF COMPOSITE MATERIALS

A.   DEFINITION

Composites, as a class of materials, are generally defined as a combination of at least two distinct components with an explicit inter-face separating the components and offering properties not achievable by either of the components acting alone. Composites typically consist of discrete fibers or reinforcement, bound together by a homogeneous matrix. Fiberous reinforcement may include aramid fibers, fiberglass, graphite, boron, refractories, etc. The matrix may consist of plastics or metal systems such as epoxy, polyester, aluminum, or titanium (References 4-1 and 4-2).

Composite materials as discussed in this report will be limited to fiber-reinforced plastics. Fibers of interest are fiberglass graphite and aramid. Under consideration will be thermoplastic or thermosetting resins such as nylon, polysulfone, polyester, or epoxy. Hybrid systems (those using several reinforcements) will also be included.

Combinations of fibers make it possible to create hybrid composites in which the best properties of each fiber is used. Most likely is the combination of low cost glass fibers having excellent impact resistance but low modulus, and graphite with low impact resistance but high modulus. The resulting hybrid composite would possess good impact resistance and high modulus. Another (Reference 4-3) example of improved properties from a glass-graphite hybrid is that of a layer of continuous graphite filament placed on each side of a conventional chopped-glass molded sheet -- the flexural modulus is increased by a factor of 7 (from 2,000,000 to 14,000,000 psi) and the flexural strength is increased by a factor of 5 (from 30,000 to 150,000 psi).

Advanced composite is a term used to describe high performance materials exhibiting high structural efficiency. Generally, these are graphite, boron, or aramid reinforced systems. These materials are typified by light weight, exceptional strength and stiffness, and a combination of mechanical properties not achievable with other materials of construction.

B.   PROPERTIES

Composite materials, and most especially advanced composites, are best noted for their low density, high modulus, and high strength. Other desirable properties are offered, however, by this interesting class of materials such as fatigue and creep resistance, proof against corrosion, excellent wear, high natural frequency, high damping characteristics, either electrically conductive or electrically resistant, dimensionally stable, and thermally insulating.

Material properties for composites with high structural efficiency (i.e., 50 to 60% fiber volume, either unidirectional or a 0/90° lay-up in fabrics) are presented in Table 4-1.

Table 4-1. Nominal Properties of Composite Materials

Composite System (Fiber/Epoxy)	F_L^{tu}	F_T^{tu}	F_L^{cu}	F_T^{cu}	F_{LT}^{su}	E_L^t	E_T^t	E_L^c	E_T^c	G_{LT}	ν_{LT}	ρ
HM or Type I Unidirectional Graphite Fiber	110	4.0	100	20	9.0	25	1.7	25	1.7	0.65	0.30	1.63
Type A or III, T-300 Unidirectional Graphite Fiber	160	7.5	160	25	10 0	17	1.7	17	1.7	0.65	0.21	1.55
T-300, 8h Satin-fabric Graphite	90	90	–	–	–	10.5	10.5	–	–	1.04	–	1.5
Type P Unidirectional Graphite Fiber	115	–	130	–	–	13	–	13	–	–	–	1.6
Kevlar-49 Unidirectional Aramid Fiber	170	4.0	38	20	8.7	10	0.8	10	0.8	0.3	0.34	1.38
Kevlar-49 Aramid Fiber 181 Fabric	70	70	13	13	5.2	4.3	4.3	4.3	4.3	–	–	1.4
E-Glass 7781 Fabric	58	47	74	63	16	3.7	3 5	4.1	3.6	–	–	1.9
Alumina Fiber (FP)/Resin Unidirectional, 60% Fiber Vol	85	8	110	–	8.4/ 11.6	32	2.5	30	–	0.76/ 0.92	0.25	2.85
FP/Resin 0-90°, 60% Fiber Vol	40	40	175	175	11.4	16	16	15	15	8.3	0.01	2.85
FP/Kevlar 49/Epoxy 24% FP/36% Unidirectional Kevlar	130	3	125	–	6.1/ 13.4	20	0.8	17	–	0.60/ 0.53	0.30	1.98
FP/Kevlar 49/Epoxy 24% FP/36% Kevlar 0-90°	84	84	105	105	12.6	84	84	95	95	0.55	–	1.98

Symbols, Basic	Subscripts	Superscripts
F: Strength, ksi	L: Longitudinal	tu Tensile Ultimate
E: Young's Modulus, Msi	T: Transverse	cu: Compressive Ultimate
G: Shear Modulus, Msi		su: In-plane Shear Ultimate
ν: Poisson's Ratio		t. Tension
ρ: Specific Gravity		c: Compression

General material properties of non-reinforced plastics including SMC are well established in the automotive and plastics industries (References 4-4, 4-5, and 4-6) and will not be repeated here.

The values listed in Table 4-1 are nominals obtained from various sources, including MIL-HDBK-17A, NASA, AFML, Union Carbide, Hercules, Fiberite, and DuPont. The properties for unidirectional materials (which provide the maximum strength and/or modulus), and for various

fabric materials, are presented to illustrate the wide range of materials properties available. Fiberglass fabric is included to provide a basis for comparison.

Considering the importance of the durability and corrosion resistance of conventional automotive vehicles -- especially trucks -- the properties of advanced composite materials in this regard are of paramount importance. The general environmental and chemical stability of fiberglass composites has been established by the wide acceptance of such materials in the boating, chemical, and other industries. They have also been used successfully for over 20 years in the General Motors Corvette. The effect of electrically-conductive graphite fibers on a contiguous metallic structure and the long-term environmental stability of graphite fiber composites require further investigation. Corrosion-resistant finishes have been developed for aerospace use, but their applicability and economic feasibility in the mass-production automotive industry has yet to be demonstrated.

Surface degradation of composite materials caused by environmental factors usually does not have a significant effect on the mechanical properties. This holds true as long as degradation extends only to attrition of binding resin. Fracture of load-carrying fibers will cause degradation of mechanical properties, the extent depending upon the design. Environmental factors must be carefully considered in this context in the design of a specific component. Moisture absorption in exposed fiber has caused degradation of mechanical properties at an elevated temperature, but no significant degradation has been reported in the ambient temperature range. For automobile applications that will experience a temperature environment in excess of about 150°F, this phenomenon will require additional investigation.

The fatigue properties of high-modulus graphite materials are exceptionally good. Data reported for HM-Type 1 graphite show a fatigue capability of 80 to 90% of ultimate load (Reference 4-7). Preliminary data indicate that Type III or Thornel 300 graphite will have a demonstrated fatigue capability in the range of 70 to 75% of ultimate tensile strength, and Kevlar 49 has shown a fatigue capability of greater than 70% of ultimate tensile strength in work done by the Boeing Company (Reference 4-8). The outstanding fatigue strengths of graphite and Kevlar are of interest for potential automotive usage. Hybrid composites are also to be considered because they have demonstrated excellent fatigue life while providing lower weight and cost (Reference 4-9).

The fracture toughness (resistance to crack propagation) of advanced composite materials, while considerably lower than that of plain carbon steel, compares favorably with that of metal structures designed to the same strength or modulus. In general, high-modulus graphite fiber composites are not quite as good as metals in this regard, while high-strength graphite fiber composites are slightly better than metals. Fracture toughness parallel to fiber direction is poor because the crack progresses through the resin or the resin/fiber interface where crack propagation resistance is low. Thus it is imperative that the design

effort carefully consider load path and design each component to minimize shear loading parallel to fiber direction (i.e. design for low interlaminar fracture properties and high cross-laminar fracture properties). Present design ground rules must be modified to maximally exploit the unique properties of anisotropic composite materials.

Graphite composites exhibit excellent resistance to creep, while resins do not; therefore, the fiber orientation in the composite determines the creep behavior. When load is applied in the fiber direction, the total creep strain is very slight and a negligible permanent strain remains after unloading. Nominal values of creep resistance of several materials is compared in Table 4-2.

Table 4-2. Resistance to Creep Load and Creep Rupture
of Several Structural Materials

Material	Orientation Degrees	Tensile Strength (ksi)	Creep (a) Load (%)	Creep Rupture (hr)
S Glass/Epoxy	0	260	85	0.01
	0	260	60	60
Aramid/Epoxy	0	200	80	2
	0	200	70	150
Graphite/Epoxy	0	200	80	>1000 (b)
7075-T6 Al	–	70	93	350

(a) % Static Ultimate

(b) No failure in 1000 hours

Typical values of the coefficient of thermal expansion, both along and across the fibers of a unidirectional graphite-fiber-reinforced polymer matrix composite, range from -0.2×10^{-6} to -0.05×10^{-6} in./in./ °F and from 11×10^{-6} to 20×10^{-6} in./in./°F, respectively. The generally negative coefficient of expansion along the fiber, coupled with freedom in selection of orientation, permits the designer to adjust the thermal coefficient over a range from approximately -1.3×10^{-6} to $+15 \times 10^{-6}$ in./in./°F.

Coefficient of thermal expansion data (Table 4-3) indicate the near-zero coefficients obtainable in quasi-isotropic laminates.

Table 4-3. Comparison of Thermal Stability of Graphite with That of Other Materials

Type of Material	Coefficient of Thermal Expansion (in./in./°F) x 10^{-6}	
	$0°$	Isotropic
Graphite AS/epoxy	-0.20	1.01
Graphite HMS/epoxy	-0.30	0.45
S Glass/epoxy	3.50	6.00
Aluminum	13.0	
Steel	7.0	
Nylon (6/6)	45.0	

Polymer matrix/graphite fiber composites exhibit relatively high thermal conductivity along the fiber and low conductivities in the transverse direction. Conductivities equivalent to that of steel can be reached along the fiber if high-fiber volume are used in the matrix. The ability to dissipate heat is thought to be an important characteristic in the increased fatigue life. Table 4-4 shows typical values.

Table 4-4. Comparison of Thermal Conductivity of Graphite with That of Other Materials

Type of Material	Conductivity Btu-ft/hr-ft^2 -°F	
	$0°$	Isotropic
Graphite AS/epoxy	4-5	3-4
Graphite HMS/epoxy	30-32	16-18
S Glass/epoxy	2	0.2
Aluminum	80-125	
Steel	9-27	

Although composites are generally characterized by the mechanical properties of unidirectional laminates, in actual practice multi-plied, multi-directional composites are usually required for structural integrity. Material strength and elastic properties are based on fiber orientation within the laminate. Complex analysis methods have been computerized. For certain combinations, however, preliminary design curves have been developed which relate directional strength and stiffness values to ply stacking arrangements. Figures 4-1 and 4-2 demonstrate these plots for the family of 0/±45/90 laminates from the USAF design guide.

Graphite/resin composite materials can be formulated in such a way as to take advantage of their electrical conductivity and lubricity properties, which can be beneficial for certain applications. Graphite -- when incorporated in a hybrid composite with fiberglass -- could be utilized for radio frequency interferences (RFI) shielding. Thus, by making the hybrid composite electrically conductive, in an automobile hood for example, ignition noise can be suppressed in addition to providing stiffness.

Electrostatic painting constitutes another potential exploitation of the electrical conductivity of graphite. The process appears to be technically sound and its adoption will depend on economics, in particular, the price of graphite. Pitch matte is currently the leading contender, although other forms of graphite could be utilized.

The wear and lubricity characteristics of graphite offer potential for brakes and bearings. A 3 to 5% graphite addition in asbestos brake linings has been demonstrated to improve wear by 30% to 50%. Phillips Petroleum has formulated Ryton bearings which contain a graphite addition.
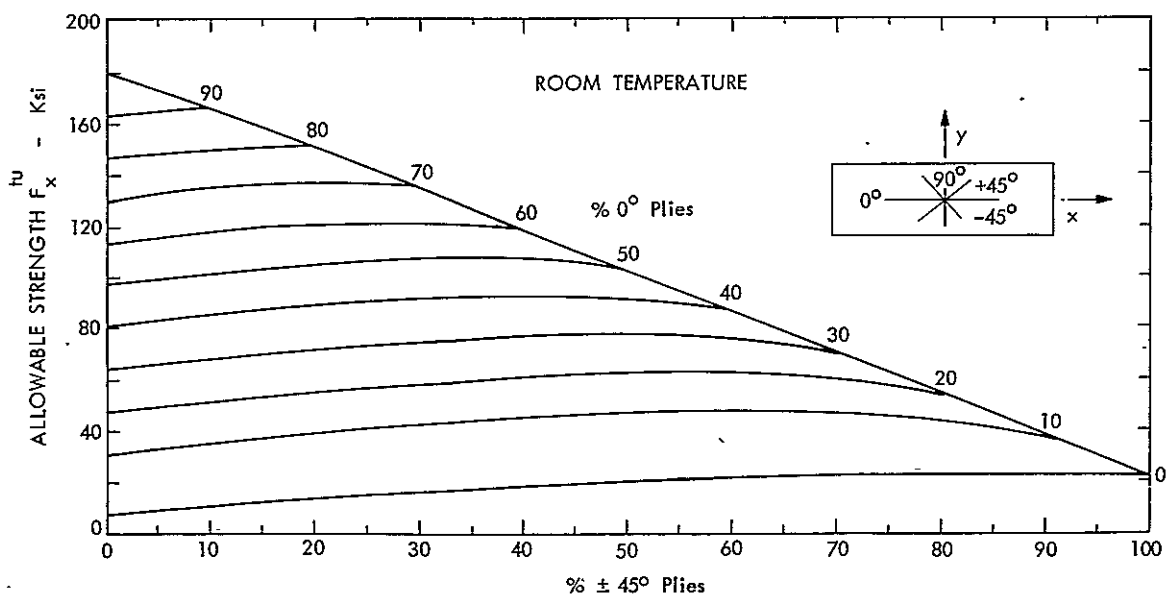
Figure 4-1. Ultimate Tensile Strength of Crossplied Graphite/Epoxy
(0, ± 45, 90) (From Reference 4-5)
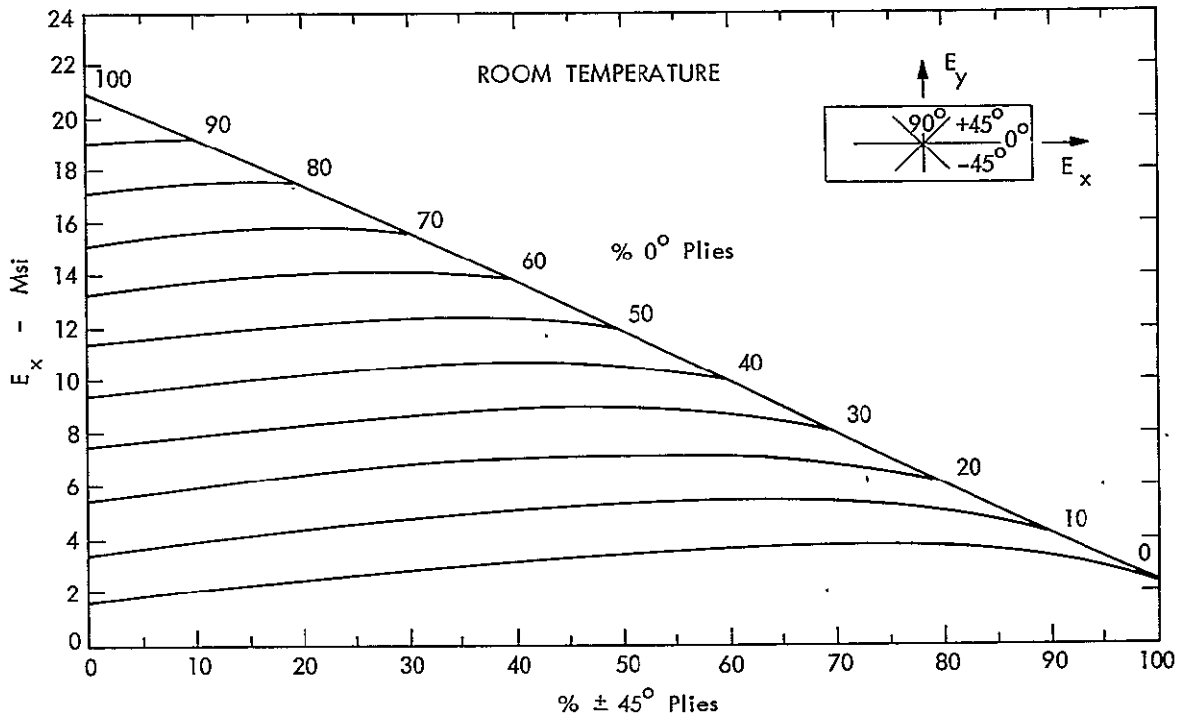
Figure 4-2. Ultimate Tensile Modulus of Crossplied Graphite/Epoxy
(0, ±45, 90) (From Reference 4-5)

Usage of different forms of graphite (e.g. chopped, blown matte, swirl matte, powder) in the previously mentioned applications of RFI shielding, electrostatic painting, brakes, and/or bearings is likely to have an effect on the cost of fiber graphite. The extent of this effect, however, is currently an open question which will be evaluated in this Project.

In addition to a fiber, a composite material system also requires a suitable resin system. Polyesters have been used the most extensively in commercial systems due to their lower relative cost and availability. Vinyl esters have also been used to a lesser, but still significant, degree. Epoxy systems, while more expensive, probably have the largest information data base available on their properties.

Composite materials systems often require a coupling agent and/or sizing at the fiber/resin interface. These agents are used to prevent a chemical reversion or decoupling at the interface, which can adversely affect the fatigue and vibration properties of the materials systems. For example, sulanylazidosilanes have been employed in fiberglass reinforced polymers containing aromatic rings (e.g., epoxies, styrenes, polyimides, etc.) for improved interfacial adhesion.

C.   POTENTIAL IMPEDIMENTS

Although composites show promise as a structural material for automotive applications, some problems remain to be solved. These problems, in their current form, can pose as impediments to the widespread economical use of composites. Disadvantages to the use of composites include:

1.   Cost

Upon introduction, graphite fibers sold for more than $500 per pound. Current prices are $20 per pound and expected to drop below $10 per pound based on volume growth and technological advances. The development of pitch-based graphite is expected to further reduce graphite fiber cost. Even fiberglass at about one dollar per pound is considerably above that of automotive steel. Density considerations, however, assist in bringing the premium material price in composite hardware into line with metal parts as a result of the composite's reduced weight.

2.   Supply

Supply and manufacturability also are serious issues. Although the technology has been around since the late 1950s, the production of graphite in the U.S. has not been higher than 250,000 pounds of fiber a year. Suppliers state that with a commitment from auto manufacturers, it would take from 5 to 10 years for them to reach projected demand levels of about 100 million pounds a year. Fiberglass has been a high-volume product with many applications in a variety of industries and is readily available.

3.   High-speed Manufacturing

High-speed manufacturing of graphite fiber composites has not yet been attempted, and the issue is just now starting to be addressed. High-speed, high-volume fiber manufacturing will be a necessary development to achieve the required quantities and to exploit the potential cost reductions.

4.   Environmental Risk

A risk of unknown magnitude is associated with widespread use of graphite fibers as a result of the fibers accidental release into the atmosphere.

Inadvertent graphite fiber release, during manufacture or by destruction of the resin binder in fire, is the major hazard associated with composites. Major manufacturers are aware of the unique problems associated with these materials and have successfully applied controls to avoid the in-plant problems. With the expected rapid growth in the use of these materials in aircraft and automobiles, however, vehicle accidents followed by fire could become a substantial possible source of fiber release. Further, the uncontrolled incineration of industrial waste and of discarded consumer products could create serious problems.

The carbon (or graphite) fibers used in the present generation of composite materials are finer than human hair, extremely good electrical conductors, and virtually indestructible. They are so light that millions are contained in a gram mass. If released into the air, they can easily be transported by winds or currents. In contact with electrical devices, they can create resistive loading, short circuits, and arcing, resulting in stoppages or destructions. A variety of actual incidents can be cited supporting the hazards the fibers pose to electrical equipment.

In some cases, electrical protection might be realized by seclusion of equipment through protective covering or air filtering. New generations of electrical and electronic equipment can be manufactured with added protection at relatively modest cost. In addition, programs are underway to alter the graphite reinforced composite in such a way as to preclude the problem from occurring including:

(1)   develop nonconductive fibers
(2)   prohibit fiber release during combustion
(3)   cause the fibers to oxidize rapidly to gaseous components.

5.   Additional Problems

A variety of other technical problems must be addressed to more fully define the range of service that composites can perform in the automotive industry, including:

(1)   Materials development and property determinations.

(2)   Ability of graphite composites to absorb energy adequately in a collision.

(3)   Recycling or disposal of discarded material.

(4)   Joining.

(5)   "Drive-away" hardware cost (must be competitive with other materials).

Materials must be developed that are compatible with the high volume production requirements of the automotive industry, yet be resistant to the performance environment of the vehicle. These may conceivably take the form of glass/graphite hybrids in thermoplastic resins. In any case, design allowables and extensive material property data must be generated on these "modified" composites.

For an elastic deforming material such as composites, rather than plastic material such as steel, component redesign is necessary to provide energy absorption during collision. The catastrophic failure of composites after elastic deformation digests energy in a different mode than plastic deformation of metal.

The final component cost is influenced not only by the material price but more substantially by the manufacturing processes to achieve high volume production. Minimum process time and facility investment are required to achieve cost competitive composite hardware. Additional manufacturing efficiencies are achieved by the reduced assemblage costs but these must be carefully considered in the overall vehicle design.

SECTION V

CURRENT MARKET USAGE AND FEASIBILITY ITEMS

A.   INTRODUCTION

An assessment of current automotive industry usage of composite
materials and future plans for them is being conducted. Exploratory
techniques have included industry visits, attendance at technical society
meetings and trade shows, and a review of pertinent technical literature.
The information gained to date is reported here and includes limited
production of automotive components made of fiberglass and demonstration
items made from graphite reinforced epoxy. A thorough assessment of the
level of production, cost effectiveness, applicability to the electric
vehicle, and crash-worthiness among other concerns has not yet been
completed.

B.   MANUFACTURED HARDWARE

The land transportation market is the largest user of reinforced
plastics/composites with accelerating growth in volume and variety of
applications.

For the automotive industry, the major incentive is weight reduc-
tion which translates into lower fuel consumption and less pollution.
To a trucker it means more payload within axle load and gross vehicle
weight restrictions.

There are more than 350 different fiberglass-reinforced plastic
parts in the 1978 model U.S. cars including front end panels and grilles,
head lamp and tail lamp housings, roofs and wheel covers, spoilers and
air deflectors, instrument panels, consoles, air condition housings, and
trim. Included also are 166 different functional components such as
engine cooling fans, fuel pumps, distributor caps, battery trays, fender
liners, and others.

The predominant raw material used in the fabrication of automotive
components is "sheet molding compound" (SMC). Sheet molding compound
consists of chopped fiberglass, randomly distributed, impregnated with
an uncured polyester resin and sandwiched between two plies of removable
polyethylene liner. The material is supplied in a roll and is generally
refrigerated for storage. Application of heat and pressure is required
to cure the polyester into a rigid structure while it is contained in
tooling to impart the desired shape.

The most noteworthy application of composites to the automotive
industry is the fabrication of the Corvette from SMC.

A visit was made to the General Motors Assembly division plant at
St. Louis, Missouri to witness the manufacture of fiberglass automotive
components (Reference 5-1). General Motors does not manufacture their

own fiberglass parts. All composite hardware is purchased from Budd Company, Carey, Ohio (fenders, hood, deck lid), General Tire, Ionia, Michigan (doors), and Rockwell International, Centralia, Illinois (rear floor panel). Sheet molding compound and bulk molding compound are used in the component fabrication. A four component polyester is the matrix (polyester monomer, styrene to cross link, promotor and catalyst with fillers sometimes included). Panels are generally molded to net size and shape.

General Motors assembles the body using adhesives (polyester and polyurethane), bolts and rivets. Production rate is 10 units per hour allowing six minutes per operation. The 1977 production figure for Corvettes was 49,213. Two shifts of 10 hours per shift per day were used for 200 units per day.

Assembly begins by fabricating a metal cage (Figure 5-1) which defines the passenger compartment. This "bird cage" is then bolted to a chain-driven assembly line dolly to provide rigidity and a fixed point from which to build the body. Assembly of the vehicle is accomplished as shown in the attached flow chart (Figure 5-2). Composite components are joined by adhesive bonding, bolting, riveting or a combination of bonding/bolting. The adhesive used is principally a room temperature cure polyester. Minor repair is accomplished with a talc-filled polyester. All assembly line operations except for the conveyer line itself are manually performed.

The finish is achieved by successive hand sanding and buffing operations followed by a primer and final coat of paint. The most demanding problem, from the assembly plant manager's view point, is the compatibility (without exception) of structural hardware with a common polyester bonding system and common paint primer (Reference 5-2).

Figure 5-1. Metal "Bird Cage" for Chevrolet Corvette

CHASSIS ASSEMBLY LINE   BODY ASSEMBLY LINE

```
                    BRAKES
                  SUSPENSION
                   GAS TANK
  METAL            SPARE TIRE
  FRAME              HOLDER                 FRONT                  METAL
                  (FIBERGLASS)   FLUID    FENDERS ──► HOOD ──► RADIATOR
                                 LINES    AND COWL                FRAME

                                STEERING
                             TRANSMISSION  REAR FENDER
                                           AND WHEEL             ROOF
                                            HOUSING             PANELS

                                ENGINE
                                           REAR FLOOR
                                 OIL          PANEL               MINOR
  ENGINE                         AND                           FIBERGLASS   STEEL BIRD
  ASSEMBLY                       TEST                            DETAILS       CAGE
  LINE                                   ⊛START ASSY                        ASSEMBLED
                                         OF GLASS BODY                       BY SPOT
                                          BIRD CAGE                          WELDING
                                 BODY      BOLTED TO
                                         BODY TRANSPORT                    OVERHEAD
                                            DOLLY                          TRANSPORT
                                                                           TO BODY
                                                                           ASSEMBLY
                                                                             LINE

                                         INSERTS AND          SANDING
                                           DECALS             BUFFING
                                 GLASS                        REPAIR
                                 TRIM                          PAINT
                                 DETAIL    BUMPER             (PRIME
                                 GAS       GUARDS              AND
                                                             FINISH)
                                          BUMPERS

                                           ◄── OVENS ◄──




                  ASSEMBLED
                   CORVETTE
                  DRIVEN OFF
                 TO FINAL TRIM
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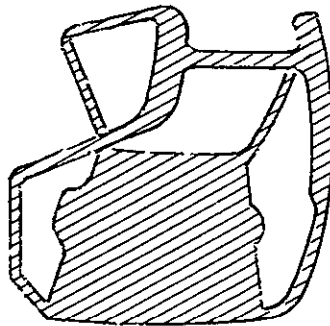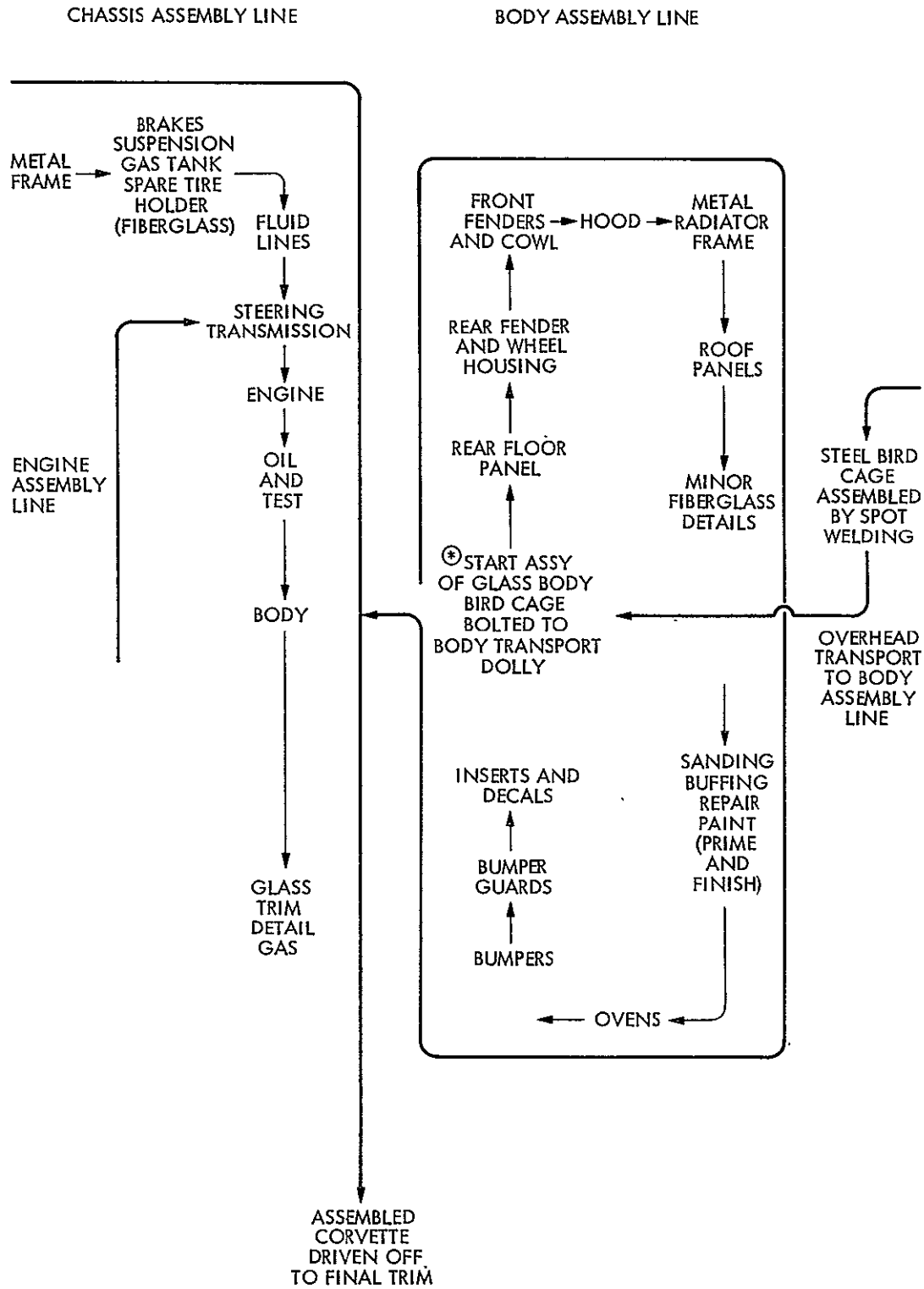
Figure 5-2. Corvette Assembly Line

The 1978 Corvette rear roof assembly underwent a styling change and parts consolidation. The new assembly consists of an outer skin which is bonded to an inner hat section reinforcement. Both components are compression-molded in matched metal dies of fiberglass-reinforced polyester sheet molding compound (SMC). The outer panel is highlighted by complex surface contours and styling lines. This roof assembly achieves the desired strength requirements with minimum mass at a weight of only 26 lb. (Reference 5-3).

The body consists of 52 glass reinforced parts for a total weight of 227 lb. Of this, 39 parts are molded of fiberglass-reinforced polyester, of which 23 are wet-molded, 13 are sheet molding compound (SMC), and 3 are bulk molding compound (BMC); 13 parts of fiber glass-reinforced thermoplastics, of which 2 are polyethylene, 7 are polypropylene, and 4 are ABS. All are press molded in matched dies, most by compression molding, some by injection molding.

Automotive manufacturers have utilized fiberglass SMC to fabricate a wide variety of secondary structural and decorative 1978 front and rear end assemblies (Reference 5-4).

The grille panel on Chrysler's 1978 Cordoba (Figure 5-3) is a highly contoured single part. It is molded in matched metal dies of 30% sheet molding compound (SMC) which was formulated to be compatible with both metal and existing systems and methods of automotive assembly. Combining high strength, corrosion resistance and dimensional stability with low tooling costs, the panel weighs only 15 lb, a great saving over heavier castings or assembled steel parts. This molding replaces an estimated 13 components that would have had to be formed and assembled had the part been made of metal. The "classic" look of the '78 Cordoba grille was accomplished by redesigning and retooling of the reinforced plastic molding used in the 1978-77 models -- an easy and inexpensive change.

The grille, 60 in. long and 15 in. wide, was molded by the Plastics Division of Eagle-Picher Industries.

The one-piece front end molding for the Dodge Diplomat is the result of a combination of material, molding, and assembled-body finishing to achieve the desired quality. The panel is compression-molded in matched metal dies using low profile sheet molding compound (SMC) with 28% reinforcement of 1-in. glass fiber. By subjecting the molding to high oven bake temperatures during cofinishing with the surrounding metal parts, a high-gloss automotive surface is achieved. The part, which provides the mounting areas for front grille and headlamps, offers good strength, dimensional stability over a wide range of temperatures and is light in weight. The 66 x 13 x 7.5 in. SMC molding weighs just 10.3 lb, the full assembly 12 lb, and it is manufactured for Chrysler Corporation by the Goodyear Tire and Rubber Company.
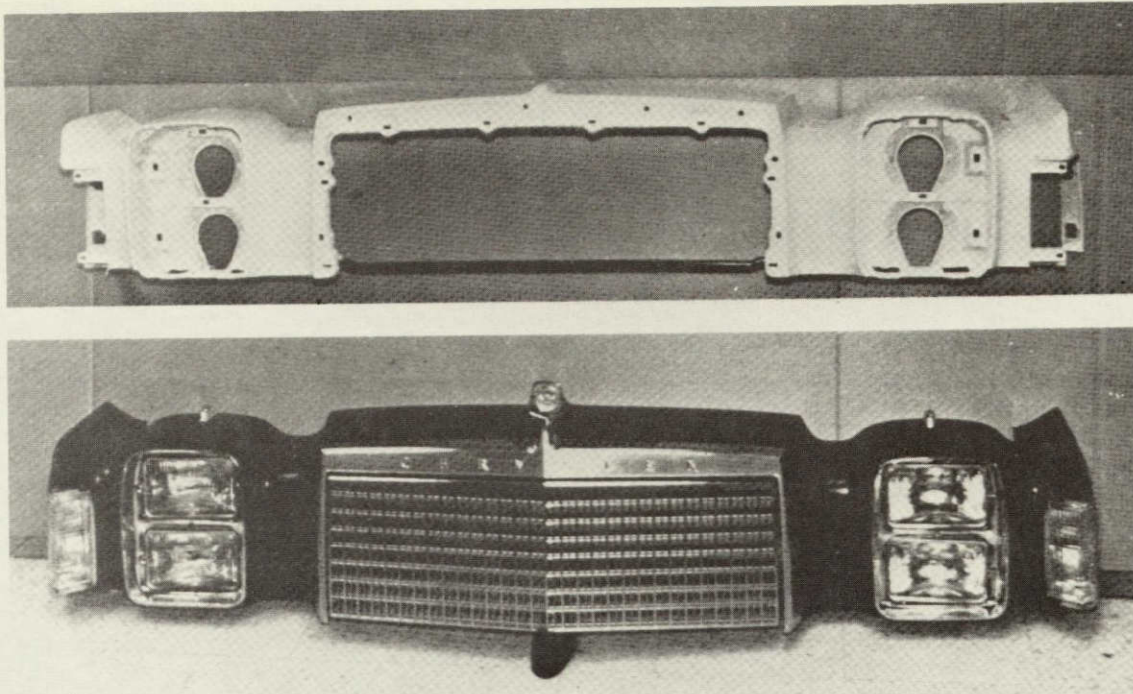
Figure 5-3.　Chrysler 1978 Cordoba Grille
(From Reference 5-4)

Ford's new 1978 Fairmount encompasses the application of reinforced
plastics to make a contribution to weight saving and ease of assembly.
Taillight housing for the Fairmount Futura (Figure 5-4) includes not only
the complex housing and reflectors but also the frame. This is believed
to be the first time both units were combined. The housing is compres-
sion molded in matched metal dies using a low-profile bulk molding com-
pound (BMC) that meets Ford specifications for strength and quality. A
class "A" surface is required and this is achieved without a prime coat.
The molder applies a Ford-specified black paint coat to the entire part,
then an aluminum paint to the reflector areas to meet a Federal standard
for reflectivity. The housing is molded in right- and left-hand units
with the latter incorporating an overlap extension for assembly. The
left-hand unit measures 38 x 9 x 8 in. and weighs 8.5 lb. The right-
hand unit measures 33 x 9 x 8 in. and weighs 7.7 lb. Both were molded
by Molded Fiberglass Tray Company. The same units are used on the
Mercury Zephyr.

In the front end of the body of the 1978 Buick Regal is a visible
multi-function one-piece molding of fiberglass reinforced polyester
sheet molding compound (SMC). The large exterior top shelf prior to the
hood has a smooth surface finish which blends with the surrounding
exterior metal parts for unified appearance. In addition, the molding
provides the front grille and headlamp mounting surfaces. The part is
compression molded of low-profile SMC embodying 28% 1-in. glass fiber
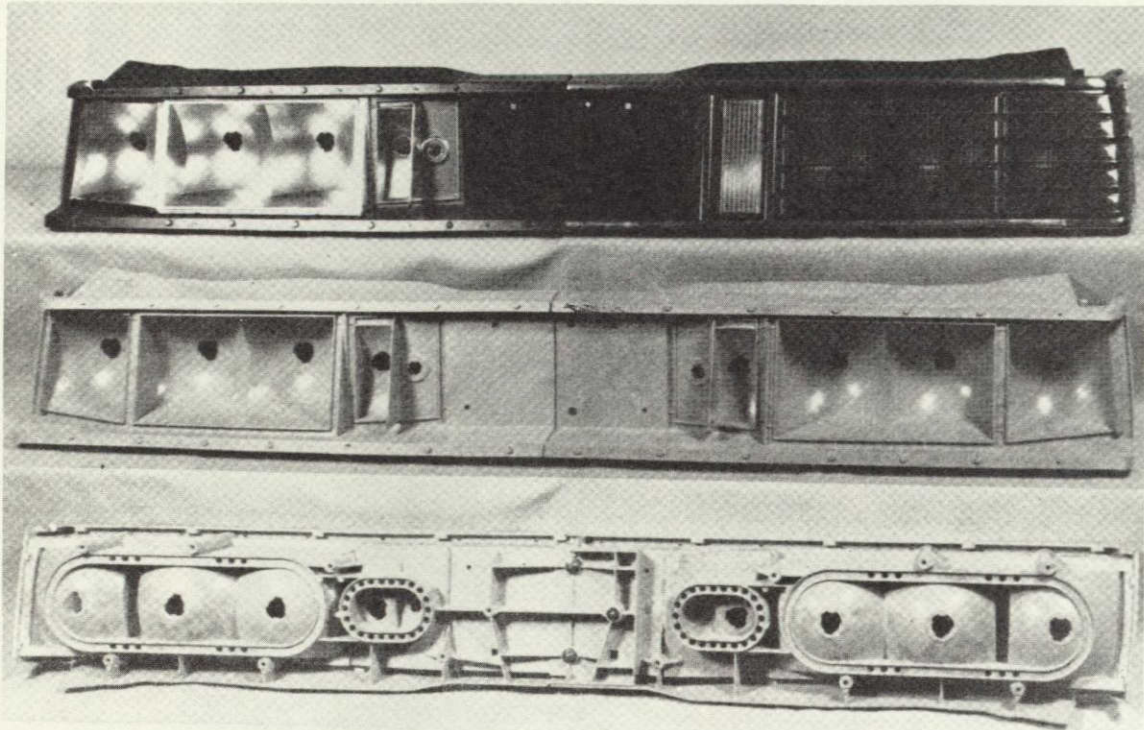reinforcement. The resultant part is corrosion resistant, has good

Figure 5-4.   Ford's Fairmount Futura Tail-light Housing
(From Reference 5-4)

physical properties, good structural integrity and dimensional stability.
The 66 x 11 in. SMC molding weighs just 12.5 lb, and it was fabricated
by Goodyear Tire and Rubber Company.

The continued use of sheet molding compound (SMC) for the 1978
Buick Riviera front end panel is further evidence of the acceptance of
this composite for automotive panels. The compression molded SMC pro-
vides the smooth curves needed in a highly visible portion of the finished
automobile and, at the same time, is cost competitive with traditional
materials. This panel typifies the advantages of SMC over sheet metal:
good surface finish, light weight for fuel economy, parts consolidation
for lower production costs, corrosion resistance, and design freedom for
styling flexibility. Compression molded of low profile, 30 percent
glass-reinforced SMC, the 72 x 12 x 7 in. part weighs just 14.5 lb and
was fabricated by Premix/E.M.S., Inc., Lancaster, Ohio.

Ford Bronco's new removable rear roof is comprised of nine
assembled sheet molding compound (SMC) parts. All are compression
molded in hydraulic presses ranging in size from 300 to 500 tons. This
unitized-constructed roof, which covers the rear seat and cargo area of
the vehicle, meets both structural specifications and the styling
features as required of the 1978 sport-utility market. Another advantage
of reinforced plastic for this roof is that it weighs 80 lb when assembled.

As a result, it can be marketed as a removable roof. The assembly is 71 in. long and 73 in. wide x 24 in. high and is manufactured by Rockwell International, Centralia, Illinois.

Fiberglass SMC is also being utilized by truck manufacturers for the fabrication of the cab portion of class "A" 30,000 lb gross weight trailer trucks. A prototype facility is being established by International Harvester's truck group to prove the feasibility of employing composite materials in the mass production of trucks and sports/utility vehicles (References 5-5 and 5-6).

Rapidly escalating tooling costs for steel bodies are necessitating a change. Tooling costs for International Scout vehicles, for example, tripled in an eight-year period.

A design group has built a working sports/utility vehicle and a variety of truck components using composite materials. The next step is to produce superior composites structures in a production environment at rates that will compete with steel and aluminum stampings. There are, however, no near-term plans to replace steel or aluminum as principal materials for International trucks. International Harvester estimates total energy needs for the manufacture of trucks that utilize composite materials are as low as 50% of what is currently required. This is because a different type of facility could be used to build composite trucks -- lower ceilings, lighter equipment, and reduced warehousing space -- and far fewer parts would have to be assembled. In addition, producing a composite truck can save energy on body preparation and treatment; the amount of energy required for cleaning, washing, phosphatizing, and painting would be substantially reduced. Painting a composite material, for example, allows a considerably lower oven temperature than does metal.

Other gains the company expects from the composite truck include fewer body parts, less time for new-product development, and more company-produced parts in each truck: Figure 5-5 illustrates a composite tilt front end cab consisting of 13 components compared to 85 components for the existing metal counterpart.

Major objectives of IH's current program are to speed up new product development, increase the company's vertical integration, develop lightweight, high-strength and durability of its products -- and emphasize a parts reduction program.

A class "A" automotive finish is being achieved by Goodyear Tire and Rubber Company in molding hood skins for the new International Harvester S-2200 trucks with low pressure sheet molding compound in cast steel dies. IH reports high quality of the molded parts and appearance of the painted units, feels it clearly demonstrates the exceptional surface finish obtained from cast tooling with low pressure molding. This complex part was molded at pressures of 659 psi.

The realization that the quality of a molded part was highly dependent on tool quality started a trend toward more expensive compression tools. With this cost increase, it became more and more
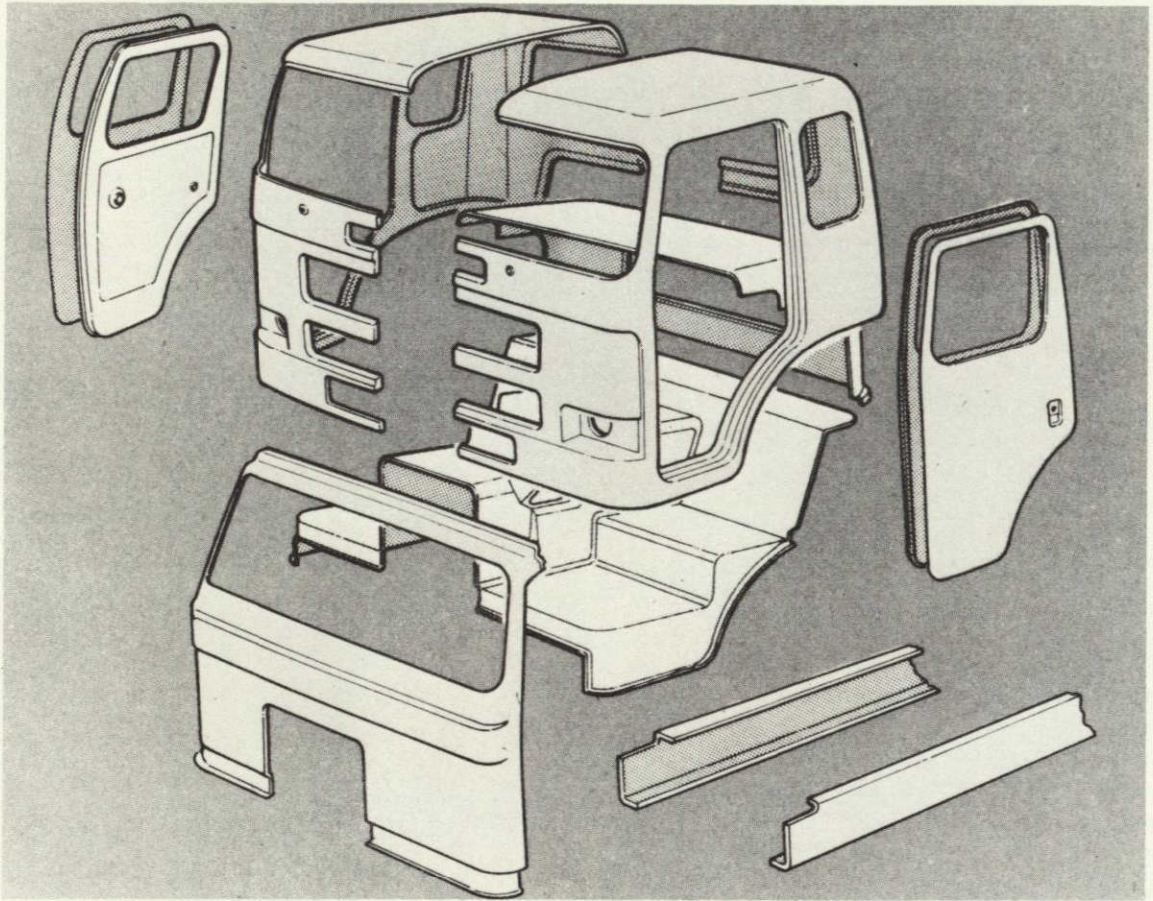
Figure 5-5. Manufacture of Truck Cab Using Only 13 Major
Subcomponents Compared to 85 for Metal
(From Reference 5-5)

difficult to justify the capital expense of sheet molding compound in
low volume programs. However, with low pressure molding, the capital
expense in tooling can be significantly reduced without any change in
tool quality or expected life of the tool.

The assembled hood skins are 40 in. high, 90 in. wide, 40 in. long
with a nominal wall thickness of 0.115 in. Weight of the assembly is 20
lb for the skin and 65 lb for the reinforcement.

The new General Motors Truck and Coach Brigadier tilt front end
(Figure 5-6) represents another large assembly application of fiber-
glass-reinforced sheet molding compound (SMC). A total of 15 reinforced
plastic matched die compression molded parts make up this front end
which, when assembled, weighs just 90 lb. A unique feature is the
removable fenders which provide ease of field service as well as provid-
ing an option for fenders of another style. The 13-piece hood assembly
is molded, assembled and prime-painted by Rockwell International before
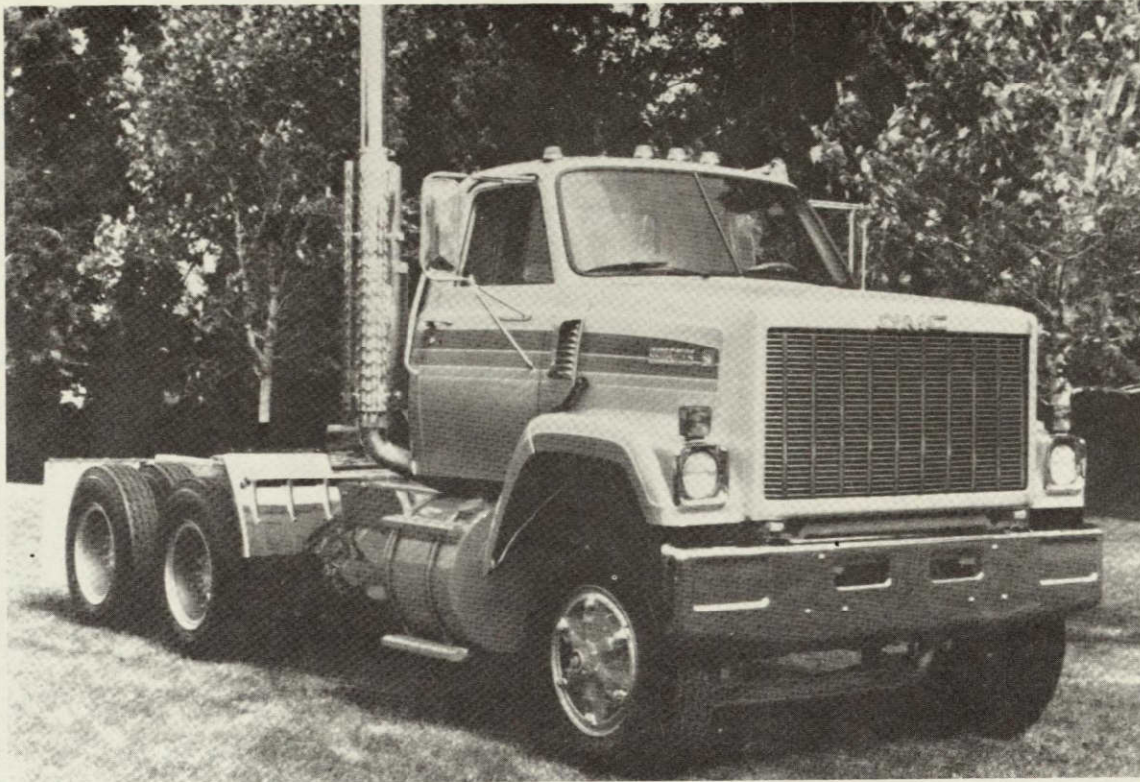
Figure 5-6.   Composite Tilt Front End for GMC "Brigadier"
(From Reference 5-4)

shipment to the customer. The two-piece fender bolt-on panels are
shipped separately. The full assembly is 40 in. long, 96 in. wide,
and 36 in. high.

As part of Ford's weight reduction program for their new CL 9000
heavy duty truck, they chose sheet molding compound for the cab's skirt
assembly. Custom molded in matched metal dies, the skirt's components
are used on cabs ranging from 54 in. B.B.C. to 110 in. B.B.C. The
skirting for the 54-in. long cab weighs only 40 lb while the assembly
for the 110-in. long cab weighs 61 lb. Each component is bolted-on for
easy serviceability which permits the use of molded replacement parts
rather than high-labor patching. The use of fiberglass reinforced
plastic provides a heavy duty skirt assembly that is light in weight
with good surface finish and resistance to heat and corrosion.

C.   DEMONSTRATION HARDWARE

The most notable of the composite demonstration programs currently
underway in the automotive industry is Ford's "all graphite" vehicle
(References 5-7 and 5-8). Ford Motor Company plans to build a prototype
car with body, chassis and powertrain components made of graphite fiber
to the maximum extent possible (Figure 5-7).
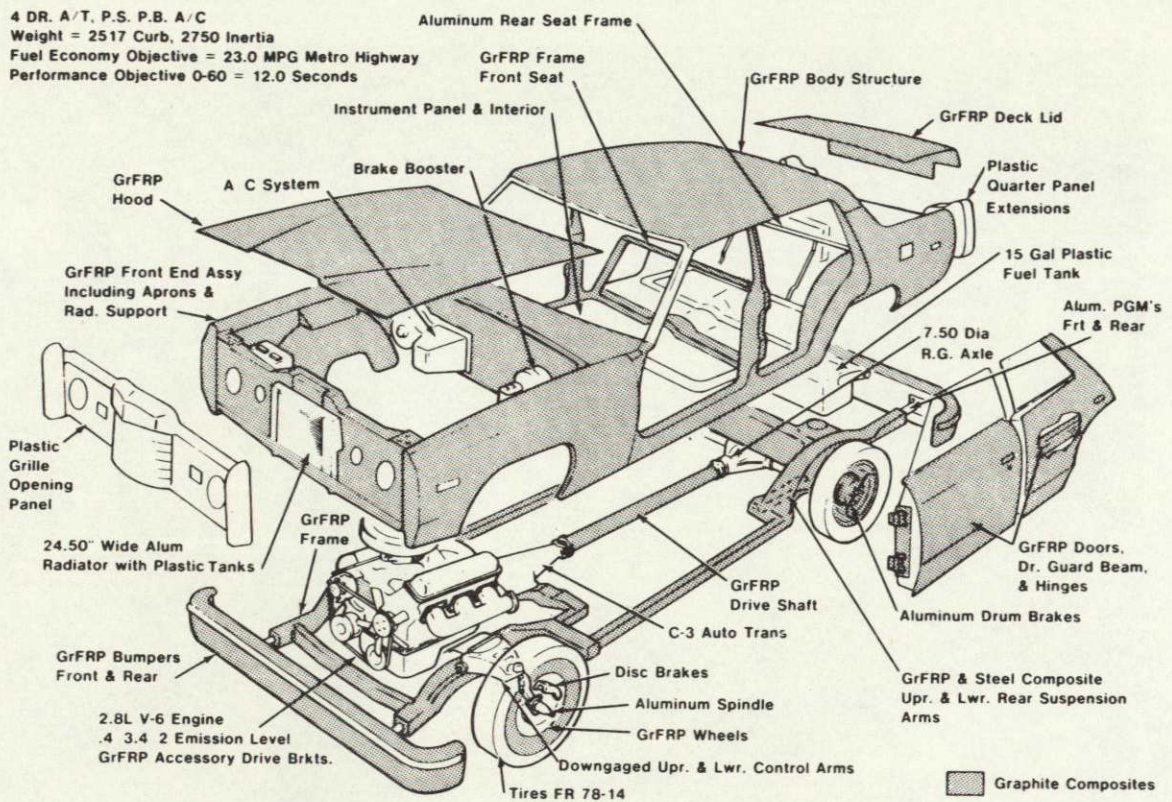
Figure 5-7. Ford Lightweight Vehicle Program
(From Reference 5-7)

The car is a six-passenger automobile about the size of today's intermediate cars. It will weigh 2,750 pounds -- some 1,250 pounds lighter than the planned 1979 intermediate cars built with conventional materials. The weight savings will result from direct material substitution without redesigning the basic vehicle.

Ford is undertaking this project as a major part of the corporate effort to improve fuel economy, and yet retain the kind of interior room, comfort, and driving characteristics the public has indicated it wants.

The experimental car program has three objectives:

(1)   To assimilate the knowledge already available and develop capabilities for design and construction of automotive components and assemblies from graphite fiber composites.

(2)   To demonstrate the capabilities of the composites for achieving dramatic weight savings and corresponding fuel-economy improvements.

(3)   To identify all of the possible near-term automotive applications for this new material, concentrating on design, manufacturing, and assembly feasibility.

The car will be powered by a 2.8 liter V-6 engine and will be equipped with such comfort and convenience options as air conditioning, automatic transmission, power steering, and power brakes -- the kinds of options the majority of buyers of mid-sized and standard-sized cars include in their purchase.

The fuel-economy target for the car is at least 23 miles per gallon on a metro-highway cycle, or six miles per gallon better than today's family-sized Ford. Also, the car is expected to be able to accelerate from zero to 60 miles an hour in 12 seconds -- which is comparable to the performance of 1978 full-sized Fords.

Ford has already demonstrated some experimental graphite-reinforced parts on a Granada. A hood, right rear door, driveshaft, air conditioning brackets, upper and lower suspension arms, door hinges, door-guard beam and crossmember are all made of graphite-reinforced epoxy. Weight savings achieved on these substitutions are illustrated in Table 5-1.

Table 5-1. Ford Lightweight Vehicle Program Graphite
Component Weight Summary

Component	Steel (lb)	Graphite (lb)	Reduction (lb)
Hood	40.00	15.00	25.00
Door, R.H. Rear	35.25	12.65	17.60
Hinge, Upper L.H. Front	2.25	0.47	1.78
Hinge, Lower L.H. Front	2.67	0.77	1.90
Door Guard Beam	3.85	2.40	1.45
Suspension Arm, Front Upper	3.85	1.68	2.17
Suspension Arm, Front Lower	2.90	1.27	1.63
Transmission Support	2.35	0.55	1.80
Driveshaft	17.40	12.00	5.40
Air Conditioning, Lateral Brace	9.50	3.25	6.25
Air Conditioning, Compressor Bracket	5.63	1.35	4.28
Total	120.65	51.39	69.26

Ford acknowledgments of other companies and organizations that are supporting the Lightweight Car Program include Cellanese Corporation, Hercules, Inc., Union Carbide, the Budd Company, the Carron Plastics Company, Merlin Technologies, the Milford Fabrication Company, Vought Corporation, Babcock and Wilcox, Graftek/Exxon Enterprises, the Stanford Research Institute, and the Aerospace and Communications Division of Ford Motor Company.

The experimental car will be ready for evaluation in the first quarter of 1979.

Exxon Enterprises has fabricated an all-electric passenger vehicle (Figure 5-8) which demonstrates the widest use of composites to date. Graftek Division of Exxon fabricated a graphite/epoxy frame (Figure 5-9) and a hybrid glass/graphite polyester body (Reference 5-9). The vehicle is powered by twelve 6-V batteries with a DC series-parallel battery switch to a DC motor. Exxon is developing an AC converter system to operate an AC motor and they expect thereby to reduce the mass of the propulsion system and increase power. The technology is being developed by Exxon Venture capital.
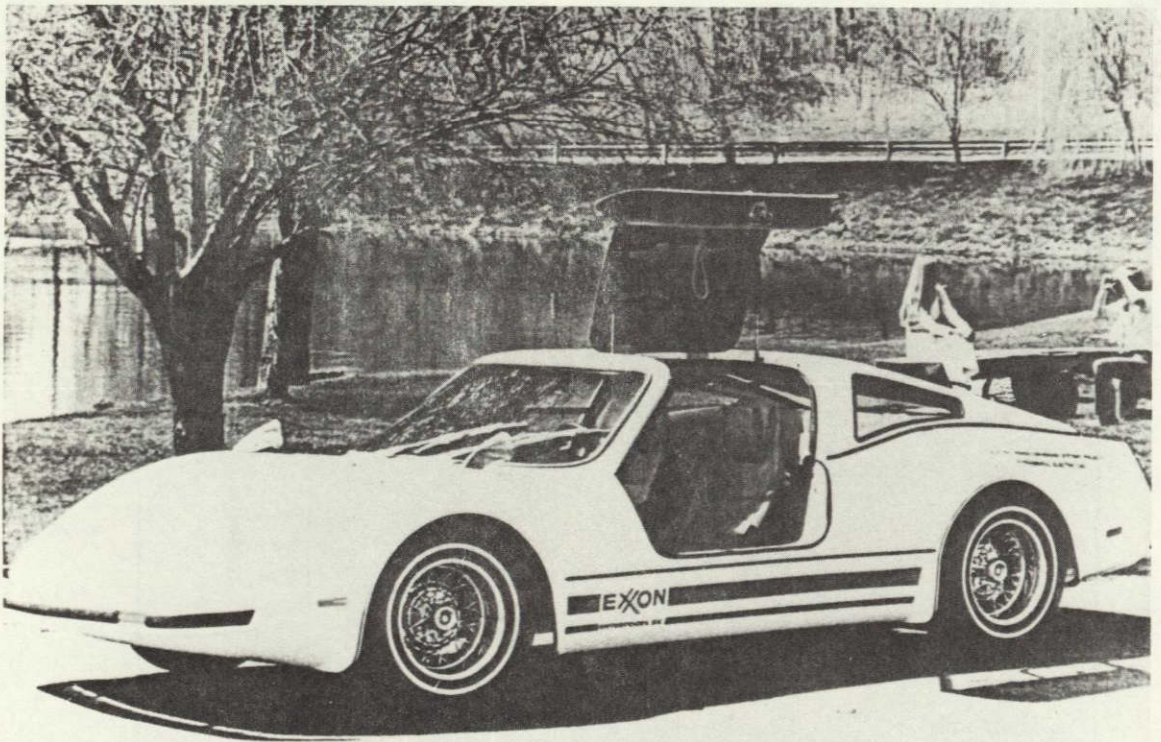
Figure 5-8. Exxon Electric Vehicle
(From Reference 5-9)
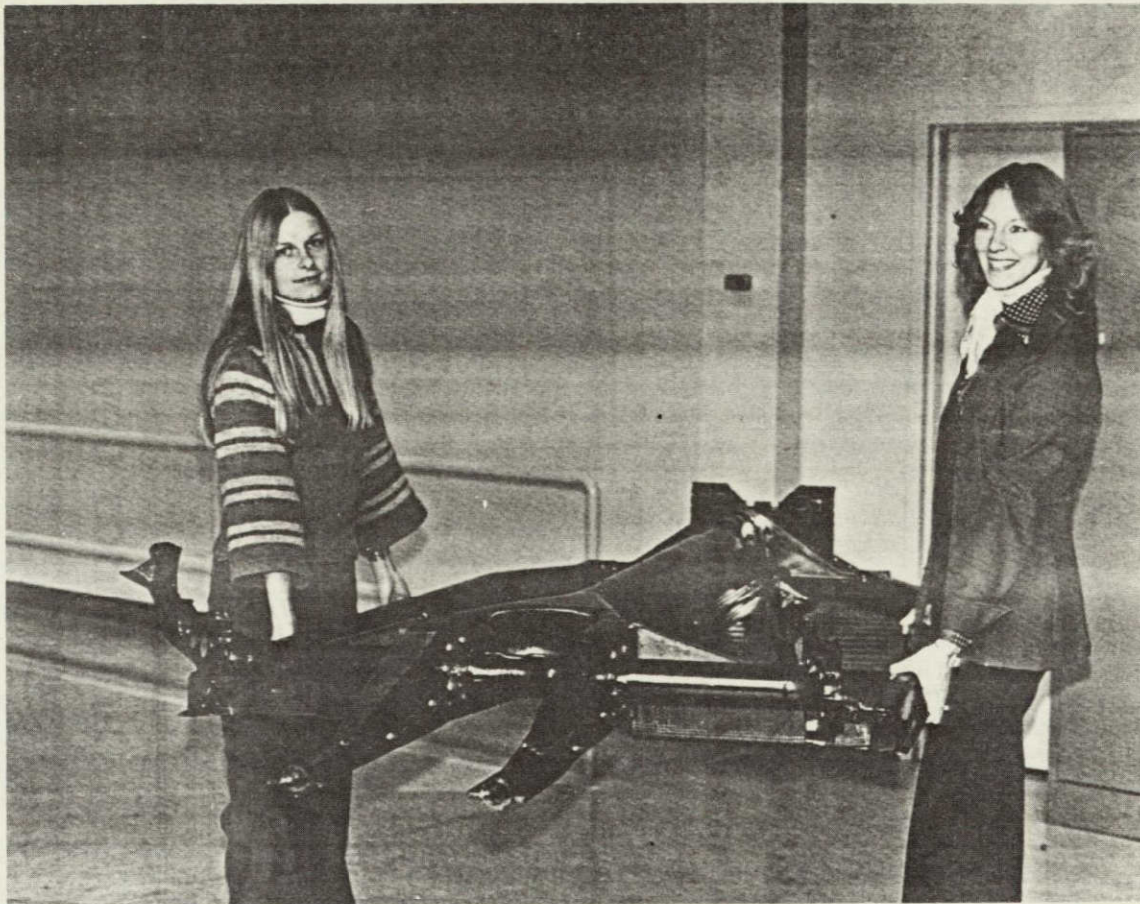
Figure 5-9.   Graphite/Epoxy "VW" Frame for Exxon Electric Vehicle
(From Reference 5-9)

A computer simulation of J227D yields a range of 28 miles at a top speed of 55 mph on the vehicle.

The car itself employs an extensive use of composites, notably as follows:

(1)   Body: The body comprises chopped fiberglass/polyester sprayed over a 4 x 4 in. graphite fiber grid of tows (to provide greater stiffness). The body gauge is nominally 3/8 in. (thickness control is a problem). The body style is a Bradley GT fabricated for Exxon by Bradley.

(2)   Frame: The frame is a standard VW one, but it is fabricated using graphite epoxy by Graftek. The frame is joined to the body with metal bolts.

(3)   Total Weight Savings: The body weight went from 230 to 130 lb using a graphite stiffening grid. Frame savings were 100 lb using G/E. Total weight savings over the standard glass Bradley GT on a VW frame was 200 lb.

John Z. De Lorean has organized a new U.S. automobile manufacturer, the De Lorean Motor Company. What is notable is the intention to use the first load bearing application of plastics: more than 600 pounds of plastics will be used per car (References 5-10, 5-11, and 5-12). The DMC-12 will be produced at a rate of 20,000 per year.

The DMC-12 will utilize a sandwich structure of urethane foam and glass reinforced thermoset resin for the structure. The sandwich will be fabricated by a one-step operation called elastic reservoir molding (ERM).

The technique is named after the key element: the layers of 1.2 lb/cu ft open-celled flexible polyurethane foam that are used as an elastic reservoir or carrier, for the thermoset resin. Featuring a clean and convenient method of introducing the resin system into laminates, manufacture involves the following sequence of operations illustrated in Figure 5-10:

(1) The thermoset and curing agents are thoroughly mixed together with any desired and/or required filler.

(2) One or more layers of open cell foam, cut to size, are impregnated with the required quantity of the mixed, catalyzed resin. Built-up layers can be applied when different thicknesses are needed.

(3) The total laminate (cut to size) is laid up in the sequence of dry fiber-reinforcement, impregnated foam reservoir, dry fiber-reinforcement (glass, graphite, Kevlar, etc., or appropriate hybrids thereof).

(4) The laminate is positioned in a heated, matched mold which is then closed to stops at 20-150 psi. As the mold is closed at a predetermined speed, the laminate goes through four stages:

(a) The foam takes the mold shape, pressing the dry reinforcement against the mold surface.

(b) The resin is squeezed toward the top and bottom, filling all foam voids.

(c) The air in the foam reservoir and the reinforcing mats are squeezed out and escapes through the still dry reinforcement.

(d) Some of the resin is squeezed out of the reservoir and impregnates the reinforcement; but sufficient resin remains in the compressed foam to form a stiff and strong, solid core after the cure for an effective sandwich structure.

MAKEUP — TOP MOLD
DRY REINFORCEMENT
FLEXIBLE FOAM
IMPREGNATED RESIN
FLEXIBLE FOAM
DRY REINFORCEMENT
BOTTOM MOLD

MOLD CLOSING
AND CURING

REMOVING
CURED PART
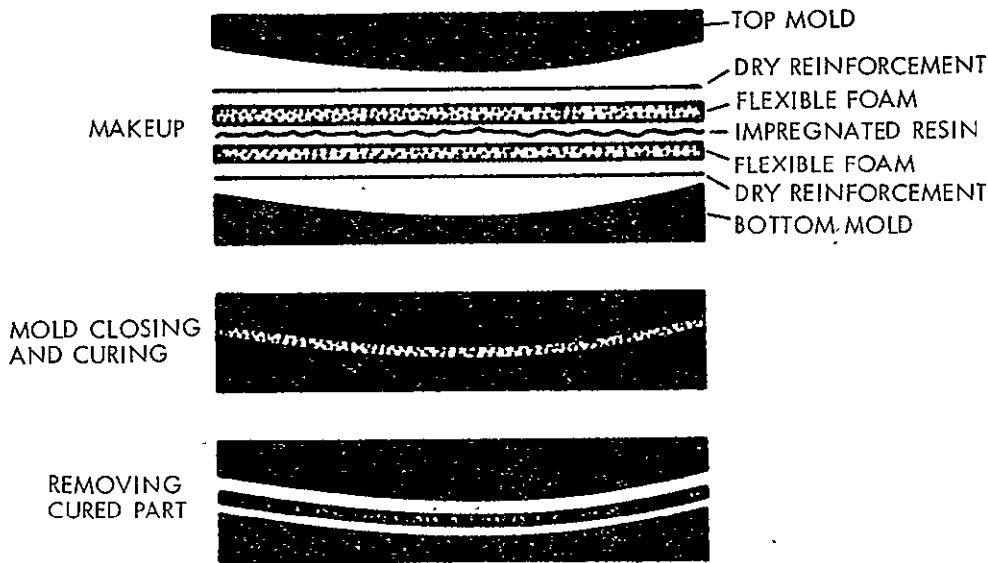
Figure 5-10.   Elastic Reservoir Molding Sequence of Operation
(From Reference 5-10)

(5)   The resin system is cured and the laminate is removed from
the mold. Thickness of the composite, as it goes into the
mold, is typically 3/4 to 2-1/2 in. Cured parts have a
smooth, hard surface and are generally in the range of 0.1
to 0.25 in. thick. Thickness tolerance can be held to
0.005 in., which is typical for matched mold accuracies.
They can be held closer, with careful mold building, to any
practical tolerance.

To solve the difficult problem of painting exterior plastic,
unpainted, stamped brushed stainless steel is used as a cover on the
plastic.

Panels consisting of thin stainless steel skins bonded to ERM are
used for the front deck lid and the two doors. ERM, without stainless
steel skin, covers the engine. Stainless-steel sheet metal is used on
the front fenders and the rear quarter panels.

The number of parts needed to fabricate the car is drastically
reduced using plastics (Figure 5-11). The underbody consists of upper
and lower halves. The upper body is also molded in two halves. Match-
ing halves are bonded with structural adhesives and in turn the upperbody
is bonded to the underbody, producing a unit construction.

5-15

ERM

STAINLESS

ERM & STAINLESS

STEEL

UPPER ROOF PANEL

LOWER ROOF PANEL

UPPER UNDERBODY
MOLDING

LOWER
UNDERBODY
MOLDING

STEEL CROSSMEMBER
WITH FRONT
SUSPENSION

STEEL REAR
SUBFRAME ASSEMBLY
WITH V-6 ENGINE
AND SUSPENSION
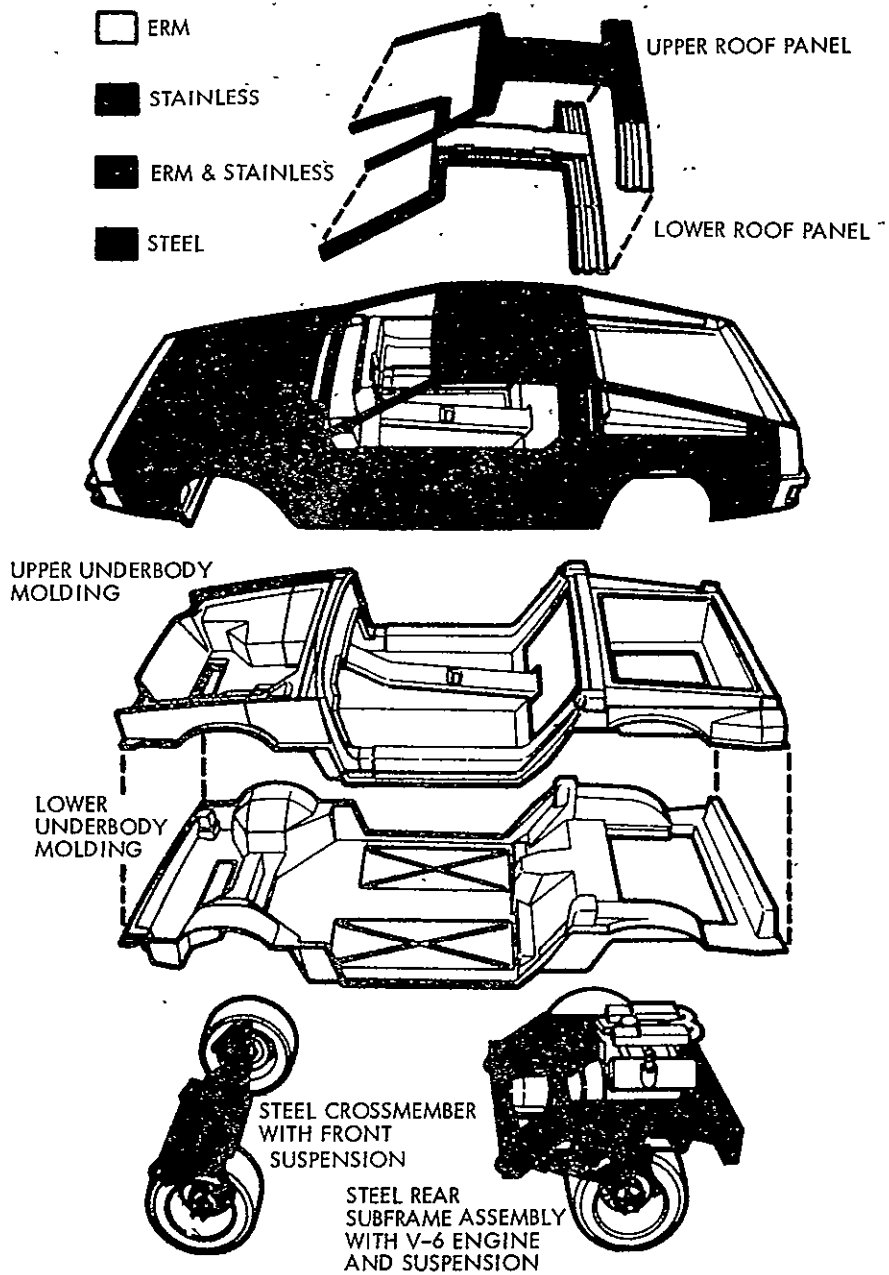
IN ASSEMBLY, ROOF PANELS AND UPPER AND LOWER UNDERBODY ELEMENTS ARE BONDED TO
PRODUCE A UNITIZED-BODY CONSTRUCTION.

Figure 5-11.   DMC Body Construction and Specifications
(From Reference 5-10)

5-16

This construction is similar to a steel integral body, but has fewer parts, reduced weight and increased performance. The ERM integral body, like the more conventional U.S. steel frame, provides the structural path from front to rear.

Under contract to the Department of Energy, AiResearch Manufacturing Co. is attempting a similarly extensive use of composites as primary structural members for an all electric vehicle (Reference 5-13). Extensive use of fiberglass reinforced polyester will be used for the main body components, door group, hood group, rear deck and hatch group and the primary body group, Figure 5-12 (Reference 5-14).

The most meaningful sources of body weight reduction will be in the selection of materials reduction of components and optimization through innovative body panel arrangements, such as utilization of hood structures to perform energy management tasks. Another example would be the use of completely closed box sections on all roof pillar, header, and transverse structure as permitted by composites rather than the open "C" sections used in conventional vehicles.

All structures of the electric-powered passenger vehicle have been designed not only for load carrying capability, but to maximize crashworthiness -- to protect the driver and passengers in case of high-speed collisions and to minimize damage upon minor, low velocity collisions.

The vehicle hood and outer front fenders are manufactured as a single unit. Because of the low hood profile and unique components of the electric vehicle design, the hood is not designed to function as a frequently removable panel as it is in conventional vehicles. This approach has led to some innovative structural concepts for crashworthiness and allows the use of more efficient interior instrument panel configurations.
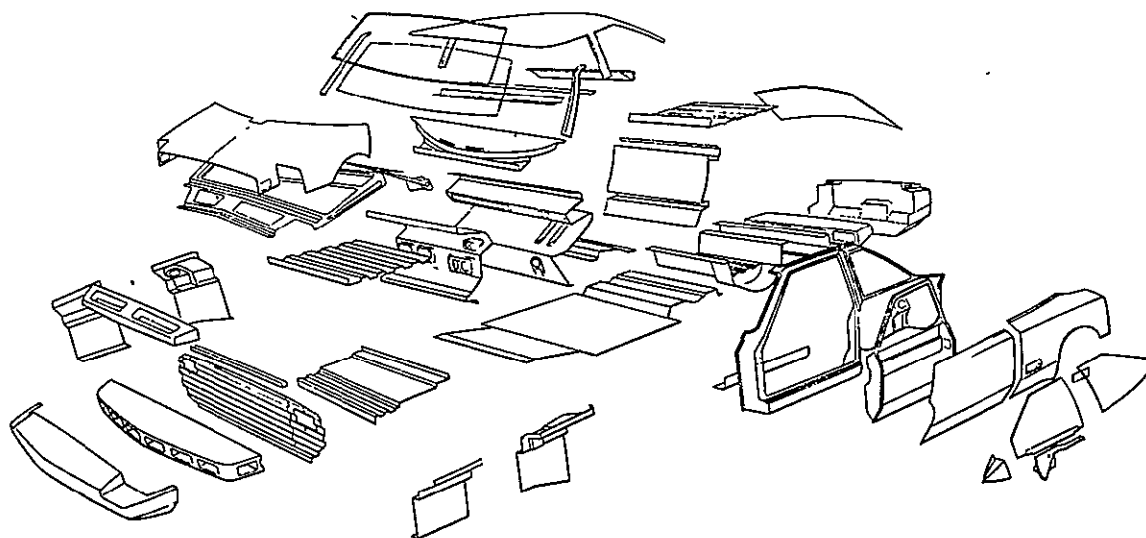

Figure 5-12.   Composite Components for Garrett Electric Vehicle
(From Reference 5-14)

Side glazing in the door area allows for full window retraction, although other concepts may be used to improve safety, increase crash-worthiness, and strengthen the structure. The window is lowered outside the door structure rather than through the structure, thus allowing a stronger, lighter door design.

The plastic body panels used in the electric vehicle are similar in configuration to conventional, steel-stamped panels, except that a greater surface area and more complex shapes can be formed in a single operation. An additional advanced design feature is that thickness may be varied in critical areas so that materials may be more efficiently used. Although initially more expensive to produce and to assemble, FRP construction will lend itself to automated production, and eventually to the manufacture of more efficient automotive bodies. The composite body must incorporate more precise joining and bonding techniques, and will therefore result in a quieter, stronger, corrosion-free automobile. Methods of determining the location and extent of structural damage are readily available in FRP parts. Techniques that will be used to facili-tate replacement of panels, such as color-coded bond surfaces and modular panel assemblies, permit reasonable and relatively low-cost repairs of FRP automobiles. Due to their high cost and weight, the use of foams has not been included; there may be considered for insulating as required.

Manufacture of the plastic panels by the Budd Company will be through wet lay-up of polyester resin on chopped randomly oriented fiberglass mat. Wood tooling is used for the limited number of replicas to be fabricated. Joining of the component parts is through adhesive bonding or bolting.

In addition to the programs described above demonstrating exten-sive use of composites, numerous smaller individual efforts are being conducted to illustrate the advantages of composites on a component by component by basis. These include leaf springs, drive shafts, hoods, doors, door intrusion beams, deck lids, wheels, gears, brackets, and support beams. Some of these will be described here to illustrate pertinent composite advantages. This should not however be considered an exhaustive listing of current activities.

The automotive drive shaft is a particularly interesting component for the use of graphite composites. As mentioned previously, the high dampening characteristics of the composite can be applied to damp out vibrations induced in the engine, transmission, differential, or wheels. The low transmissability factor tends to separate wheel and differential noise from transmission and engine noise. The low noise of the carbon fiber composite, coupled with the high lateral stiffness, permits high rotational speeds to be achieved successfully.

Two drive shafts, one of steel and one of a carbon fiber composite were fabricated by Bristol Composites Materials for a European vehicle. The steel drive shaft has an angle offset housing and dampener combina-tion on the front end, and a center bearing to dampen out engine-induced vibration. This shaft is articulated to handle the high rotational speed

(7,200 rpm) of the vehicle in normal operation. The carbon fiber composite shaft has bonded-in metal end fittings. The steel shaft weighs 22.6 lb and the composite shaft 9.5 lb, of which approximately 8 lb is the metal end fittings. The composite shaft substantially reduced the sound level in the passenger compartment.

Documentation of the reduction in sound level was provided by a microphone attached to the frame of a test vehicle. Audio traces were generated when the vehicle accelerated from 20 to 80 mph with declutching then coasting back to 20 mph. The sound trace of the metal shaft and that of the carbon fiber composite drive shaft showed considerably less noise transmitted into the passenger compartment for the graphite drive shaft. The tests were run on the same road and on the same vehicle with the same driver, and only an hour apart. This is certainly a graphic demonstration of the high damping characteristic and the low transmissability factor of carbon fiber composites. Because of the complexity of the metal drive shaft, the cost of each approach is about the same, with the carbon fiber composite design providing the additional benefits of lighter weight, simpler construction, and quieter operation.

Ford (Reference 5-15) has evaluated a filament-wound drive shaft of graphite-epoxy. The seven-layered tube has an inside diameter of 2.75 in. and a nominal wall thickness of 0.1 in. The tube is adhesively bonded to conventional steel yokes.

These drive shafts, which weigh 5 lb less than steel counterparts, have been vehicle-tested for some two years with no evidence of temperature or environmental problems. In particular, a heat shield is the only provision made in response to the proximity of the exhaust-system catalyst; also, a rubber coating is sufficient protection from stone impingement damage.

Filament-wound composite drive shafts have some particularly attractive features, quite apart from weight reduction and a composite's mechanical damping capabilities. They exhibit excellent torsional strength and require less balancing than conventional driveshafts. Filament-wound composite drive shafts have been made in the U.S. by Shakespeare Company, Columbia, S. C. (Reference 5-16).

In addition to vibrational criteria, drive shafts must withstand static and fatigue torques. The freedom to design with composites allows drive shafts to be hybridized. Graftek, a Division of Exxon Enterprises (Reference 5-17), has designed, analyzed, fabricated, and tested drive shafts that are hybrids of aluminum and graphite composite. The aluminum tube primarily reacts the torque, while the graphite composite increases critical speed.

For example, a 64-inch centerline to centerline drive shaft in steel weighs 15.7 lb (without end fittings) and has a critical speed of 77 Hz. An aluminum tube with sufficient capacity to carry the torsional load corresponding to the 15.7-lb steel tube weighs 5.5 lb. The amount of added graphite composite needed to attain a desired critical speed (stiffness) for the aluminum/composite hybrid is shown in Figure 5-13.

It is evident that the amount of graphite composite is small with respect to the total weight, and hence gives a cost effective system. Figure 5-13 is for a specific application and range of responses.
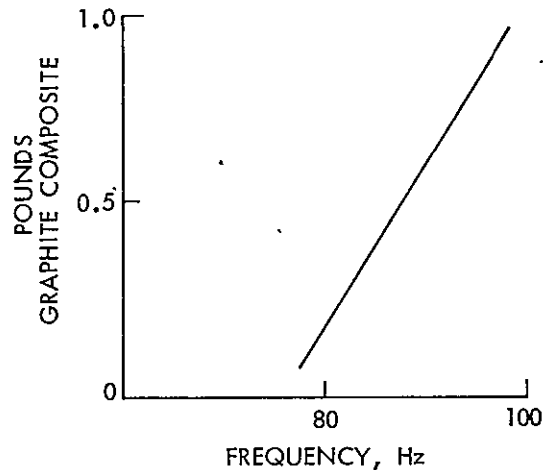
Figure 5-13. Graphite Composite/Alumiunum Hybrid Drive Shaft
(From Reference 5-18)

Leaf springs are another ideal and widely investigated application for graphite or hybrid composites. The high specific strength of graphite composites leads to weight savings of from 40% to 85% compared to steel.

In designing a composite leaf spring to replace a steel spring, the load rate will remain unchanged if at each cross section the factor EI for all leaves is maintained or if the deflection of the leaf tips of the front and rear cantilevers is kept identical to those of the steel spring without attempting to duplicate the EI factor or the shape of the elastic curve of the spring.

These stiffness characteristics must be achieved without exceeding the allowable bending and shear stresses of the composite material being . considered. The number of leaves required is dependent on the allowable stress levels both in bending and in shear. The shear stresses at the spring tip are important. Compared to steel, the allowable shear stresses for graphite composite materials are quite low and must be analyzed thoroughly.

The graphite composite systems which are candidates for leaf springs have, compared with their strength, a relatively high modulus of elasticity. It is therefore not difficult to meet stiffness requirements with one leaf or with a number of leaves. However, strength limitations, particularly for fatigue loading, call usually for a larger number of leaves than is present in the steel spring design.

Two extremes of composite springs can be designed and fabricated: a minimum weight spring with fatigue life compared to a steel spring, (typical fatigue life of 10^5 cycles) and a maximum fatigue life (10^7 cycles) with weight comparable to a steel spring. Between these two extremes a wide range of acceptable spring designs which comprise weight savings and fatigue life can be made.

The principal advantages of using graphite composites in a leaf spring are light weight and the ability to design for either softer or stiffer ride characteristics. In addition, such a spring does not corrode, provides better vehicle handleability, and reduces the noise level in the vehicle.

A four-leaf steel truck spring weighing 28 lb was duplicated by Lockheed Missile and Space Company from a graphite/fiberglass hybrid at a weight of 5 lb.

The two springs provide the same spring rate and load carrying capability and thus the composite spring results in a vehicle weight reduction of more than 45 lb. Extensive fatigue testing has proved the viability of the composite spring design.

Prototype springs for cars and trucks are also among Ford's development efforts. A truck spring of graphite/epoxy weighs 30 lb -- exactly 100 lb less than its steel equivalent. A single-leaf spring under development for automotive use weighs 4.5 lb, down from 28 lb for its four-leaf steel counterpart. Composite springs have been designed with the same rates and load capabilities as the steel springs they would replace; vehicle testing has confirmed their interchangeability. Both graphite and graphite/glass hybrids have been evaluated, with the latter employing distinct layers of each fiber.

Composite springs would appear to be especially cost-effective in truck applications. Reduced weight -- and increased payload -- could mitigate a fleet owner's higher initial cost. A composite spring design also has the potential for modifying spring rates and loads within a given geometric envelope.

NASA (Reference 5-19) has studied the feasibility of reinforcing truck frame rails with graphite/epoxy strips. Currently, many of these frame rails have steel reinforcing sections, spot-welded in place. An alternate composite concept, would be to adhesively bond prepreg strips to the rail and hold them in place by expandable, rubber-backed steel guides. Differential thermal expansion of the rubber would generate the required pressure for a heated cure cycle. NASA estimates that this concept could reduce reinforcement weight by a factor of 10 and yield a 35% weight reduction in the finished frame rail. Their evaluations of 1/3 scale models indicate excellent fatigue strength and increased stiffness of this composite substitution. Additional work seems indicated, however, to analyze load-transfer stresses in adjacent, unreinforced portions of the rail.

All composite truck rails have been fabricated by General Dynamics/ Convair for a class "A", 30,000 gross weight GMC "General" trailer truck rig. Two beam members, an "I" beam and a "C" channel were constructed of graphite/Kevlar/epoxy. The "C" channel weighs approximately 150 lb and is 19 ft long. The equivalent weight of an aluminum beam of the same volume would be about 275 lb, and it would be equally stiff but not as strong. An equivalent volume steel beam would be stiffer and would have approximately the same strength, but it would weigh approximately 800 lb.

The rails are currently in service and are joined to the truck and to iron cross members by bolts.

There has been considerable work during the past several years in composite transmission supports. In some cases, all-glass fiber composites meet the requirement. However, in those cases in which fatigue, high heat distortion temperature, or increased stiffness are needed, a hybrid of carbon fibers and glass fibers should be beneficial.

Another area of interest is radiator supports, in which a hybrid composite of carbon fibers and glass fibers should provide an excellent marriage of materials to provide strength, stiffness, high heat distortion capability, and corrosion resistance.

Suspension arms, a fatigue-critical, safety-related component, is an excellent candidate for a carbon fiber composite not only because of the fatigue factor, but because it becomes part of the unsprung weight of a vehicle, thus maximizing the effect of weight reduction through secondary weight savings.

An air conditioner mounting bracket using 85% less glass cloth and 16% AS-3 graphite in 3501 and 934 epoxy resins was fabricated by Hercules Incorporated (Reference 5-20). Composite weight was 2-1/2 lb versus 12 lb for the steel component. The composite component matched or exceeded the natural frequency of the steel part and provided more vibration damping.

A transmission crossmember support bracket for a Ford LTD was fabricated by Budd at 4-1/2 lb versus 20 lb for the steel bracket. Manufactured of graphite/polyester, fabrication time was 3 min at 300°F.

Another component in the unsprung weight area is the wheel (Reference 5-21). Composite wheels primarily made of glass fiber reinforced polymers, have been under test both here and in Europe. Carbon fibers have been suggested as an additive to the glass fibers to assist in controlling creep, extending fatigue life, and, if required, increasing stiffness. It appears that carbon fibers can be applied selectively in areas of need in a wheel application depending on the particular molding practice employed.

Wheels of FRP saw their first use on shipboard helicopters. This application, though, involved essentially static stress alone. Currently, several companies are exploring the feasibility of glass/polyester and glass/epoxy wheels for passenger-car use, including Budd Co. and Owens Corning Fiberglass.

The 1971 Citroen SM had optional wheels of glass/epoxy. Manufactured by Michelin, these were 60-70% random glass; the balance was epoxy with metal reinforcing inserts around the bolt holes. The SM was a high-performance front-wheel-drive design. Each FRP wheel weighed about 8.5 lb compared to 20 lb for a steel counterpart. Although this application may have been somewhat premature, an SM completed the 1971 Moroccan Rally fitted with FRP wheels.

Owens-Corning is another company developing FRP wheels. Sheet molding compounds of relatively moderate glass content (30-65%) are being evaluated. OCF reports that 45-50% may be optimal. Above this, there are potential problems of flow; with less, the wheels may become creep- and strength-limited.

To estimate the potential weight savings, consider three wheels for the Chevrolet Corvette. The styled steel wheel weighs around 22.5 lb; its cast aluminum counterpart, about 16.5 lb; and one of FRP, a bit less than 14.0 lb. Projected FRP wheel cost is said to compare with that of cast aluminum.

The chief shortcoming of aluminum is its fatigue strength. Where runout strength of steel is round 50% of initial value, aluminum's is closer to 30%.. Also, it exhibits a certain sensitivity to notching not shared by steels.

Another company, MWH Racing Developments, is investigating advanced composite wheels. While specific makeup is not identified, the wheels are compression molded from glass/graphite/epoxy. For example, MWH has developed 10-in. wheels for a rally Mini Cooper. These weigh roughly 40% less than their aluminum counterparts despite the fact that they were copied essentially from the cast aluminum design. Wheels of this type lasted through a Monte Carlo Rally; although nicked from road hazards, they experienced no failures.

Their developer stresses the importance of protective coatings for FRP wheels. After molding, surfaces tend to have high resin content and offers little abrasion resistance. A special coating seals the surface and also protects it from nicks and light impact damage.

Ford's Lightweight Vehicle Program experimental car will feature graphite composite wheels. It is generally felt that 100% graphite fiber in this application constitutes something of a design exercise, however.

Glass/epoxy wheels, compression-formed from molding compounds, would appear the most promising. Some of the unknowns, however, include fatigue properties, impact resistance, and appearance over extended usage. Also, like any innovative material, FRP must often confront test

and evaluation procedures designed for materials with somewhat different failure modes and mechanical behavior.

High-Strength steel wheels offer perhaps the fewest developmental problems, but probably the least weight reduction as well. Of light-weight candidates, aluminum has the broadest data base, but not necessarily the lowest ultimate cost. Composites might offer the best tradeoff of weight and cost, but at this point it has the largest collection of unknowns.

In another NASA-funded study (Reference 5-22), various applications of composites in automotive doors have been explored. Because of the potential for considerable weight reduction, composite anti-intrusion beams received special attention.

Conclusions, however, appear to be mixed. Current metal beams absorb energy through plastic deformation, a mechanism alien to composite structures. Thus, other criteria of design must be explored. A sug-gested composite alternative employs two graphite/epoxy belts, separated by structural-foam standoffs, mounted to the door pillars by means of steel end-plates. The design has a dual mode of energy absorption. Initially, the standoffs make the composite belts function in unison as a beam. With increased load, the standoffs shear, and the two belts behave independently as membranes in carrying loads to the metal end-plates. Substantial weight savings are indicated, although it is not certain that such structures would meet current Federal regulations. These statutes were written specifically with deformable metal struc-tures in mind.

Specific conclusions from the analytical program were:

(1)   The door component that offers the most dramatic improvements through the use of composite materials is the anti-intrusion beam. This component exhibits high weight savings, compe-titive long term costs and increased energy absorption over the existing metal components while still satisfying the stringent anti-intrusion load requirements. The composite anti-intrusion beam can provide an impressive weight savings of 70-80% (12-13.5 lb).

(2)   From a structural standpoint, the KEVLAR anti-intrusion beam offers the highest weight savings, i.e. 78% which is equal to 13.5 lb/door; and the highest energy absorption, i.e. 1444% increase over the existing beam which is equal to 28,000 in.-lb.

(3)   The anti-intrusion loading criteria defined by the Federal Motor Vehicle Safety Standard report number 214 (written around large yielding deformable materials) restricts the application of composite materials to an automotive door.

(4)   Two composite anti-intrusion beam concepts were presented,
       the belt-beam and the direct substitution. It is fairly
       certain that the belt-beam concept could be used as shown
       to meet the current FMVSS requirements. The belt-beam,
       however, has significant cost penalties. Use of the direct
       substitution beam would be, in part, dependent upon the end
       fittings having sufficient yielding properties to allow a
       minimum movement of the beam.

(5)   Use of composite components for weight savings on structures
       such as the inner door panel that are characterized by large
       area to material thickness ratios is extremely limited.
       Little weight savings can be achieved and the cost would be
       prohibitive. This type of application would be limited to
       extremely low production components (such as the Corvette
       body panels) where lower tooling cost for composites is a
       factor, or where the component carries no appreciable
       structural load (such as inner panels) where the economics
       of injection molded inexpensive unreinforced thermoplastics
       can be utilized.

Over the past few years Ford Motor Company has been engaged in the
development of lightweight plastic body panels in support of a major
corporate effort to improve fuel economy by reducing vehicle weight
(Reference 5-23). Specific objectives initially are to develop a cost
and weight effective hood panel (Figure 5-14) which requires no major
appearance or performance compromises versus current steel designs.

METAL OUTER PANEL

SECTION A

HINGE
REINFORCEMENT

PLASTIC INNER PANEL

LATCH REINFORCEMENT
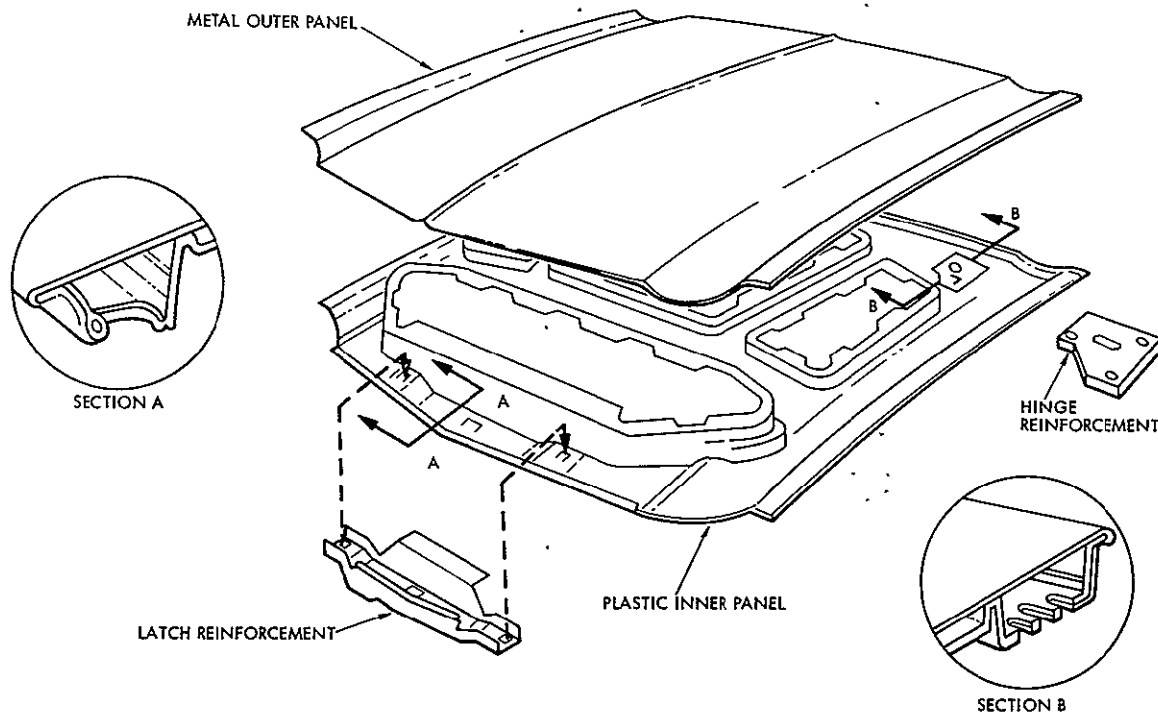
SECTION B

Figure 5-14.   Ford Composite/Metal Hood
              (From Reference 5-24)

Early Ford Motor Company efforts to develop lightweight two-piece plastic hood panels produced several significant results:

(1) The plastic constructions were capable of meeting all major hood structural and performance requirements.

(2) SMC surface appearance defects, such as, microporosity and waviness indicated a low potential for use as high volume hood outer panels. Lower visibility panels, such as deck lids and tailgates, appeared to be more suitable for compliance with rigorous appearance requirements.

(3) While the weight reduction potential was substantial (40%), variable costs were substantially higher than corresponding steel hood constructions.

Accordingly, a reduced thickness (0.026 in. for steel; 0.04 in. for aluminum) metal outer panel reinforced with a SMC inner panel was developed (Reference 5-22). A 40% glass reinforced vinyl ester resin was selected as the inner panel material for toughness, rigidity, strength and moldability. The two panels were joined by an adhesive bond and hem-flanged. A weight reduction of 9 pounds or 25% was achieved. Approximately 60 composite hood vehicles have been produced and placed in service.

The conclusion from this development program were as follows:

(1) Composite hood panels of metal and reinforced plastic have a high potential for near term high volume automotive applications for weight reduction purposes.

(2) Initial indications are that these constructions will provide cost effective weight reduction alternatives to aluminum, HSLA steel and other design possibilities.

(3) A comprehensive series of functional tests has identified no fundamental performance problems. Long term acceptability in service does not appear to be a major risk factor at this time.

Manufacturing and assembly trial results to date, while not yet conclusive, are positive relative to high volume feasibility.

In a separate program, a Ford Fiesta hood was designed by Hercules and fabricated by Budd-Milford Fabricating Division. It is fabricated from graphite/epoxy and it reduces the weight of the hood from 24 to 7 lb; a reduction of 71%. The hood is stiffness-critical in bending and torsion.

Stampable thermoplastic (nylon) sheet has been used (References 5-25, 5-26, and 5-27) to demonstrate the feasibility of stamping a plastic deck lid. Reinforcing channels and ribs of medium depth were formed without apparent difficulty. Measurements of torsional and bending rigidity did reveal greater deflection in the nylon deck lid than in the steel.

Owens Corning Fiberglass has designed an all composite door (Reference 5-27 and Figure 5-15) for a two-door coupe in the 2700 and 3700 pound weight class. The design would reduce door weight by 29 pounds over a steel counterpart.

Inner and outer panels are composites made up of glass fiber sheet molding compound. The side impact beam is steel.
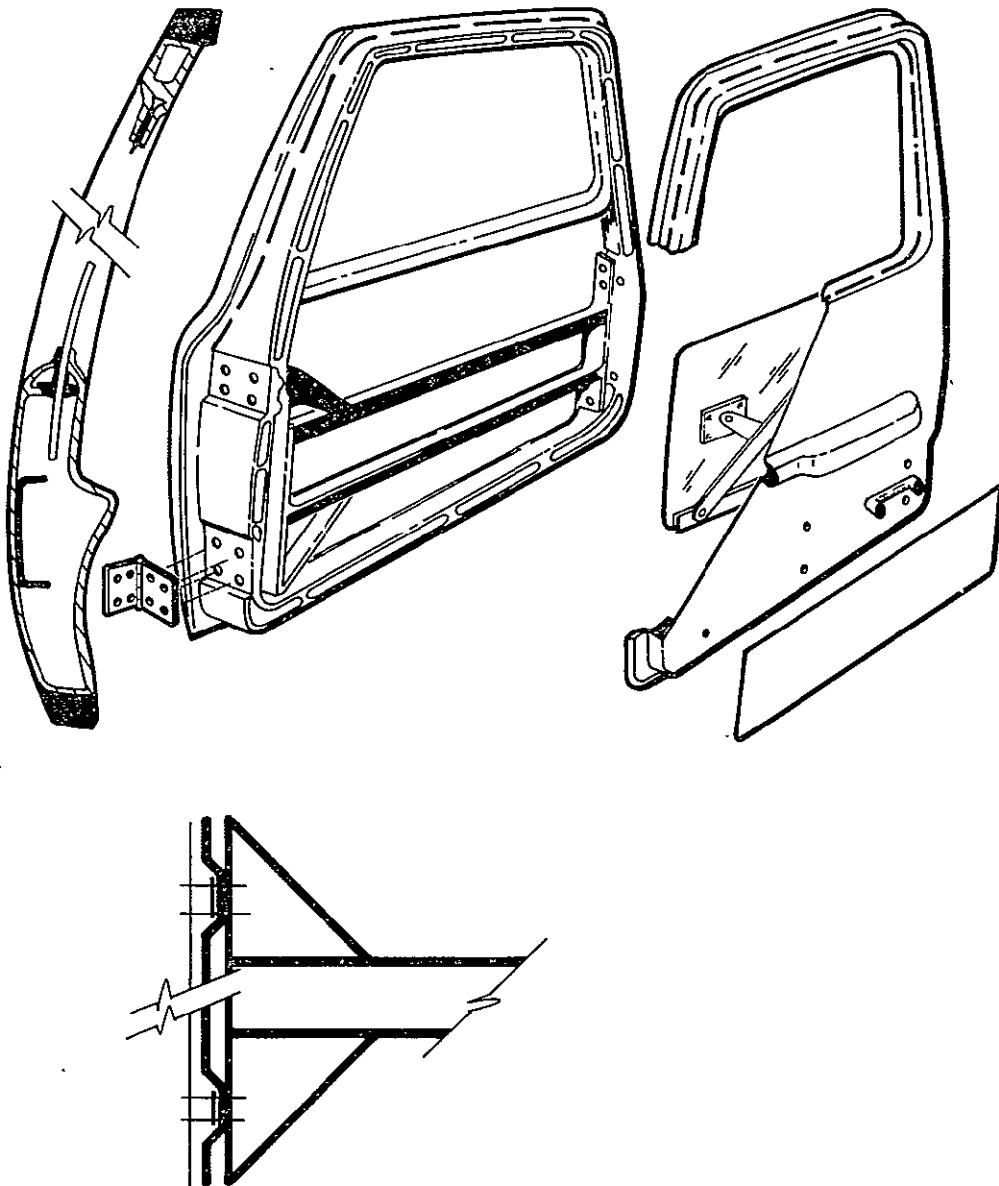
Figure 5-15. Owens-Corning Design for an All-Composite Door (From Reference 3-2)

Owens-Corning reports that on the basis of 250,000 doors, the fiberglass/plastic/steel versions would cost an estimated $24.54 per unit. Its estimate for a comparable door in steel is $34.93 per unit. The study indicates production of 1.2 million doors per year would make SMC economically feasible.

Assembly costs are reduced as a result of component consolidation, and elimination of replacement costs as a result of improved performance and corrosion resistance.

Owens-Corning has calculated a net energy saving of 8.5 million Btu (9 million kJ) over steel and 3.6 million Btu (3.9 million kJ) over aluminum for a two-door coupe using this two-piece door system.

The figures are based on the energy required to process the raw material (including the alternate fuel value of the petrochemical feedstocks used to make polyester resin), energy required to manufacture the door, and energy saved from reduced fuel consumption over the anticipated life of the car.

Gears, bearings, brakes suspension components and engine components have been fabricated from composite materials. These applications are of less interest to the electric vehicle and generally achieve relatively small reductions in weight. However, secondary benefits (or in some cases more important benefits) accrue, such as reduced noise, increased wear, or improved fatigue resistance.

Hercules has supplied chopped graphite fiber molding compound to several manufacturers to be used to fabricate gears. Gears have been injection molded and gated to generally align the fibers in a radial direction. Improvements have been noted over other materials such as low friction, high stiffness and strength, good wear resistance and high fatigue resistance.

Push rods for automotive and truck use are of great interest, and it has been reported that significant performance advantages should be achieved by the use of a carbon fiber composite push rod. Performance advantages are primarily in the engine output characteristic, reduced noise, and noise transmission within the engine.

In the case of connecting rods where resistance to hot oil and fatigue are factors, carbon fiber composites provide an ideal construction material. If this can be demonstrated, the application becomes of significant interest.

Rocker arms are under consideration for potential noise and weight reduction. An examination of push rods, connecting rods, and rocker arms, and possibly the use of a composite wrist pin, indicates that the weight reduction on any one of these single components is relatively small. However, the secondary benefit, after weight and noise reduction, is better engine performance. These weights, taken together and doubled because of counterweight reductions on the crankshaft, may allow increased engine output per cubic inch of displacement, resulting in the ability

to incrementally downsize an engine. Considerable additional work is required before any one of these components can be put in production.

Widespread use of composite materials by the automotive industry is contingent upon the development of cost-effective materials and manufacturing processes. The aerospace industry has used composites for years, but has a low production volume and is very labor-intensive. Aerospace manufacturing processes consist mainly of hand layups and have long cure cycles. The automotive industry has a very high volume of production and requires fast rates of production. Auto manufacturers have been studying the use of injection molding, reaction injection molding, and stamped thermoplastics, but it is not yet clear whether any of these processes can be used for the high volume, low cost, high quality control production required.

Vought Corporation (Reference 5-28) has demonstrated, in a labor-intensive situation, that composite components can be manufactured for less cost than corresponding metal components. Under contract to the U.S. Air Force, Vought has produced 2016 composite wing panels for the A-7D attack fighter and 240 composite spoilers for the S-3A. The units are currently in service and product assurance showed acceptance of 95% of those produced according to Table 5-2.

Parts consolidation is dramatically illustrated by the reduction, primarily of fasteners, of the S-3A components from 1115 to 19, Table 5-3.

Reduction of manufacturing cost, without benefit of capitalization is illustrated in Figures 5-16 and 5-17. In addition to achieving cost reductions through use of composite hardware, Vought was able to reduce weight and extend fatigue life 100%. The Vought manufacturing experience on aircraft is translatable to the automotive industry as identified by Ford Motor Company.

Table 5-2. Vought Acceptance of Composite Wing Panels and Spoilers.

Component	A-7D Composite Wing Panel	S-3A Composite Spoiler
Units Fabricated	2016	240
Number Rejected	107 (5%)	12 (5%)
Number Scrapped	10 (0.5%)	0

Table 5-3.   Reduction of Parts for the S-3A Spoiler

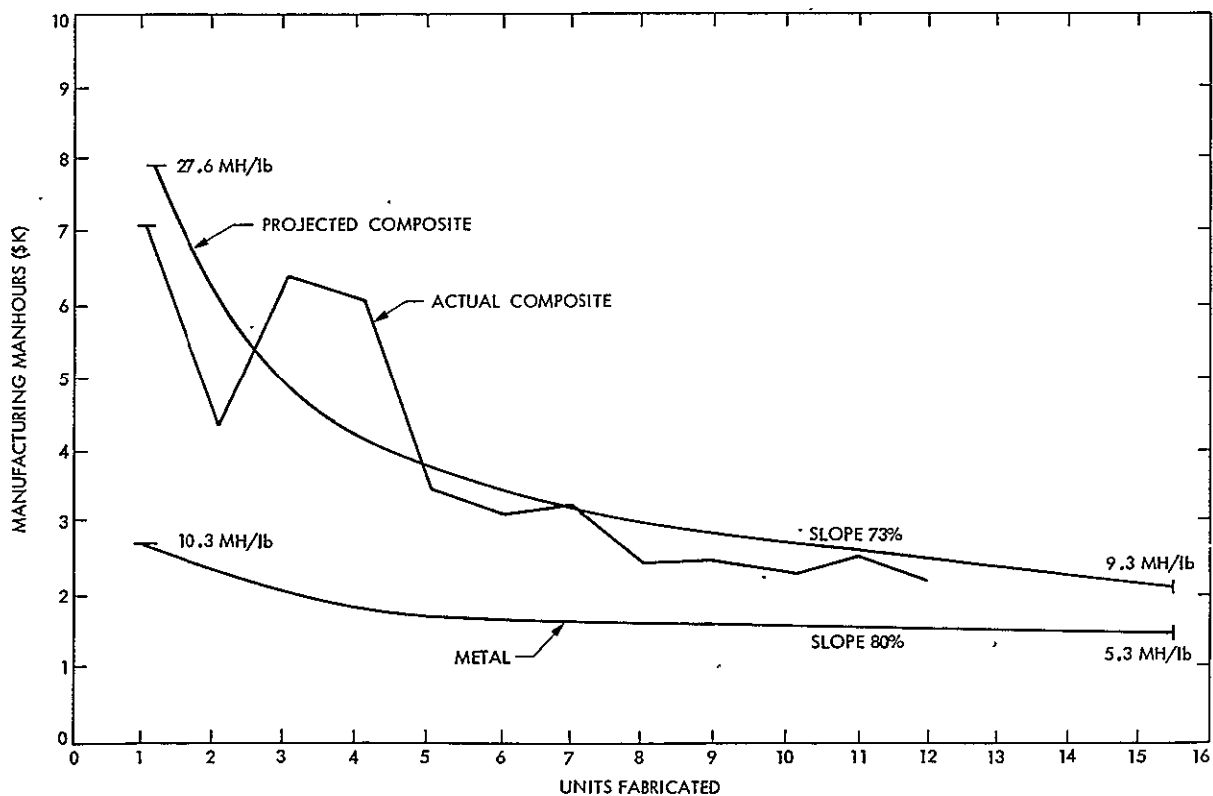| Component	Metal	Composite	Reduction
Fittings	2	2	—
Skins	1	2	—
Stiffeners, Angles	61	1 (Honeycomb)	100%
Attachments, Inserts	950	14	100%
Total	1015	19	

Figure 5-16.   Manufacturing Cost Comparison A-7 Total Outer Panel
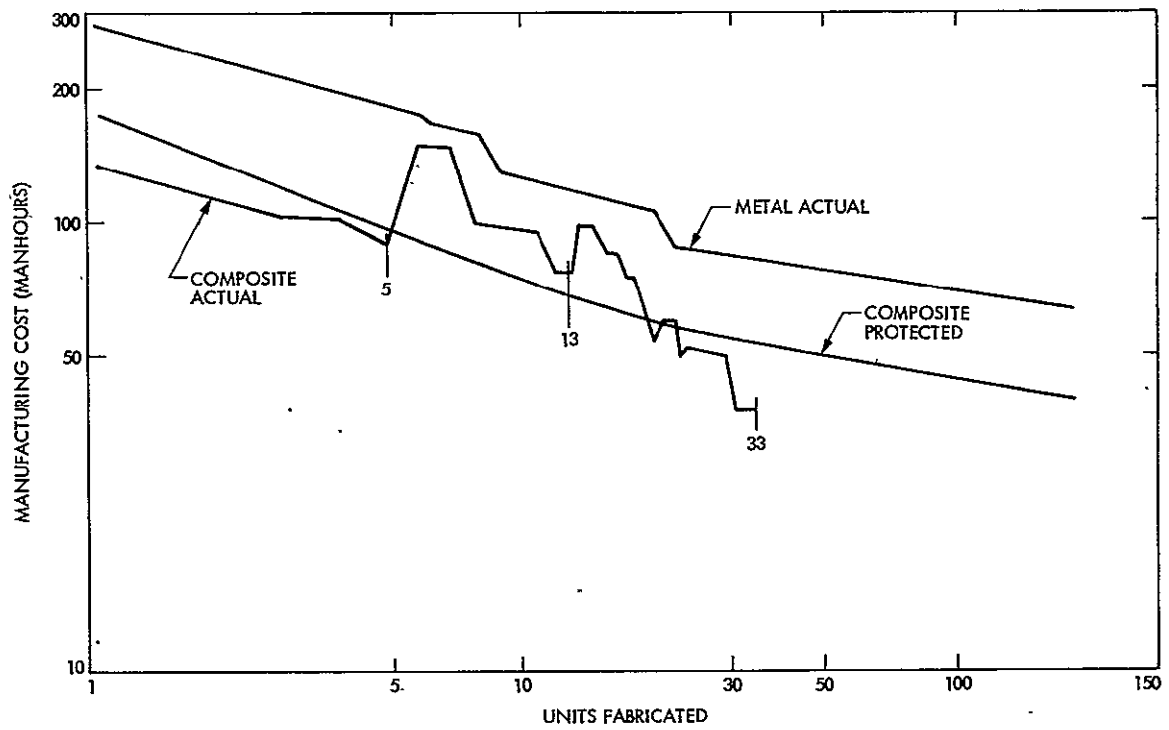(From Reference 5-28)

Figure 5-17.   Manufacturing Cost Comparison, Metal/Composite 53 P
Composite Spoiler (From Reference 5-28)

SECTION VI

COST ANALYSIS

Composites will be introduced into the automotive industry only if they can function successfully in a cost-competitive environment. Accordingly, of primary importance are the raw material prices and the manufacturing costs associated with high volume production of composite components.

It is necessary to determine a price-volume relationship, and its evolution over time, for the composite raw materials families considered for fabrication. By "raw materials" are meant the reinforcement and matrix materials. The reinforcement materials may take various forms (e.g., filament or macerated, directional or random, etc.). Components may be fabricated from these raw materials starting with either the individual reinforcement and matrix constituents, or various intermediate combinations thereof (such as tapes, fabrics, or prepregs).

The most basic starting materials for the materials-producing industry are defined, for purposes of this study, as either "precursor materials" or "feedstocks". The term "raw materials" is reserved for the starting materials used by fabricator(s) as noted in the previous paragraph.

To determine the cost of raw materials to the automotive industry, it is necessary, as stated previously to forecast the price-volume relationship, and its evolution over time, for the composite raw material families considered in this study. Several factors enter into such a determination and chief among them are the cost of the feedstock materials, and the production technologies available over time.

To characterize each of these, the Materials Production Analysis would be divided into the following areas:

(1) Understanding and projecting feedstock availability and costs to the materials producers, recognizing competing demands.

(2) Understanding the current state-of-the-art in raw materials production.

(3) Forecasting advances in materials-production technology, and the probable economies of scale.

(4) Estimating plant and equipment costs, and associated lead times.

(5) Identifying possible significant adverse environmental and occupational-safety impacts and the associated abatement costs.

(6) Estimating other significant categories of cost.

(7) Identifying potential materials-producing industry
structural options.

(8) Estimating energy requirements, as a function of production
volume (for the net energy, as well as the cost, analysis).

(9) Integrating the above estimates into a projection of raw
material price-versus-volume at selected points in time.

The capability to meaningfully project raw-material producers' selling
price versus volume at selected future points in time requires, in turn,
the understanding and corresponding projection of feedstocks availability
and their costs. Such feedstock projections must give full recognition
to source security and competing demands. This is particularly important
in cost projections if either petroleum-based or natural-gas-based
feedstocks are involved.

Reductions in raw-materials producers' selling prices are antici-
pated due to several major effects. First are the expected economies
of scale resulting from lower unit costs provided by significantly
increased production volume. Secondly, technological innovations in
composite-materials production techniques may lead to one or more
processes which will lower cost and/or facilitate increased production
volume. Finally, in the expansion of a given process to significantly
higher volumes, the "learning-curve" phenomenon is often operative.

The possible major adverse environmental, health and safety
impacts and associated abatement costs of materials production should
be identified. Potential impacts are: (1) Air pollution caused by
both on-site energy consumption and by gaseous effluent from the process
itself, (2) Water consumption and pollution, including particulates,
dissolved chemicals, and thermal pollution, and (3) Worker health and
safety effects from: volatilized gaseous materials, particulates, and
dermatitis contracted from improper handling of certain materials.

For the most part, the components of the raw material, as
described, consist of mature industries and products, susceptible to
intelligent forecasting. These include fibers (glass and organic) and
resins (polyester, thermoplastics). Graphite fibers, however, can still
be classified as an infant industry without a growth history. As such
additional imponderables will complicate cost forecasting. An indepen-
dent private financed survey (Reference 6-1) in 1977, Table 6-1, has
forecasted a quadrupling of fiber requirement in the next five years.
Of this, the predominant growth is shown to be in the industrial and
marine sector, Table 6-2. It should be noted that the units, pounds of
prepreg, are multiplied by 0.6 to determine pounds of graphite fiber.
Such dramatic increases in volume along with technological improvements
will result in the projected cost decreases to the $5 to $15 per pound
level in the 1980s.

In contrast, plastics, being a more mature industry, will be less
responsive to price fluctuations and more responsive to the constraints
of the previous discussion. An SPI survey (Reference 6-2) of all resins
by 1977 showed an 11 billion pound industry (Table 6-3) with projections
of 200 billion pounds by 2000 A.D.

Table 6-1. Graphite Prepreg Summary (in thousands of pounds)

Component	1976	1977	1978	1979	1980	1981	1982
Airframe Manufacturers	36.5	67.0	134.6	240.0	360.5	482.0	611.5
Spacecraft & Missile Mfgrs	32.2	41.9	49.4	59.7	65.7	73.4	83.5
Helicopter Manufacturers	2.8	6.7	11.5	21.3	28.3	37.0	42.0
Aircraft Engine Mfgrs	1.2	3.0	6.8	9.5	13.3	17.2	21.5
Aircraft Brakes	3.3	5.4	15.7	26.3	34.9	47.5	63.1
Miscellaneous Aerospace	5.4	6.5	7.0	7.4	7.9	7.9	8.2
Aerospace Subtotals:	81.4	130.5	225.0	364.2	510.6	665.0	829.8
Sports Equipment	162.4	215.2	266.4	314.8	353.8	394.2	439.0
Industrial & Marine	79.2	165.6	288.2	447.2	731.3	1,036.8	1,461.8
Non-Aero. Subtotals	241.6	380.8	554.6	762.0	1,085.1	1,431.0	1,900.8
Grand - Totals - Prepreg	323.0	511.3	779.6	1,126.2	1,595.7	2,096.0	2,720.6

Table 6-2. Summary of Graphite Prepreg Usage in the Non-Aerospace Industrial and Marine Sector (1977) (pounds)

Component	1976	1977	1978	1979	1980	1981	1982
Canoes, Kayaks & Sailboats*	150	400	1,500	3,000	8,000	12,000	15,000
X-Ray Film Cassettes	3,000	3,800	4,000	4,300	4,600	4,800	5,000
Musical Instrument*	200	400	700	1,000	1,500	2,500	4,000
CB Antennas*	*	*	*	*	*	*	*
Sound System Components	500	700	1,000	1,200	1,300	1,400	1,500
Prosthetics & Misc, Medical	200	600	1,000	2,000	3,000	4,000	5,000
Textile Machinery Parts*	100	100	100	100	100	100	100
Paper Handling & Other High-Speed Machinery	20,000	40,000	50,000	60,000	70,000	80,000	100,000
Automotive (Including Trucks & Recreational Vehicles)	1,500	8,000	30,000	75,000	150,000	250,000	450,000
Public Transportation (Rail)	100	500	2,500	6,000	10,000	20,000	40,000
Hydrofoils & Other Marine	200	800	2,000	4,000	7,000	11,000	15,000
Non-Aero. Pultrusions (All Other*)	*	*	*	*	*	*	*
Thermoplastic Molded Parts (All Other)	50,000	100,000	150,000	200,000	300,000	400,000	500,000
Thermosetting & SMC Molded Parts	2,000	5,000	20,000	40,000	75,000	100,000	125,000
Oil Field Pump Components*	200	300	400	600	800	1,000	1,200
All Other	1,000	5,000	25,000	50,000	100,000	150,000	200,000
Subtotals	79,150	165,600	288,200	447,200	731,300	1,036,800	1,461,800

*Also User of Untreated Fiber

Table 6-3. Sales of Plastics for 5 Months through May 1977
Compared with 1976, as Reported by SPI

| Resin Type | Sales (thousands of pounds) | | Increase 1977 over 1976 |
	1977	1976	(%)
Thermoplastic Resins			
Low-density polyethylene	2,706,958	2,451,390	10.4
Polyvinyl chloride	2,130,658	1,900,396	12.1
High-density polyethylene	1,457,531	1,317,571	10.6
Pol styrene	1,429,400	1,312,400	8.9
Polypropylene	1,170,126	1,094,350	6.9
Acrylonitrile-butadiene-styrene	446,071.	382,360	16.7
Polyvinyl acetate	303,628	271,666	11.8
Nylon	104,749	91,380	14.6
Other vinyl resins[b]	84,295	86,709	(2.8)[c]
Styrene-acrylonitrile	48,215	45,938	5.0
Other thermoplastics[d]	371,758	347,852	6.9
Total thermoplastic resins	10,253,443	9,302,012	10.2
Thermosetting resins			
Phenolic resins	559,120	531,304	5.2
Unsaturated polyesters	430,376	395,494	8.8
Urea resins	365,086	336,827	8.4
Epoxy resins	107,420	98,983	8.5
Melamine resins	81,231	76,396	6.3
Total thermosetting resins	1,543,233	1,439,004	7.2
Total All Resins	11,796,676	10,741,016	9.8

[a]Revised

[b]Polyvinyl butyral, polyvinyl formal, and polyvinylidene chloride

[c]Decrease

[d]Styrene-based latexes and other styrene polymers, and polyvinyl alcohol

Polyesters, especially, are widely used in SMC as a condensation
product. They are obtained by reacting polyfunctional alcohols (glycols)
with unsaturated dibasic acids, along with saturated acids, reactive
monomers, catalysts, and inhibitors. They are cured to rigid thermoset
materials and are used in almost limitless applications. There are over
50 starting chemicals which can be used to satisfy almost any end-use
requirement in the construction industry, in automotive structural
components, in boat hulls, in applicances, in consumer and sporting
goods, and many other fields.

Consumption of thermosetting polyesters totaled 959 million pounds in 1976 (including 12 million exports) as against 771 million pounds (including 13 million of exports) in 1975. Growth of the domestic markets was thus 24.9 percent. An industry spokesman has predicted a total of 1.3 billion pounds for 1978.

Current production capacity for unsaturated polyester resins is approximately 1.5 billion pounds. Announced expansions are expected to bring the total to 1.8 billion pounds by the end of next year.

There are six major parts in the manufacturing cost analysis: (1) Raw material costs (previously described in this Section), (2) Resource costs, (3) Fixed manufacturing costs, (4) Tooling costs, (5) Variable manufacturing costs, and (6) Retail price. These are described in more detail in the following paragraphs (Reference 6-3).

Resource Costs

Resources represent the collection of tools, equipment, and facilities required to produce a component. Given the technical characterization of the resources required to produce specific components, the next task is to assign costs to these resources. The steps involved are:

(1) Determine the capacity requirements for the resources. The classes and/or models of vehicles using composites must be identified and then, using existing fleet sales projections, the number of units actually incorporating composite materials, or the "projected planning volume", be determined. With the single resource throughput rates known, as determined from the technical resource requirements, the number of resource units required is established for the previously determined planning volume.

(2) Acquire estimates of the costs for the tools or equipment. Suppliers of tools and equipment are identified by evaluating the technical resource requirements with regard to the type of equipment currently produced and/or purchased by the automotive, plastics, and composites (existing) industries.

(3) Estimate the resource installation costs.

(4) Estimate the cost of any new facilities required to house the equipment and tools within the industry.

(5) Estimate the setup and launching costs.

(6) Estimate the capital requirements (including secondary effects).

(7) Sum the above costs to estimate the total cost of the resource.

These resources costs are disaggregated into fixed costs and tooling costs. For example, the building and facilities are fixed costs, whereas some tools can be used only for a specific design and are therefore tooling costs. This distinction is necessary since the fixed costs are amortized over the useful economic lifetime of the facility, while the special tooling costs are amortized over the design life.

Fixed Manufacturing Costs

The fixed manufacturing costs comprise principally:

(1)   Resource costs, excluding special and expendable tooling costs.

(2)   All non-production-related materials and consumables.

(3)   Maintenance and support labor not related to the production volume.

These costs are derived from the resource costs and projected to the appropriate time period.

Special Tooling Costs

Special tooling costs are those costs which are specific to the design of a component. These tooling costs are composed principally of:

(1)   Design and engineering costs, but not including research and development.

(2)   Tools which are specific to the component and not readily adapted to other designs.

(3)   Certain molds and dies.

(4)   Special fixtures.

Variable Manufacturing Costs

The principal variable costs are:

(1)   Materials costs.

(2)   Direct manufacturing labor.

(3)   Parts purchased from vendors.

(4)   Expendable tooling.

(5)   Consumable supplies.

The·weights and unit costs of composite materials required are estimated from the detailed designs developed. The labor hours are estimated by examination of the labor requirements for the production·resources for the various composite components. The labor wage rate is derived from standard economic projections for the appropriate time period.

Tool Manufacturing Costs and Retail Price

The manufacturing costs for both the composite vehicle are found incrementally from respective fixed and variable costs.

The final retail ("sticker") price is determined from the manufacturing cost by adding:

(1)   Marketing, advertising, and other sales costs.

(2)   General and administrative cost.

(3)   Corporate overhead (including Research and Development).

(4)   Warranty costs.

(5)   Profit.

(6)   Transportation costs.

(7)   Dealer mark-up.

When addressing the dual issues of product marketability and consumer acceptability, the retail price of EV models incorporating composite technology, as well as those using conventional materials, will need to be known. From the standpoint of the sophisticated buyers -- such as van fleet buyers, and perhaps some households -- the retail price will be combined with the other cost on which preferences and choices could be based. In the case of the producer, the ability of a composite vehicle to compete with a conventional vehicle will be determined on the basis of retail price and other favorable attributes resulting from the use of composites.

SECTION VII

SOCIAL IMPLICATIONS

For purposes of this discussion, it is assumed that composite components for the EHV or ICE automobile will consist of an average of 20% graphite, 40% fiberglass, and 40% resin.

The principle impact of an increased demand for graphite fibers will be to increase consumption of glass fibers and increased demand on petrochemical raw materials for resins. With the projection for increases in graphite fiber demand to 10 million pounds in 1990 (to be conservative in terms of estimating maximum petroleum requirements), a maximum of 20 million pounds of plastics would be required as the matrix. This amounts to about only 2% of the total projected plastics consumption in that time frame. Currently, the entire plastics industry consumes only 2% of the total petroleum and natural gas expended in the U.S. This small percentage sustains a huge industry. The industry is adding significant value to the petroelum feedstock by creating durable goods of significant contribution to our GNP.

However, considerable research has been conducted in the use of alternative feedstock materials for the manufacture of plastics (Reference 7-1). Alternate sources other than petroleum for obtaining chemicals for plastic manufacture include coal, shale oil and renewable feedstock such as agricultural by-products, agricultural oils and wood. Alternate sources are more expensive than petroleum and processing is more complex. No motivation therefore presently exists for plastics producers to convert to alternate sources. With the economics of higher priced petroleum and potential supply irregularities, other feedstocks would be seriously considered.

However, composites have the potential of significantly reducing transportation energy consumption, and therefore petroleum consumption (Reference 7-2). The transportation sector of the economy consumed nearly one-third of the net national energy production, and over half of the available petroleum. To satisfy petroleum demand nearly one-third of the crude oil supply had to be imported. Passenger automobiles consumed over half of all transportation energy. Automobiles and trucks combined consumed 71.5% of all transportation energy, essentially all as petroleum fuels. Automobiles and trucks fuel was approximately 40% of the total petroleum consumption.

A realistically projected usage of composites is limited to about 20 lb of hybrid composites in smaller vehicles, and 600 lb of hybrid composite per vehicle in luxury cars which would comprise 10% of the market. The sales weighted composite usage is about 80 lb of hybrid per car. Assuming the decrease in fuel consumption projected above, the use of advanced composites should result in a realistic reduction in fuel consumption of about 50 gallons over the lifetime of a car, or about 5 gallons/year. This would correspond to decrease in fuel consumption of about 1.4% for the average automobile.

Use of composites on the electric and hybrid vehicle would pay added dividends in range and performance which would signal consumer acceptance, thus ultimate program success.

Several areas of environmental concern have been addressed including air and water quality, disposal, accidental fiber release, and health issues.

It should be recognized that composite usage in the automotive industry will be an evolutionary process mostly likely with fiberglass components increasing their share of the vehicle and graphite being introduced through hybridized products and in selective small components such as brackets, supports, hinges, etc. Because of this evolutionary process, a sudden dislocation in any area of social concern is unlikely to occur.

No adverse impact is anticipated in air and water quality. Potential solvent discharges into the air from the manufacture of resins, prepreg, and components is controlled by existing legislation and, where necessary, would result in additional air pollution control equipment. Water is used only as a cooling fluid in various composite processes and would not be a candidate for pollution. In fact, use of corrosion resistant composites, as water purification equipment would more economically improve the quality of water.

Composites of graphites, glass, or kevlar do not constitute a health hazard. The filamentary nature of the reinforcing fibers present a potential hazard when not contained in the matrix such as in the manufacture of the raw material. All of these reinforcements have diameters sufficiently large as to be classified by NIOSH as to be of little hazard to health other than as an external irritant and nuisance dust.

The chemicals used to produce and formulate the resulting resins can be hazardous. As a minimum, exposure to many of the unreacted components can cause severe dermatitis. These hazards potentially exist only in the manufacture of the raw materials and are already carefully contained and controlled by existing legislation.

Manufactured composite hardware is fully inert and does not constitute a health hazard. In fact many beneficial results are available through the use of composites in medical equipment, body or denture implants, etc.

A potential problem associated with organic matrix composites that contain graphite fibers, is the accidental release of conductive fibers into the atmosphere and the subsequent interference with electrical circuits and equipment. Graphite filaments, released from a composite as a result of explosion and fire, can become airborne and be transported by air currents over a relatively wide area. Fibers which settle on/or across electrical contacts or circuits can cause resistive loading, temporary shorts, or electrical arcing which could damage electrical equipment or result in its malfunction (Reference 7-3).

In the past, there have been malfunctions of electrical and electronic equipment in plants producing or using free fibers. These problems have been brought under control in graphite manufacturing facilities by the institution of protective measures and procedures.

The uncontrolled release of graphite fibers or lint from burning graphite-organic matrix composites is an area of current concern. The matrix can be preferentially consumed in a burning composite, resulting in the formation of uncontained graphite fibers. Current programs are underway to assess the risk of such occurrences and, if applicable, devise corrective measured to prevent fiber release.

GLOSSARY

ACCELERATOR – A material which, when mixed with a catalyst resin, will speed up the chemical reaction between the catalyst and resin; either in polymerizing of resins or vulcanization of rubbers. Also known as "promoter."

ACTIVATOR – An additive used to promote the curing of matrix resins and reduce curing time. (See accelerator.)

ADDITIVE – Any substance added to another substance, usually to improve properties.

ADHEREND – A body which is held to another body by an adhesive.

ADHESION – The state in which two surfaces are held together at an interface by forces or interlocking action or both.

ADDITION – The state in which two surfaces are held together at an interface by forces or interlocking action or both.

ADDITION POLYMERIZATION – A chemical reaction in which simple molecules (monomers) are added to each other to form long-chain molecules (polymers) and no by-products are formed.

ALKYD PLASTICS – Plastics based on resins composed principally of polymeric esters, in which the recurring ester groups are an integral part of the main polymer chain, and in which ester groups occur in most crosslinks that may be present between chains. (See polyester plastics.)

ALKYD RESINS – Products resulting from the condensation of polybasic alcohol with a polybasic organic acid.

ALLYL PLASTICS – Plastics based on resins made by addition polymerization of monomers containing allyl groups; diallyl phthalate (DAP), diallyl isophthalate (DAIP).

AMINE RESIN – A syntehtic resin derived from the reaction of urea, thiourea, melamine or allied compounds with aldehydes, particularly formaldehyde.

ANISOTROPIC – Exhibiting different properties when tested along axes in different directions. (Anisotropy.)

ANISOTROPIC LAMINATE – A laminate in which the strength properties are different in different directions.

ANISOTROPY OF LAMINATES – The difference of the properties along the directions parallel to the length or width into the lamination planes: or parallel to the thickness into the planes perpendicular to the lamination.

ARAMID – Aromatic polyamide, generic description for Kevlar manufactured by DuPont.

A-S – Commercial designation of high strength, low modulus graphite fiber manufactured by Hercules, Inc.

ASPECT RATIO – The ratio of length of diameter of a fiber.

AUTOCLAVE – A closed vessel for conducting a chemical reaction or other operation under pressure and heat.

B-STAGE – An intermediate stage in the reaction of certain thermosetting resins in which the material swells when in contact with certain liquids and softens when heated, but may not entirely dissolve or fuse; sometimes referred to as resistol. The resin in an uncured prepreg or premix is usually in this stage. (See A-stage and C-stage).

BARCOL HARDNESS – A hardness value obtained by measuring the resistance to penetration of a sharp steel point under a spring load. The instrument, called the Barcol Impressor, gives a direct reading on a 0-100 scale. The hardness value is often used as a measure of the degree of cure of a plastic.

BIAXIAL LOAD – A loading condition in which a laminate is stressed in at least two different directions in the plane of the laminate; a loading condition of a pressure vessel under internal pressure and with unrestrained ends.

BI-DIRECTIONAL LAMINATE – A reinforced plastic laminate with the fibers oriented in various directions in the plane of the laminate; a cross laminate (see unidirectional laminate).

BISPHENOL A – A condensation product formed by reaction of two (bis) molecules of phenol with acetone (A). This polyhydric phenol is a standard resin intermediate along with epichlorophydrin in the production of epoxy resins.

BMC – Bulk Molding Compound, chopped reinforcing fibers coated with resin generally supplied in loose form or bulk. Usually formed by compression molding.

BRANCHED POLYMER – A polymer in which side chains branch out from the main chain at irregular intervals.

BROADGOODS – Woven glass or synthetic fiber or combination thereof, over eighteen inches in width.

C-STAGE – The final stage in the reaction of certain thermosetting resins in which the material is relatively insoluble and infusible; sometimes referred to as resite. The resin in a fully cured thermoset molding is in this stage (see A-stage and B-stage).

CATALYST - A substance which changes the rate of a chemical reaction without itself undergoing permanent change in its composition: a substance which markedly speeds up the cure of a compound when added in minor quantity as compared to the amounts of primary reactants. (See hardener, inhibitor, promoter, and curing agent.)

CLASS "A" SURFACE - In automotive industry a term to describe a highly finished smooth·surface free of defects and irregular highlights.

COEFFICIENT OF ELASTICITY - The reciprocal of Young's modulus in a tension test.

COEFFICIENT OF EXPANSION - The fractional change in dimension of a material for a unit change in temperature. Also, "coefficient of thermal expansion."

COLD FLOW - The distortion which takes place in materials under continuous load at temperatures within working range. (See creep, strain relaxation.)

COMPOSITE - A homogeneous material created by the synthetic assembly of two or more materials (a selected filler or reinforcing elements and compatible matrix binder) to obtain specific characteristics and properties. Composites are subdivided into classes on the basis of the form of the structural constituents: Laminar: Composed of layer or laminar constituents; Particulate: The dispersed phase consists of small particles; Fibrous: The dispersed phase consists of fibers; Flake: The dispersed phase consists of flat flakes; Skeletal: Composed of a continuous skeletal matrix filled by a second material.

COMPRESSION MOLD - A mold which is open when the material is introduced and which shapes the material by heat and by the pressure of closing. Also "compression molding."

CONDENSATION POLYMERIZATION - A chemical reaction in which two or more molecules combined, with the separation of water or some other simple substance. If a polymer is formed, the process is called polycondensation. (See polymerization.)

CONDENSATION RESIN - A resin formed by polycondensation; for example, the alkyd, phenol-aldehyde, and urea formaldehyde resins.

CONTINUOUS FILAMENT - An individual rod of glass of small diameter, which is flexible and of great or infinite length.

CONTINUOUS FILAMENT YARN - Yarn formed by twisting two or more continuous filaments into a single, continuous strand.

COPOLYMER - A long-chain molecule formed by the reaction of two or more dissimilar monomers. (See polymer.)

COPOLYMERIZATION – The building up of linear or nonlinear macromolecules (copolymers) in which many monomers, possessing molecules having one or many double bonds, have located in every macromolecule of different size which constitutes the copolymerizate, following alternations which may be regular or not. (See also Polymerization.)

CORE – The central member of a sandwich construction to which the faces of the sandwich are attached: the central member of a plywood assembly; a channel in a mold for circulation of heat-transfer media; part of a complex mold that forms undercut parts. ·

CRAZING – Fine cracks which may extend in a network on or under the surface of a plastic material.

CREEP – The change in dimension of a plastic under load over a period of time, not including the initial instantaneous elastic deformation. (Creep at room temperature is called "cold flow".)

CURING AGENT – A catalytic or reactive agent which when added to a resin causes polymerization: synonymous with hardener.

CURING TEMPERATURE – Temperature at which a cast, molded, or extruded product, a resin-impregnated reinforcement, an adhesive, etc., is subjected to curing.

CURING TIME – The period of time during which a part is subjected to heat or pressure, or both, to cure the resin: interval of time between the instant of cessation of relative movement between the moving parts of a mold and the instant that pressure is released. (Further cure may take place after removal of the assembly from the conditions of heat or pressure.)

D-GLASS – A high boron content glass made especially for laminates requiring a precisely controlled dielectric constant.

DEFLECTION TEMPERATURE UNDER LOAD – The temperature at which a simple beam has deflected a given amount under load (formerly called heat distortion temperature).

DELAMINATE; DELAMINATION – To split a laminated plastic material along the plane of its layers. (See laminate.) Physical separation or loss of bond between laminate plies.

DENIER – A yarn and filament numbering system in which the yarn number is equal numerically to the weight in grams of 9000 meters. (Used for continuous filaments.) The lower the denier, the finer the yarn.

DIELECTRIC CURING – The curing of a synthetic thermosetting resin by the passage of an electric charge produced from a high frequency generator through the resin.

DIMENSIONAL STABILITY – Ability of a plastic part to retain the precise shape to which it was molded, cast, or otherwise fabricated.

DMC - DeLorean Motor Corporation.

E-GLASS - A borosilicate glass; the type most used for glass fibers for reinforced plastics; suitable for electrical laminates because of its high resistivity. (Also called "electric glass".)

EDGE DISTANCE RATIO - The distance from the center of the bearing hole to the edge of the specimen in the direction of the principal stress, divided by the diameter of the hole.

EHY - Electric and Hybrid vehicle.

EI FACTOR - Product of modulus of elasticity and deflection.

EJECTION - The process of removing a molding from the mold impression; by mechanical means, by hand, or by the use of compressed air.

ELASTIC DEFORMATION - That part of the total strain in a stressed body which disappears upon removal of the stress.

ELASTICITY - That property of plastics materials by virtue of which they tend to recover their original size and shape after deformation.

ELASTIC LIMIT - The greatest stress which a material is capable of sustaining without permanent strain remaining upon the complete release of the stress. A material is said to have passed its elastic limit when the load is sufficient to initiate plastic, or nonrecoverable, deformation.

END - A strand of roving consisting of a given number of filaments gathered together. (The group of filaments is considered an "end" or strand before twisting; a "yarn" after twist has been applied): an individual warp yarn, thread, fiber, or roving.

ENVIRONMENTAL STRESS CRACKING - The susceptibility of a thermoplastic resin to crack or craze when in the presence of surface active agents or other environments. (E.S.C.)

EPOXY PLASTICS - Plastics based on resins made by the reaction of epoxides or oxiranes with other materials such as amines, alcohols, phenols, carboxylic acids, acid anhydrides and unsaturated compounds.

ERM - Elastic Reservoir Molding.

FATIGUE - The failure or decay of mechanical properties after repeated applications of stress. (Fatigue tests give information on the ability of a material to resist the development of cracks which eventually bring about failure as a result of a large number of cycles.)

FIBER ORIENTATION - Fiber alignment in a non-woven or a mat laminate where the majority of fibers are in the same direction, resulting in a higher strength in that direction.

FILAMENT WINDING - A process for fabricating a composite structure in which continuous reinforcements (filament, wire, yarn, tape or other) either previously impregnated with a matrix material or impregnated during the winding are placed over a rotating and removable form or mandrel in a previously prescribed way to meet certain stress conditions. Generally the shape is a surface of revolution and may or may not include end closures. When the right number of layers are applied the wound form is cured and the mandrel removed.

FILL - Yarn running from selvage to selvage at right angles to the warp in a woven fabric.

FILLER - A relatively inert material added to a plastic mixture to reduce cost, to modify mechanical properties, to serve as a base for color effects, or to improve the surface texture. (See reinforced plastic, binder, extenders.)

FINISH - A material applied to the surface of fibers in a fabric used to reinforce plastics and intended to improve the physical properties of such reinforced plastics over that obtained using reinforcement without finish.

FOAMED PLASTICS - Resins in sponge form, flexible or rigid, cells closed or interconnected, density anywhere from that of the solid parent resin to 2 pounds/cubic feet. Compressive strength of rigid foams is fair, making them useful as core materials for sandwich constructions. Both types are good heat barriers. Also, a chemical cellular plastic whose structure is produced by gases generated from the chemical interaction of its constituents.

FREE-RADICAL POLYMERIZATION - A type of polymerization in which the propagating species is a long chain free-radical initiated by the introduction of free-radicals by thermal or photochemical decomposition.

GEL COAT - A resin applied to the surface of a mold and gelled prior to lay-up. (The gel coat becomes an integral part of the finished laminate, and is usually used to improve surface appearance, etc.)

GLASS FINISH - A material applied to the surface of a glass reinforcement to improve its effect upon the physical properties of the reinforced plastic. (Also "bonding agent".)

HAND - The softness of a piece of fabric, as determined by the touch (individual judgment).

HAND LAYUP - The process of placing (and working) successive plies of reinforcing material or resin-impregnated reinforcement in position on a mold by hand.

HARDENER - A substance or mixture added to a plastic composition to promote or control the curing action by taking part in it. Also, a substance added to control the degree of hardness of the cured film. (See catalyst.)

HONEYCOMB -- Manufactured product or resin-impregnated sheet material (paper, glass fabric, etc.) or sheet metal, formed into hexagonal-shaped cells. Used as a core material in sandwich construction (which see).

HYBRID - Generally a combination of two or more reinforcements in a common matrix to provide a set of properties not indigenous to the individual reinforcements. May also be combination of composite and metal.

HTS, HMS - Commercial designation of graphite fiber reinforcement by Hercules, Inc. HTS - high tensile strength, surface treated; HMS - high modulus, surface treated.

IMPREGNATE - In reinforced plastics, the saturation of the reinforcement with a resin.

INHIBITOR - A substrate which retards a chemical reaction: used in certain types of monomers and resins to prolong storage life.

ISOTROPIC LAMINATE - One in which the strength properties are equal in all directions.

LOW PROFILE - A polyester resin developed to minimize surface defects in fabricated composites.

M-GLASS -- A high beryllia content glass designed especially for high modulus of elasticity.

MATCHED METAL MOLDING - A reinforced plastics manufacturing process in which matching male and female metal molds are used (similar to compression molding) to form the part - as opposed to low pressure laminating or spray-up.

MATRIX - See resin.

MOLD SHRINKAGE - The immediate shrinkage which a molded part undergoes when it is removed from a mold and cooled to room temperature: the difference in dimensions, expressed in inches per inch between a molding and the mold cavity in which it was molded (at normal temperature measurement): the incremental difference between the dimensions of the molding and the mold from which it was made, expressed as a percentage of the dimensions of the mold.

MONOMER - A simple molecule which is capable of reacting with like or unlike molecules to form a polymer: the smallest repeating structure of a polymer (mers); for additional polymers, this represents the original unpolymerized compound.

OPEN CELL FOAMED - A cellular plastic in which there is a predominance of interconnected cells.

ORIENTED MATERIALS - Materials, particularly amorphous polymers and composites, whose molecules and/or macroconstituents are aligned in a specific way. Oriented materials are anisotropic. Orientation can generally be divided into two classes: uniaxial and biaxial.

ORTHOTROPIC - Having three mutually perpendicular planes of elastic symmetry.

PHENOLIC, PHENOLIC RESIN - A synthetic resin produced by the condensation of an aromatic alcohol with an aldehyde, particularly of phenol with formaldehyde.

POLYAMIDE - A polymer in which the structural units are linked by amide or thioamide groupings. Many polyamides are fiber-forming.

POLYESTERS - Thermosetting resins, produced by dissolving unsaturated, generally linear, alkyd resins in a vinyl-type active monomer such as styrene, methyl styrene, and diallyl phthalate. Cure is effected through vinyl polymerization using peroxide catalysts and promoters, or heat, to accelerate the reaction. The resins are usually furnished in solution form, but powdered solids are also available.

POLYIMIDE - A polymer produced by heating of polyamic acid. It is a highly heat resistant resin (600°F+) suitable for use as a binder or as an adhesive. Requires extensive cure cycles.

POLYMER - A high-molecular-weight organic compound, natural or synthetic, whose structure can be represented by a repeated small unit, the "mer": for example, polyethylene, rubber, cellulose. Synthetic polymers are formed by addition or condensation polymerization of monomers. Some polymers are elastomers, some are plastics. When two or more monomers are involved, the product is called a copolymer.

POST-CURE - Additional elevated temperature cure, usually without pressure, to improve final properties and/or complete the cure. In certain resins, complete cure and ultimate mechanical properties are attained only by exposure of the cured resin to higher temperatures than those of curing.

POSTFORMING - The forming, bending, or shaping of fully cured, C-staged thermoset laminates that have been heated to make them flexible. On cooling, the formed laminate retains the contours and shape of the mold over which it has been formed.

PREFORM - A preshaped fibrous reinforcement formed by distribution of chopped fibers by air, water flotation, or vacuum over the surface of a perforated screen to the approximate contour and thickness desired in the finished part. Also, a preshaped fibrous reinforcement of mat or cloth formed to desired shape on a mandrel or mock-up prior to being placed in a mold press. Also, a compact "pill" formed by compressing premixed material to facilitate handling and control of uniformity of charges for mold loading.

PREPREG - Ready-to-mold material in sheet form which may be cloth, mat, or paper impregnated with resin and stored for use. The resin is partially cured to a "B" stage and supplied to the fabricator who lays up the finished shape and completes the cure with heat and pressure.

PULTRUSION - Reversed "extrusion" of resin-impregnated roving in the manufacture of rods, tubes and structural shapes of a permanent cross-section. The roving, after passing through the resin dip tank, is drawn through a die to form the desired cross-section.

REINFORCED PLASTIC - A plastic with strength properties greatly superior to those of the base resin, resulting from the presence of reinforcements imbedded in the composition.

REINFORCEMENT - A strong inert material bonded into a plastic to improve its strength, stiffness, and impact resistance. Reinforcements are usually long fibers of glass, asbestos, sisal, cotton, etc. in woven or nonwoven form. To be effective, the reinforcing material must form a strong adhesive bond with the resin. ("Reinforcement" should not be used synonymously with "filler".)

RESIN - A solid, semisolid, or pseudosolid organic material which has an indefinite and often high molecular weight, exhibits a tendency to flow when subjected to stress, usually has a softening or melting range, and usually fractures conchoidally. Most resins are polymers (which see). In reinforced plastics, the material used to bind together the reinforcement material: the "matrix."

RFI - Radio frequency interference.

RIM - Reaction injection molding, a process where polymeric reactants are mixed together and automatically injected into a mold.

S-GLASS - A magnesia-alumina-silicate glass, especially designed to provide very high tensile strength glass filaments.

SANDWICH CONSTRUCTIONS - Panels composed of a lightweight core material honeycomb, foamed plastic, etc., to which two relatively thin, dense, high-strength faces or skins are adhered.

SINK MARK - A shallow depression or dimple on the surface of an injection molded part due to collapsing of the surface following local internal shrinkage after the gate seals; an incipient short shot.

SIZE - Any treatment consisting of starch, gelatine, oil, wax, or other suitable ingredient which is applied to yarn or fibers at the time of formation to protect the surface and aid the process of handling and fabrication, or to control the fiber characteristics. The treatment contains ingredients which provide surface lubricity and binding action but, unlike a finish, contains no coupling agent. Before final fabrication into a composite, the size is usually removed by heat-cleaning, and a finish is applied.

SMC – Sheet molding compound, a form of raw material generally consisting of chopped randomly oriented glass fiber several inches in length and impregnated with a polyester resin system.

SPRAY-UP – Techniques in which a spray gun is used as the processing tool. In reinforced plastics, for example, fibrous glass and resin can be simultaneously deposited in a mold. In essence, roving is fed through a chopper and ejected into a resin stream which is directed at the mold by either of two spray systems. In foamed plastics, very fast-reacting urethane foams or epoxy foams are fed in liquid streams to the gun and sprayed on the surface. On contact, the liquid starts to foam.

STAPLE FIBERS – Fibers of spinnable length manufactured directly or by cutting continuous filaments to short lengths. (Usually 1/2 to 2 inches long: 1 to 5 denier.)

STRUCTURAL BOND – A bond that joins basic load-bearing parts of an assembly. The load may be either static or dynamic.

SURFACING MAT – A very thin mat, usually 7 to 20 mils thick, of highly filamentized fiberglass used primarily to produce a smooth surface on a reinforced plastic laminate.

SURFACE TREATMENT – A meterial applied to a reinforcing fiber during the forming operation or in subsequent processes (that is, size or finish).

SYNTACTIC FOAM – A cellular plastic which is "put together" by incorporating preformed cells (hollow spheres or microballoons) in a resin matrix; as opposed to "foamed plastic" in which the cells are formed by gas bubbles released in the liquid plastic by either chemical or mechanical action.

THERMOPLASTIC – Capable of being repeatedly softened by increase of temperature and hardened by decrease in temperature; applicable to those materials whose change upon heating is substantially physical rather than chemical. Generally somewhat soluble in organic compounds.

THERMOSET – A plastic which, when cured by application of heat or chemical means, changes in a substantially infusible and insoluble material.

TOOL –A rigid surface, used to impact contour to the plastic during the elevated temperature and pressure forming or curing cycle. Usually metal but for a few replications may be wood, fiberglass/plastic or plaster.

TRANSFER MOLDING – Method of molding thermosetting materials, in which the plastic is first softened by heating and pressure in a transfer chamber, and then forced by high pressure through suitable sprues, runners and gates into the closed mold for final curing.

TRANSVERSE – Normally refers to the perpendicular direction to the primary load in a stressed laminate.

TYPE I, II, III - Commercial designation for some types of high modulus graphite fibers.

     I = High Modulus (60 Msi) low strength
    II = Lower Modulus (40 Msi) high strength
   III = Lower Modulus (30 Msi) highest strength

UNIDIRECTIONAL LAMINATE - A reinforced plastic laminate in which substantially all of the fibers are oriented in the same direction.

UHM - Ultra high modulus graphite fiber nominally 70 Msi.

VACUUM BAG MOLDING - A process for molding reinforced plastics in which a sheet of flexible transparent material is placed over the lay-up on the mold and sealed. A vacuum is applied between the sheet and the lay-up. The entrapped air is mechanically worked out of the lay-up and removed by the vacuum, and the part is cured. Also, "bag molding."

VEIL - An ultrathin mat similar to a surface mat, often composed of organic fibers as well as glass fibers.

WARP - The yarn running lengthwise in a woven fabric; a group of yarns in long lengths and approximately parallel, put on beams or warp reels for further textile processing including weaving; a change in dimension of a cured laminate from its original molded shape.

WET LAYUP - The reinforced plastic which has liquid resin applied as the reinforcement is laid up. The opposite of "dry layup," "prepreg."

WOVEN FABRICS - Those produced by interlacing strands at more or less right angles.

WOVEN ROVING - A heavy glass fiber fabric made by the weaving of roving.

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