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Automobile Materials Competition: Energy Implications of Fiber-Reinforced Plastics

J. Cummings-Saxton

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AUTOMOBILE MATERIALS COMPETITION: ENERGY IMPLICATIONS OF FIBER-REINFORCED PLASTICS

by

J. Cummings-Saxton

Energy and Environmental Systems Division
Special Projects Group

October 1981

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CONVERSION TO INTERNATIONAL (SI) UNITS

Multiply	By	To Obtain
Btu	1.055×10^3	J
Btu/lb	2.33×10^3	J/kg
°F - 32	0.556	°C
gal (U.S. liquid)	3.785	L
in.	2.54	cm
kWh	3.6×10^6	J
lb	0.454	kg
mi	1.609	km

ACRONYMS

ACRONYMS

ABS	acrylonitrile butadiene-styrene
ACM	advanced composite materials
BMC	bulk molding compound
BOF	basic oxygen furnace
CAFE	corporate average fuel economy
CRLC	cold-rolled, low-carbon
DAP	diallyl phthalate
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EAF	electric-arc furnace
EG	epoxy graphite
FRP	fiber-reinforced plastic(s)
HDPE	high-density polyethylene
HHV	higher heating value
HSLA	high-strength/low-alloy
HSS	high-strength steel(s)
LDPE	low-density polyethylene
LHV	lower heating value
LLDPE	linear low-density polyethylene
LPG	liquid petroleum gas
MDPE	medium-density polyethylene
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
OHF	open-hearth furnace
PAN	polyacrylonitrile
PP	polypropylene
PS	polystyrene
PVC	polyvinyl chloride
RRIM	reinforced reaction-injected molded (plastics)
RTP	reinforced thermoplastics
SAN	styrene-acrylonitrile
SMC	sheet molding compound
TMC	thick molding compound
TP	thermoplastic(s)
TS	thermosetting
UPE	unsaturated polyester

AUTOMOBILE MATERIALS COMPETITION:
ENERGY IMPLICATIONS OF FIBER-REINFORCED PLASTICS

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ABSTRACT

The embodied energy, structural weight, and transportation energy (fuel requirement) characteristics of steel, fiber-reinforced plastics, and aluminum were assessed to determine the overall energy savings of materials substitution in automobiles. In body panels, a 1.0-lb steel component with an associated 0.5 lb in secondary weight is structurally equivalent to a 0.6-lb fiber-reinforced plastic component with 0.3 lb in associated secondary weight or a 0.5-lb aluminum component with 0.25 lb of secondary weight. (Secondary weight refers to the combined weight of the vehicle's support structure, engine, braking system, and drive train, all of which can be reduced in response to a decrease in total vehicle weight.) The life cycle transportation energy requirements of structurally equivalent body panels (including their associated secondary weights) are 174.4×10^3 Btu for steel, 104.6×10^3 Btu for fiber-reinforced plastics, and 87.2×10^3 Btu for aluminum. The embodied energy requirements are 37.2×10^3 Btu for steel, 22.1×10^3 Btu for fiber-reinforced plastics, and 87.1×10^3 Btu for aluminum. These results can be combined to yield total energy requirements of 211.6×10^3 Btu for steel, 126.7×10^3 Btu for fiber-reinforced plastics, and 174.3×10^3 Btu for aluminum. Fiber-reinforced plastics offer the greatest improvements over steel in both embodied and total energy requirements. Aluminum achieves the greatest savings in transportation energy.

EXECUTIVE SUMMARY

AUTOMOBILE MATERIALS COMPETITION

Concern about the availability and cost of petroleum has resulted in steadily improving vehicle fuel efficiencies. Although the improved efficiencies have been achieved by automobile manufacturers to help maintain their market competitiveness, an important initial factor was the Energy Policy and Conservation Act of 1975. This act establishes corporate average fuel economy (CAFE) standards for automobile manufacturers, which are scheduled to increase from 18 mpg in 1978 to 27.5 mpg in 1985.

Reducing vehicle weight has been the dominant strategy for improving fuel economy. (Other means have included reduced parts friction and improved engine performance, aerodynamic design, tire design, and drive train performance.) Average vehicle dry weight is projected to decline 30%, from 3750 lb in 1977 to 2600 lb in 1985. This is being accomplished mostly by downsizing, conversion to front wheel drive, and engine modifications. Only about 18% of this reduction is expected to be achieved by materials substitution. Further decreases in vehicle weight, however, will have to depend mainly on materials substitution.

Materials substitution in automobiles has been relatively minor. Plastics usage increased from 104 lb in 1971 to 200 lb in 1980, and is projected to increase to 260 lb in 1985. Aluminum usage has increased more gradually, from 76 lb in 1971 to 132 lb in 1980 and to a projected 210 lb in 1985. These increases, though modest, are taking place within the context of significant decreases in total vehicle weight. By 1985 plastics and aluminum will represent 10.0% and 8.1%, respectively, of vehicle weight. Use of conventional steel decreased from 2400 lb in 1971 to 1900 lb in 1980, and will likely fall to 1270 lb in 1985. Cast iron, which decreased slightly from 572 lb in 1971 to 515 lb in 1980, is expected to decrease to 260 lb in 1985. Use of the recently introduced high-strength steels (HSS) is rapidly growing. They are expected to triple their market share between 1977 and 1985, but this will not be enough to counter the overall decline in steel usage.

Plastics have been used almost exclusively in cosmetic applications or where parts consolidation is possible, such as in integral front ends. To achieve wider application, plastics must be used for structural components. Fiber-reinforced plastics (FRP), which have structural properties rivaling those of steels, are the leading candidates for increased plastics use in automobiles. One Detroit designer estimates that automobile weight can be reduced to 2000 lb during the 1990s through the use of up to 45% plastics if FRP successfully displace steel in body panels.*

FIBER-REINFORCED PLASTICS

Plastic Resins

The mechanical strength of plastic resins can be increased by fiber reinforcement. Unsaturated polyester (UPE) resins form a particularly synergistic combination with reinforcing fibers. These thermosetting (TS) resins tend to be brittle when not reinforced. Reinforcement provides the necessary structural stability, so that their low cost, dimensional stability, and excellent chemical and electrical properties can be fully exploited. Unsaturated polyester resins account for nearly 80% of FRP usage. Other TS resins account for an additional 10% and thermoplastic (TP) resins for slightly over 10%.

Production of UPE resins proceeds in two steps. First, a set of dibasic acids (or anhydrides) are combined with a polyhydric alcohol to produce the basic UPE polymer. This is a condensation reaction involving both saturated and unsaturated dibasic acids, the relative amounts of which

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*Reinforced reaction-injected molded (RRIM) plastic components are also being introduced into some automobile body component applications. This report restricts its attention to FRP components as representative of the type of market competition and resulting energy adjustments taking place.

determine the extent of cross linking in the polymer. As more unsaturated acid is used, a more rigid final product is produced due to greater cross linking. Most commonly, maleic anhydride is the unsaturated anhydride, phthalic anhydride is the saturated anhydride, and propylene glycol is the dihydric alcohol. In the second step of the production sequence, these constituents are combined with a reactive monomer, usually sytrene. This monomer eventually reacts with the resin in the curing, or molding, process. Its addition at this stage transforms the resin paste into a liquid that can be handled easily during intermediate processing steps, such as molding compound formulation. A typical resin composition is 16% maleic anhydride, 21% phthalic anhydride, 28% propylene glycol, and 35% styrene.

Once the basic resin mix has been established, a number of additives may be introduced to achieve desired properties, e.g., an inhibitor to retard curing of the resin prior to the molding process, a thickener to impart desired handling properties, a pigment or dye to achieve desired color, a TP additive to improve surface properties, and/or a stabilizer to improve product resistance to light and heat. Additives can be mixed with the resin by the plastic resin manufacturer or by a different type of processor known as a compounder.

The embodied energy of the plastic resin is of particular interest because hydrocarbon feedstocks are consumed in the production of each of the four major constituents. For example, styrene is made from ethylbenzene; ethylbenzene is made from ethylene and benzene; benzene is obtained from petroleum reformate; and ethylene is made from ethane, gas oil, or naphtha. To estimate the embodied energy of styrene, both the participation level of each process step and the process and feedstock energy requirements of each step have to be determined. The same inputs are required for maleic anhydride, phthalic anhydride, and propylene glycol. The feedstock energy requirements of UPE resins were calculated to be 22.16×10^3 Btu/lb and the process energy requirements to be 12.47×10^3 Btu/lb. Thus, the total embodied energy for UPE resins is 34.63×10^3 Btu/lb.

Reinforcements

A variety of reinforcing materials have been used: glass, asbestos, cotton, nylon, sisal, and cellulose. Type-E fiberglass is the reinforcement currently used in nearly all automotive applications. The tensile strength of fiberglass (500×10^3 psi) is 10 times that of steel, while its tensile modulus (10.5×10^6 psi) is three-eighths that of steel.* Advanced composite materials (ACM) have been developed that have better mechanical properties than those of fiberglass. These materials use more expensive reinforcements, such as carbon/graphite fibers, aramids, and metal whiskers. Their substantially greater cost -- $20/lb or more as compared with $0.60-70/lb for fiberglass -- has severely restricted their use.

Reinforcing materials perform their function by absorbing essentially the entire mechanical stress as it is applied to the composite. The

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*Tensile strength is the tensile stress required to achieve material rupture. Tensile modulus is the slope of the stress-strain curve in the elastic region and provides a measure of material stiffness.

reinforcing fibers can be thought of as a set of "ropes" scattered throughout the resin matrix. Their strength can be exerted only when they are stretched taut by tension along their axes. Therefore, fiber orientation relative to the applied stress determines the strength of the composite. For example, if all of the fibers are aligned in a single direction, stress applied in that direction will be resisted by all fibers, providing maximum strength; however, stress applied in a different direction will encounter little resistance. Thus, fiber orientation must be carefully tailored to the anticipated stress environment. Maximum strength must frequently be sacrificed to achieve good multidirectional strength through use of random fiber orientation.

A second critical parameter is the quantity of reinforcing fibers. Composite strength is proportional to the amount of reinforcement, i.e., two times the amount of reinforcing fibers generally leads to two times the composite strength. A third important parameter is fiber length. The longer the fiber in a given direction, the greater is the continuity of stress transfer in that direction. Extremely strong FRP have been achieved by using long, unidirectionally oriented fibers in quantities up to 80%. For these materials, the primary purpose of the resin is to lock the fibers in place.

Fiberglass manufacture involves three process steps: (1) mixing the mainly inorganic raw materials to form the glass batch, (2) heating the batch to approximately 2700°F to melt and refine the mixture, and (3) drawing the glass through platinum bushings to form the 0.1-0.75 mil glass fibers. The energy required for these steps is 21.80 x 10^3 Btu/lb. When this is added to the 0.3 x 10^3 Btu/lb to mine the raw materials, the total embodied energy becomes 22.10 x 10^3 Btu/lb.

Although carbon/graphite fibers have been proposed for future use in automotive applications, their continued high cost, even when projected future economies of scale are taken into consideration, will probably limit their use to hybrid composites that also contain fiberglass. Carbon/graphite fibers are manufactured in a two-step sequence. A precursor material, such as polyacrylonitrile fiber, is held under tension as it is heated to 480-750°F. Once the precursor material has been fully oxidized, the temperature is increased to 2730-4530°F. All of the atoms except the carbon ladder backbone are pyrolyzed at this higher temperature. Total energy requirements of the two steps are estimated at 88.8 x 10^3 Btu/lb, an amount four times higher than that for fiberglass manufacture.

Fillers

The fillers added to FRP reduce cost, help to achieve desired flow properties, and provide a smoother surface. Fillers usually cost less than $0.20/lb compared to the $0.60-0.70/lb cost for the fiberglass and resin they displace. Their granular or platelet shapes enable them to flow more easily than the fiberglass filaments, thereby decreasing the pressure necessary for molding and permitting more complex shapes. Calcium carbonate is by far the most widely used filler, both in automotive and other applications.

The energy requirements to produce fillers are related to mining and beneficiating the inorganic materials. For calcium carbonate, the total energy required is only 0.35 x 10^3 Btu/lb. Therefore, using large quantities of filler -- 40% is typical -- greatly reduces the total embodied energy of FRP.

Sheet Molding Compound

The resin, filler, and reinforcement can be joined together during the molding operation, as is done in the hand lay-up of boats. In nearly all high-volume operations, however, an intermediate molding compound is formulated. The kind most frequently employed in automotive applications is sheet molding compound (SMC). As its name indicates, the mixture is assembled in sheet form. A thickening agent is used to impart rigidity so that the SMC can be easily handled and stored. In many respects, it can be treated like metal sheet products.

To initiate the product manufacturing sequence, SMC is cut to size and manually placed in a compression mold. The mold then closes, forcing the SMC into the desired product configuration. A small amount of heat usually is added to initiate the reaction, and a catalyst insures that the curing reaction proceeds rapidly. Although the actual molding operation is complete in about 20 s, the part has to remain in the mold for nearly 2 min until curing is complete. This time requirement compares unfavorably with the few seconds required for a steel or aluminum stamping operation. Manufacturers of FRP attempt to counter this disadvantage by parts consolidation, whereby a single molding operation achieves the same result as several stamping and joining operations.

Sheet molding compound with 30% fiberglass is the most widely used type in the automotive industry. The energy required for SMC formulation and molding is 4.30 x 10^3 Btu/lb. The aggregate energy for manufacturing the FRP product comprises the energies needed to produce the resin, fiberglass, and filler, plus the energy for SMC formulation and molding. For SMC-30, which contains 30% fiberglass, 30% resin, and 40% calcium carbonate, the total energy is 24.4 x 10^3 Btu/lb. This value includes materials losses (4%) during SMC manufacture, scrappage losses (10%) during product manufacture, and 0.22 x 10^3 Btu/lb transportation energy.

STEEL

The use of steel in automobiles is projected to decrease 34%, from 2320 lb per vehicle in 1977 to 1530 lb in 1985. Nevertheless, steel will remain the predominant automobile material in 1985, accounting for 58.8% of total vehicle dry weight. New varieties of HSS are being introduced in an attempt to maintain steel's market share as vehicle weight is reduced. Dual-phase steels appear to be the most promising of the HSS. They provide good ductility during stamping operations but then set into crystalline structures that provide ultimate strengths of 60-145 x 10^3 psi. The chief impediment to their increased use is the need for the industry to invest in continuous annealing furnaces, which are highly capital intensive.

Steel production involves 14 separate processes. The most energy intensive of these are the production of hot metal by blast furnaces; molten steel by open-hearth, basic oxygen, or electric-arc furnaces; and slabs by the casting of ingots or by energy-conserving continuous casting. Approximately three-fourths of automotive steel is produced via the blast-furnace/basic-oxygen-furnace route and one-fourth via the blast-furnace/open-hearth-furnace route. Essentially none is produced via the scrap-fired electric-arc furnace, which is less energy intensive. Continuous casting now accounts for 17% of slab production, and further growth is anticipated. The production-weighted energy requirements from all participating processes are 18.1 x 10^3 Btu/lb. An additional 0.4 x 10^3 Btu/lb is required for transport to Detroit, and product fabrication energy is approximately 0.13 x 10^3 Btu/lb. The offal rate for production of steel automotive parts averages 25%. The resulting total embodied energy for steel is 24.8 x 10^3 Btu/lb.

ALUMINUM

Aluminum is a lightweight alternative to steel for many automotive applications. This material, which is three times lighter than steel, can be handled on the same types of equipment as steel, and its assembly techniques are well established. However, the weight advantage of aluminum relative to steel is offset both by its cost, which is three times higher, and by a tensile modulus that is only one-third that of steel. A low tensile modulus reduces aluminum's weight advantage in applications where stiffness is important. Primarily because of its cost, aluminum sheet has been used mostly in short-term applications to achieve specific weight reduction goals. Many of these aluminum parts are replaced subsequently by improved steel components.

Aluminum production is extremely energy intensive. The alumina electrolysis step accounts for three-fourths of the energy needed to produce aluminum sheet from bauxite. This step can be bypassed, when scrap is available, by using a reverbatory furnace. Producing aluminum ingots using this furnace requires only 10% of the energy needed to proceed to that point from bauxite ore. Ten percent of aluminum sheet output is produced from recycled post-consumer scrap. In addition, the reverbatory furnace processes the large quantities (35% of the aluminum ingots) of mill scrap generated during aluminum sheet fabrication. The production-weighted average energy of aluminum sheet manufacture via the two furnaces is 120.9 x 10^3 Btu/lb. An additional 400 Btu/lb is needed for transport to Detroit and 130 Btu/lb for product fabrication. An offal rate of 25% is sustained during product fabrication. Thus, total embodied energy is 161.9 x 10^3 Btu/lb, more than six times that for steel or FRP.

ENERGY IMPLICATIONS OF AUTOMOBILE MATERIALS SUBSTITUTION

Weight Reduction

Fiberglass and carbon/graphite fibers have, respectively, five to ten times the tensile strength of steel. Carbon/graphite fibers have a tensile modulus equal to that of steel, while the modulus for fiberglass is only three-eighths as great. In addition, fiberglass is three times lighter and carbon/graphite is four times lighter than steel. As a result of these properties, fiberglass and carbon/graphite fibers are used in composite materials to achieve overall mechanical properties comparable to those of steel, but at significantly lower weights. Aluminum achieves specific properties comparable to those of steel by offsetting lower mechanical properties with a density that is three times lower than that of steel. Aluminum components have achieved, on average, weight reductions of 50% relative to steel, while SMC and epoxy/graphite (EG) components have achieved 40% and 50% reductions, respectively. The high cost of carbon/graphite fibers precludes their extensive use in automotive applications within the foreseeable future.

If materials substitution takes place within the context of an overall weight reduction effort, a number of secondary weight reductions are possible. These consist of opportunities to reduce the weights of the support structure, engine, braking system, and drive train. Values for the ratio of secondary to primary weight savings range from 0.4 to 1.6. Ford Motor Company recently achieved a 0.76 secondary weight reduction ratio in an advanced concept lightweight vehicle. This report uses 0.5 as being representative of the general potential for secondary weight reduction in present-day vehicles.

Transportation Energy

Automobile weight reduction through materials substitution translates directly into savings in vehicle fuel (transportation energy). The U.S. Department of Transportation (DOT) has correlated fuel economy with vehicle weight for all models over a period of years. Their correlations include the effects of both reduced weight and improved aerodynamics. For a 3000-lb gasoline vehicle with a performance parameter equaling 0.03 hp/lb, the effect of weight reduction, corrected for aerodynamic drag, is 0.93×10^{-5} gal/mi/lb. Thus, assuming a vehicle lifetime of 100,000 mi, each pound of weight reduction saves 0.93 gal of gasoline. In energy terms, this is a 116×10^3 Btu savings per pound of weight reduction.

Overall Savings

The embodied energy, weight reduction, and transportation energy data together yield the overall energy savings achievable by materials substitution. In body panels, a 1.0-lb steel component with an associated 0.5-lb in secondary weight is structurally equivalent to a 0.6-lb FRP component with a 0.3-lb secondary weight or a 0.5-lb aluminum component with a 0.25-lb secondary weight. (Because of its predominant usage, steel is assumed to be the secondary material in each case.) The transportation energy requirements of the steel, FRP, and aluminum components are 174.4×10^3 Btu, 104.6×10^3 Btu, and 87.2×10^3 Btu, respectively. The embodied energy requirements are 37.2×10^3 Btu, 22.1×10^3 Btu, and 87.2×10^3 Btu, respectively. Total energy requirements are 211.6×10^3 Btu, 126.7×10^3 Btu, and 174.3×10^3 Btu, respectively. Thus, FRP offer the greatest improvements in both embodied and total energy. Aluminum, on the other hand, achieves the greatest savings in transportation energy, but this does not fully compensate for its large embodied energy requirements.

The type of energy resources consumed is also important. For example, the iron and steel industry depends on coal and coke (63%), the aluminum industry on electricity (68%), and the fiberglass industry on natural gas

(75%). The amount of petroleum (oil) consumed is of particular interest because that energy resource is currently of great concern. Electricity consumption also is important because its use translates into higher fuel consumption when the thermal losses of electricity generation are taken into account. Based on the average fuel usage of each industry and on the fuel requirements of current patterns of electricity generation: (1) direct energy requirements of steel, FRP, and aluminum are, respectively, 22.6 x 10^3 Btu/lb, 18.3 x 10^3 Btu/lb, and 70.3 x 10^3 Btu/lb, and (2) assuming 34.12% thermal efficiency in electricity generation, total fuel requirements are, respectively, 24.8 x 10^3 Btu/lb, 24.4 x 10^3 Btu/lb, and 161.9 Btu/lb. Petroleum (oil) requirements are 3.5 x 10^3 Btu/lb, 9.6 x 10^3 Btu/lb, and 27.7 x 10^3 Btu/lb, respectively. If all new aluminum production were supplied by dedicated, base-load, coal-fired electricity, aluminum's petroleum consumption would fall to 4.0 x 10^3 Btu/lb, while its coal consumption would rise to 143.9 x 10^3 Btu/lb. The comparisons for petroleum consumption in an automobile materials context (structurally equivalent body panels -- 1.0 lb steel, 0.6 lb FRP, and 0.5 lb aluminum, with associated secondary weights -- over a vehicle lifetime of 100,000 mi) are 179.7 x 10^3 Btu for steel, 111.4 x 10^3 Btu for FRP, and 101.9 x 10^3 Btu for aluminum. Fiber-reinforced plastics compete favorably against steel in all respects. The desirability of aluminum in energy terms depends on the fuels used to generate electricity for aluminum production. If fossil fuels alone were used, aluminum would require 38% more total energy than that required by FRP but 18% less energy than that needed for steel. If large amounts of hydropower were employed in aluminum manufacture, however, the total energy requirements would be reduced accordingly. For example, 40% hydropower usage would reduce aluminum's total energy requirements to 118.6 x 10^3 Btu/lb, 6% less than those for FRP.

FIBER-REINFORCED PLASTICS RESEARCH AND DEVELOPMENT NEEDS

Both a lack of knowledge of the material characteristics of FRP and inadequate production techniques constrain the use of FRP for automobile components. Inadequacies include surface quality deficiencies, low production rates, undeveloped assembly techniques, uncertain energy absorption characteristics, inadequate knowledge of material properties, and lack of recyclability. To respond to these needs, research and development is required to develop improved processing techniques and to assemble a product characterization data base. Although some research and development effort is underway in each of these areas, it is generally at a low level because of the ongoing cash flow problems in Detroit and the emphasis being given to vehicle downsizing as the primary method for achieving improved fuel efficiency. Extensive materials substitutions are likely to be delayed for several years until the more cost effective downsizing opportunities are fully exploited. At present rates of investigation, however, the necessary FRP data will not be developed in time for the next round of decision making concerning desirable strategies for achieving the improved fuel efficiencies that have been discussed for the mid-1990s. Therefore, industry representatives are indicating that support for research and development by a government agency, such as the U.S. Department of Energy (DOE), would be helpful. The potential savings in total energy and petroleum consumption through use of FRP automobile components might justify such support.

The governmental role could take two forms: (1) financial support for research and development in the use of FRP for automotive applications, and (2) in-house development of basic FRP engineering data. The National Aeronautics and Space Administration (NASA) already performs such a role in support of FRP research and development related to aerospace applications. Since the NASA effort is focused on low-volume applications where cost is a secondary consideration, results generally are not applicable to the high-volume automotive industry. Projects conducted by industry might focus on development of improved FRP processing techniques for automotive applications, while programs at universities and/or government laboratories might emphasize exploratory engineering design.

1 INTRODUCTION

The use of plastics in automobiles has been steadily increasing over the last 15 yr, both in total quantity and in relative market share. Overall, the trend has been for plastics and aluminum to increase their market penetration at the expense of iron and steel. The national emphasis on improved transportation efficiency since the oil embargo of 1973-1974 has tended to reinforce the penetration of plastics and aluminum, because they are lighter in weight than iron and steel in most automotive applications.

As the role of plastics has grown, concern has been expressed as to their dependence on crude oil. Because plastics are composed primarily of hydrocarbons obtained from natural gas and crude oil, these resources are required both as an energy input during fabrication and for the plastics molecules themselves. It is generally easier to use alternative energy sources for processing than for feedstocks.* Therefore, concern about the displacement of iron and steel or aluminum by plastics largely stems from the crude oil requirements for plastics feedstocks.

The effect of increased emphasis on transportation efficiency can be seen in recent trends of automobile weights. Table 1.1 gives the materials used in automobiles from 1965 to 1980. Since the values are production-weighted averages, they reflect both the weight of the vehicles manufactured in each size range (e.g., compact) and the number of vehicles purchased from each group. From 1965 to 1971, consumers purchased more spacious, luxurious, and heavier cars. Even though manufacturers could not immediately change basic vehicle characteristics after the 1973-1974 oil embargo, consumer purchases reduced the average weight of vehicles sold in 1974 by 4% compared to 1971. Subsequent manufacturer adaptations to changed demand reduced average vehicle weight by 17% in 1980 compared to 1971. In addition, a Detroit designer has estimated that if fiber-reinforced plastics (FRP) successfully displace steel in automobile body panels, automobile weight would be reduced during the 1990s to 2000 lb through the use of up to 45% plastics.

As can be seen in Table 1.1, the use of steel remained nearly constant and cast iron use increased by 36% from 1965 to 1977; both then fell off slightly from 1977 to 1980. Iron and steel remain the predominant materials in present-day cars, accounting for 72.7% of vehicle weight in 1980. Plastics participation increased dramatically over the 15-yr period -- from 1.0% in 1965 to 6.0% in 1980. The compound annual growth rate in pounds of plastic per vehicle was 12.3%. Aluminum also increased its market penetration but at a slower rate, growing from 1.8% in 1965 to 4.0% in 1980. Plastics and aluminum were the only automobile materials whose use increased over the entire 1965-1980 period.

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*A substantial amount of work is underway to develop coal-based feedstocks for petrochemical processes.

Table 1.1 Automotive Materials Composition for Selected Car Model Years (lb/automobile)

Material	1965	1968	1971	1974	1977	1980[a]
Iron	469	500	572	590	640	515
Steel	2133	2210	2400	2250	2320	1900
Aluminum	62	66	76	83	110	132
Zinc	59	58	60	34	24	19
Copper	35	36	32	23	20	30
Lead	35	36	40	36	26	22
Glass	97	98	104	96	90	92
Rubber	166	182	204	199	100	100
Plastics	35	73	104	152	190	200
Miscellaneous	359	375	408	378	230	310
Average vehicle dry weight[b]	3450	3640	4000	3841	3750	3320

[a] General Motors Corporation average vehicle.

[b] Vehicle inertia weight equals vehicle dry weight plus passengers and fluids. Average vehicle inertia weight was 3650 lb in 1980.

Sources: Refs. 1 (1965-1974), 2 (1977), and 3 (1980).

This report examines the energy tradeoffs associated with increased plastics use in automobiles. Fiber-reinforced plastics are emphasized,* because they are strong enough to compete directly with iron, steel, and aluminum in automotive structural applications. Because the final product fabrication steps represent such a small fraction of overall production energy, the materials are compared with regard to the energy consumed along the entire production sequence. Consumption of automotive fuels also is taken into account.

On the basis of total energy consumption, FRP are preferable to steel and aluminum. In addition, because of the large petroleum requirements for vehicle transportation energy, FRP and aluminum both provide significant reductions in petroleum consumption compared to steel. However, greatly expanded usage of FRP in automotive applications is constrained by undeveloped assembly techniques and by a lack of materials property data.

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*Reinforced reaction-injected molded (RRIM) plastic components are also being introduced into some automobile body component applications. This report restricts its attention to FRP components as representative of the type of market competition and resulting energy adjustments taking place.

2 FIBER-REINFORCED PLASTIC SYSTEMS

Fiber-reinforced plastics were first employed during World War II for military applications. Subsequently, FRP shipments grew steadily to an estimated 2.05 x 10^9 lb in 1979, then declined with the economy in 1980 (see Table 2.1). While marine applications dominated in the early 1970s, they were displaced in 1976 by land transportation uses. Land transportation applications represented 27% of the estimated total in 1979, reflecting an annual growth in land transportation uses of 13.4% from 1974 through 1979.

Each FRP contains two essential components that form a synergistic composite -- plastic resin and reinforcing material. The resin provides a matrix to stabilize the fiber and acts to resist compression. The resin also establishes the chemical, electrical and, to a large extent, the thermal properties of the composite. The reinforcing material provides mechanical strength, taking the load when FRP are subjected to tensile stress. A third and less expensive constituent -- filler -- is now employed in most FRP systems to reduce costs and to achieve desired flow properties. The granular fillers flow more easily than the viscous resins or the geometrically awkward fibers.

Fiber-reinforced plastics are generally 25-35% (by weight) resin, with the remainder allocated between reinforcement and filler according to desired

Table 2.1 Shipments of Fiber-Reinforced Plastics by Market (10^6 lb)[a]

Market	1974	1975	1976	1977	1978	1979	1980 Estimate
Aircraft and aerospace	30	24	22	23	22	23	25
Appliances and equipment	82	64	98	112	123	130	104
Construction	198	175	248	276	323	335	265
Consumer goods	75	64	102	116	116	126	99
Corrosion-resistant products	174	163	157	189	216	238	249
Electrical rods, tubes, and parts	94	82	123	154	170	190	162
Marine and marine accessories	320	285	365	400	430	385	275
Land transportation	293	265	398	460	532	550	436
Miscellaneous	75	58	66	72	74	79	70
Total	1341	1180	1579	1802	2006	2056	1685

[a] Thermoset and thermoplastic. Weights include resin, reinforcement, and filler.

Sources: Refs. 1 (1974-1975) and 4 (1976-1980).

product properties. Although as much as 80% reinforcement is employed for high-strength applications, reinforcement usually accounts for only 30% of the total. Generally, filler represents 35-45% (by weight).

In addition to discussing the three principal components, Sec. 2 describes the preparation of molding compounds and the molding operation. Most automobile applications employ molding compounds.

2.1 PLASTIC RESINS

Plastic resins are either thermoplastic (TP) or thermosetting (TS). Thermoplastic resins consist of long molecules (linear or branched) having side chains or groups that are not attached to other molecules. They can be repeatedly softened by heating and hardened by cooling. Thermosetting resins have a three-dimensional, relatively rigid structure as a result of cross linking between adjacent molecules during the polymerization process. Once hardened, these resins cannot be softened without breaking some of the cross linkages.

Thermoplastic resins are far more common. They accounted for approximately 85% of total plastics production from 1975 to 1980 (see Table 2.2). However, in FRP systems, TS resins account for approximately 90% of the total; unsaturated polyester (UPE) resins alone account for nearly 80%. The disparity between overall resin use and use in FRP can be traced to resin mechanical properties. Thermoplastic resins have good mechanical properties even when unreinforced; the high-performance, more costly TP resins are known as "engineering plastics." In contrast, many TS resins are more brittle. However, reinforced TS resin systems achieve substantially better mechanical properties at lower cost than the strongest TP resins.

2.1.1 Thermosetting Resins

The five major classes of TS resins are listed in Table 2.2. Since UPE resins are used more often than the others in FRP systems, these resins will be used to illustrate the principal features of TS resins in FRP. The reasons for the market success of UPE resins are twofold: (1) good overall properties (dimensional stability; ease of handling; and mechanical, electrical, and chemical resistance) and (2) relatively low cost ($0.56-0.59/lb in June, 1980[5]) of general-purpose UPE resins.

Unsaturated polyester resin products are produced in four steps as depicted in Fig. 2.1. First, a set of dibasic acids (or anhydrides) are combined with a polyhydric alcohol* to produce the basic UPE polymer. This polymer is then combined with a reactive monomer, which subsequently reacts in the curing step to form the final UPE product. Next, additives can be mixed with the resin to establish desired properties. These additives may include: (1) an inhibitor to retard curing of the resin prior to the molding process; (2) a thickener to impart the desired handling properties; (3) a

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*Dibasic acids have two replaceable hydrogen atoms, and polyhydric alcohols have several hydroxyl groups.

Table 2.2 Total U.S. Plastics Production and Captive Use by Material, 1975-1980 (10^6 lb)

Resin	1975		1976		1977	
	Production	Captive Use	Production	Captive Use	Production	Captive Use
Selected thermosetting plastics						
Epoxy	198	187	244	250	261	278
Phenolic	1,051	1,034	1,340	1,305	1,458	1,400
Unsaturated polyester (UPE)	834	771	1,042	959	1,061	1,045
Urea	690	685	821	809	963	951
Melamine	115	117	186	182	200	203
Total	2,888	2,794	3,633	3,505	3,943	3,877
Selected thermoplastics						
Acrylonitrile butadiene-styrene (ABS)	642	621	988	925	1,069	1,057
Styrene-acrylonitrile (SAN)	110	75	113	104	115	113
High-density polyethylene (HDPE)	2,468	2,305	3,125	3,127	3,652	3,557
Low-density polyethylene (LDPE)	4,743	4,725	5,813	5,765	6,471	6,488
Nylon	135	143	247	221	254	250
Polypropylene (PP)	1,902	1,903	2,632	2,536	2,747	2,698
Polystyrene (PS)	2,662	2,640	3,195	3,145	3,446	3,557
Polyvinyl chloride (PVC)	3,648	3,615	4,716	4,638	5,253	5,232
Total	16,310	16,027	20,829	20,461	23,007	22,952
Total selected plastics	19,198	18,821	24,462	23,966	26,950	26,829
All other plastics	3,630	2,341	4,734	3,018	6,998	4,227
Total	22,828	21,162	29,196	26,984	33,948	31,106

Table 2.2 (Cont'd)

Resin	1978		1979		1980	
	Production	Captive Use	Production	Captive Use	Production	Captive Use
Selected thermosetting plastics						
Epoxy	299	316	361	332	315	319
Phenolic	1,617	1,543	1,781	1,732	1,499	1,517
Unsaturated polyester (UPE)	1,209	1,199	1,147	1,152	947	949
Urea	1,122	1,103	1,367	1,355	1,165	1,147
Melamine	202	186	200	192	167	166
Total	4,449	4,357	4,856	4,763	4,093	4,098
Selected thermoplastics						
Acrylonitrile butadiene-styrene (ABS)	1,134	1,118	1,191	1,183	920	916
Styrene-acrylonitrile (SAN)	120	121	124	126	111	103
High-density polyethylene (HDPE)	4,201	4,165	5,010	4,893	4,405	4,394
Low-density polyethylene (LDPE)	7,111	7,147	7,793	7,815	7,291	7,467
Nylon	275	278	327	315	274	271
Polypropylene (PP)	3,074	3,055	3,841	3,894	3,648	3,714
Polystyrene (PS)	3,823	3,870	4,005	3,997	3,521	3,518
Polyvinyl chloride (PVC)	5,723	5,810	6,119	6,138	5,470	5,407
Total	25,461	25,564	28,410	28,361	25,640	25,790
Total selected plastics	29,910	29,921	33,266	33,124	29,733	29,888
All other plastics	7,695	5,142	8,311	5,593	5,714	5,297
Total	37,605	35,063	41,577	38,717	35,447	35,185

Sources: Refs. 1 (1974-1975) and 4 (1976-1980).

1. UNSATURATED DIBASIC ACID (OR ANHYDRIDE) + SATURATED DIBASIC ACID (OR ANHYDRIDE) + DIHYDRIC ALCOHOL $\xrightarrow[\text{SOLVENT}]{\text{HEAT}}$ UNSATURATED POLYESTER RESIN
2. UNSATURATED POLYESTER RESIN + REACTIVE MONOMER $\longrightarrow$ COPOLYMER RESIN
3. COPOLYMER RESIN + ADDITIVES $\longrightarrow$ MOLDING COMPOUND
4. MOLDING COMPOUND $\xrightarrow[\text{PRESSURE}]{\text{HEAT/CATALYST}}$ CURED PRODUCT

Fig. 2.1 Steps in the Production of Unsaturated Polyester Resin Products

pigment or dye to achieve the desired color; (4) a TP additive to improve surface properties; (5) a stabilizer to improve product resistance to light and heat; (6) fiber reinforcement (see Sec. 2.2); and (7) filler (see Sec. 2.3). The additives may be mixed with the resin at the plastics material manufacturer or at a separate set of processors known as compounders. The fourth step is the molding process, during which the product shape is formed and resin curing takes place. A curing agent (catalyst) and heat usually are employed to initiate the cure. The molding process, which is accomplished at the fabricator, is discussed in Sec. 2.5.

The first step in the sequence is the condensation reaction of two dibasic acids -- one saturated, one unsaturated -- with a dihydric alchohol to form the UPE polymer. The relative amounts of saturated and unsaturated acids determine the extent of cross linking in the polymer. As more unsaturated acid is used, a more rigid final product is produced due to greater cross linking. The unsaturated dibasic acid used in most instances is maleic anhydride. Various saturated acids (or anhydrides) are employed, depending on the desired properties of the product. Phthalic anhydride is by far the most frequently used. Alternatives include isophthalic acid, bisphenol A, and "Het" anhydride. Isophthalic acid yields a resin with higher viscosity and end products with greater hydrolytic stability, greater toughness, higher heat distortion temperature, and better chemical resistance. Bisphenol A and "Het" anhydride also lead to improved hydrolytic stability. The former improves corrosion resistance, and the latter reduces flammability. The dihydric alcohols employed include propylene glycol, ethylene glycol, dipropylene glycol, diethylene glycol, and neopentyl glycol. Propylene glycol is the most widely used, accounting for nearly 70% of the total.

Reaction of the dibasic acids or anhydrides and the dihydric alcohol produces the basic polymer. Usually a solvent and heat are used to facilitate this esterification reaction. It is a condensation reaction in that the reactant molecules are joined in the product molecule, with water as the only by-product. The reaction mixture is cooled to stop the reaction when the desired molecular weight and viscosity are reached.

A reactive monomer is added to the UPE resin in the second step. Its addition at this stage serves to impart desired flow properties. The monomer transforms the resin paste into a liquid, which can be handled easily during intermediate processing and during the final molding operation. Styrene is frequently used as the reactive monomer; other alternatives include vinyl toluene, methyl methacrylate, diallyl phthalate (DAP), and mono-chloro-styrene. Vinyl toluene is less volatile than styrene, reducing subsequent monomer evaporation. Methyl methacrylate provides improved ultraviolet stability. Diallyl phthalate is even less volatile than vinyl toluene and provides good electrical properties. Mono-chloro-styrene provides more rapid cures. The monomer that is added eventually reacts with the resin in the curing, or molding, process.

Curing can begin as soon as the reactive monomer is added. Therefore, an inhibitor must be added, usually during the third step, unless the resin-monomer system is to be used immediately. The inhibitor is added in very low concentrations (0.02-0.05%) and acts to absorb the energy of the resin-monomer reactions. This prevents the onset of the chain reaction leading to the copolymer product. The inhibitor can only delay curing, because it loses its effectiveness over time due to the activation of its molecules. A wide range of inhibitors are employed (e.g., hydroquinone, p-t butyl cotechol, phenolic resins, aromatic amines, picric acid, and quinones).

Other additives may be introduced during the third step. In addition to reinforcements and fillers, colorants are employed, including dyes and pigments as well as metallics and pearlescent powders or inclusions. Some colorants provide ultraviolet stability. The colorants may be subject to fading, present uniformity problems, or speed up or delay the polymerization process. Other additives include: (1) stabilizers; (2) antistatic agents that reduce the buildup of static electricity in the final product; (3) lubricants that improve polymer flow during subsequent molding or extrusion operations; (4) flame retardants; and (5) processing aids, such as viscosity depressants, mold releases, slip agents, emulsifiers, and antiblocking agents. At the end of the third step, the resin system enters the molding (or product fabrication) process. Resin curing takes place during this operation.

The most significant components to be taken into account from an energy usage point of view are the two dibasic acids or anhydrides, the dihydric alcohol, and the reactive monomer. The typical UPE used in FRP systems employs maleic anhydride as the unsaturated acid, phthalic anhydride as the saturated acid, propylene glycol as the dihydric alcohol, and styrene as the reactive monomer. Representative participations of each are 16%, 21%, 28%, and 35% (by weight), respectively. This chemical composition will be used in this report as characteristic of UPE resins.

2.1.2 Thermoplastic Resins

As shown in Table 2.2, TP resins are the largest volume plastic resins. Their greater production volume and generally simpler chemistry make them less expensive. For example, high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS) were priced in 1979 at about \$0.35/lb, compared to nearly \$0.50/lb for

UPE.* The lower cost of high-volume TP resins has motivated efforts to make greater use of them in FRP systems. Such reinforced thermoplastics (RTP) were first introduced in 1955, and their annual sales volume grew to 15 x 10^6 lb by 1967 and 182 x 10^6 lb by 1973. Estimated sales for 1978 and 1979 were 214 x 10^6 lb and 242 x 10^6 lb, respectively. This latter figure represents 11.8% of 1979 FRP sales (see Table 2.1).

A significant advantage of TP resins is their excellent compatibility with injection molding, the highest volume molding process. (Thermosetting resins also can be molded in this way, but not as easily.) A second advantage is that TP resin wastes can be remelted and fed back into the production process. Also, TP resins can be used with TS resins if a good surface finish is required. Using TP resins alleviates the sink mark and surface crack difficulties experienced by TS resin products during cooling. Up to 40% TP resin can be employed in Class A surface molding compounds. For these reasons, TP resins should occupy a gradually increasing share of the FRP market. Nevertheless, TS resins should retain their dominant FRP market position because of their favorable physical properties.

2.2 REINFORCEMENT

A variety of reinforcing materials have been used, including glass, asbestos, cotton, nylon, sisal, and cellulose. Asbestos has been one of the largest volume, low-cost filler-reinforcement materials, but it is being phased out in nearly all applications because of its health hazards. Several high-performance advanced composite materials (ACM) have been developed (e.g., whiskers, carbon/graphite fibers, and aramids), but their higher cost severely limits their use. Fiberglass, type E, is the most widely used reinforcement at the present time and should continue to be for the foreseeable future.

Discussion of reinforcing material properties requires a brief introduction to the terminology conventionally employed in describing mechanical properties. Figure 2.2 shows how material strain develops in an elastic manner. Upon removal of the stress, the rod will return to its original dimensions. Stress and strain in the elastic region are related by Hooke's Law:

$$S = E\varepsilon \qquad (1)$$

where:

S = stress (psi)

ε = strain (in./in.), and

E = Young's modulus (psi).

Young's modulus, in this case the elastic or tensile modulus, is the slope of the stress-strain curve from the origin to A. The greater the value of the

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*Engineering TP are much more costly ($1-15/lb in June, 1980). Engineering TP include acetal, polycarbonate, polyphenylene sulfide, TP polyester, polysulfone, modified polyphenylene oxide, polyimide, and polyamide-imide.

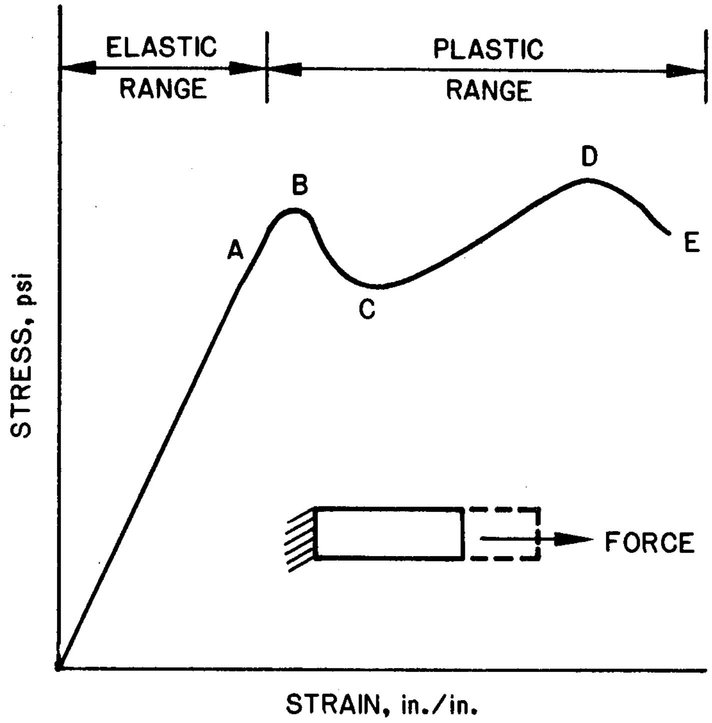

Fig. 2.2 Tensile Stress-Strain Curve

elastic modulus, the stiffer and more resistant to elongation is the material. Once A, known as the elastic limit, is exceeded, further increases in stress move the strain along a nonlinear path through B, C, and D, until the material ruptures at E. Points B, C, and D are termed, respectively, the upper yield point, lower yield point, and ultimate strength of the material. Frequently, materials are characterized simply by their elastic modulus and ultimate strength. Similar curves can be developed for torsion, bending, compression, and shear.

Reinforcing materials take on essentially the entire mechanical stress when it is applied to the composite. In effect, the resin matrix is transparent to the mechanical stress, passing it directly to the reinforcing fibers. The modulus of the resin must be less than the modulus of the reinforcement, or the resin will assume part of the stress and will tend to crack.

The three most important parameters determining reinforcement effectiveness are the orientation of the reinforcing fibers relative to the applied stress, and the amount and length of the fibers. The fibers can be thought of as a set of ropes scattered throughout the resin matrix. Like ropes, their strength can be exerted only when they are stretched taut by tension along their axes. Also of importance is a good bond between the fiber and resin so that the resin matrix can transfer the stress to the fiber and elastically deform in a way that maintains the resin-fiber contact.

The design of composite products must take into account the nature of the stresses encountered during use. If all of the fibers are aligned in a single direction, stress applied in that direction will be resisted by all of the fibers, providing maximum strength; however, stresses applied in a different direction will encounter little resistance. Therefore, only the very specific situation of one-dimensional stress can utilize the maximum possible tensile properties of the fibers. In all other cases, a tradeoff must be made between maximum strength in any one direction and load-bearing capacity in other directions. Generally, reinforcements are either unidirectional, bidirectional, or multidirectional (isotropic).

The second parameter, the amount of reinforcing fibers, is expressed by the following law of mixtures for composites:

$$S_c = V_f S_f + V_m S_m \tag{2}$$

where:

S_c = composite strength,

S_f = fiber strength,

S_m = resin matrix strength,

V_f = volume fraction of fiber, and

V_m = volume fraction of resin matrix.

This relationship must be corrected for the effects of short fiber lengths, transfer efficiency between fiber and resin, and fiber orientation. Some extremely high-strength composites have recently been introduced that employ long, unidirectionally oriented fibers in quantities up to 80%. In this case, the resin serves primarily as a means of holding the fibers in place. Figure 2.3 illustrates the combined effect of orientation and fiber quantity on composite tensile strength.

The third parameter is fiber length. The longer the fiber length in a given direction, the greater is the continuity of stress transfer in that direction and the greater is the load-bearing capacity in that direction. This benefit, of course, is subject to the same directional constraints as were discussed for fiber orientation. In addition, longer fibers are more difficult to process than shorter fibers. Consequently, fiber lengths are less than 2 in. in most applications. Attention has recently been given to shorter fiber reinforcements (i.e., 1/4 in. to 1/32 in. and less). These lengths provide ease of processing and aid in dimensional stability.

Fiberglass reinforcements come in eight principal forms: continuous strand, continuous strand roving, spun strand roving, chopped strand, milled fibers, reinforced mat, woven roving, and industrial textile yarn, the latter being used for woven fabrics. The basic unit is the glass filament, which ranges in diameter from 0.1 mils. to 0.75 mils. More than 200 filaments are gathered together to form a single fiberglass strand. Continuous strand rovings are formed by gathering a group of essentially parallel strands into a ribbon and winding them on to a cylindrical tube. In spun strand roving, the strands are looped back and forth on themselves and held in place by a slight twist and resinous sizing. Chopped strands and chopped rovings 1/8 in. to 2 in. are the most widely used reinforcement.

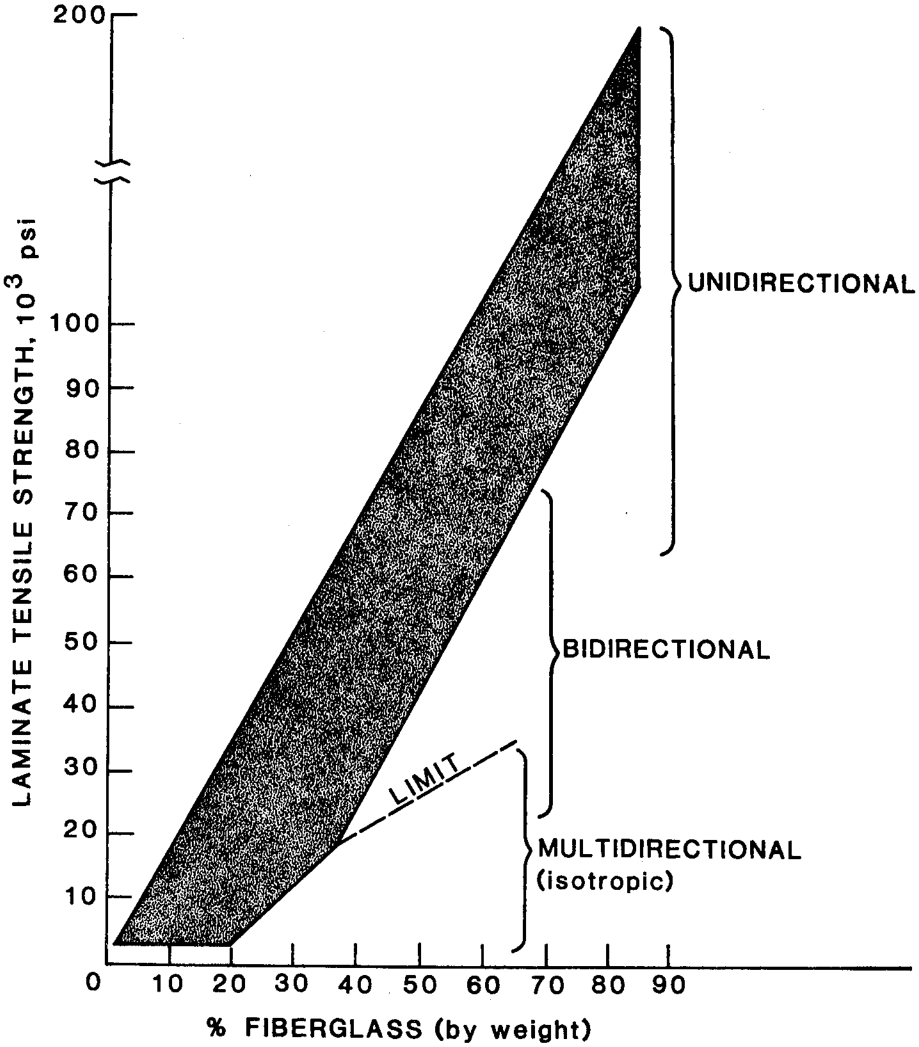

Fig. 2.3 Fiber-Reinforced Plastic Composite Tensile Strength as a Function of Fiberglass Quantity and Orientation (Source: Adapted from Ref. 6)

Milled fibers are continuous strands that have been hammer-milled into short particles of glass ranging in length from 1/64 in. to 1/4 in. Reinforced mats are formed by dropping chopped strands in a swirling pattern onto a flat surface, so that the strands are randomly oriented in a two-dimensional pattern. The strands are usually held together by resinous binders. Woven rovings are formed by weaving rovings with conventional techniques into a material weighing 12-48 oz/yd. Table 2.3 gives the relationship of fiberglass form to fiber orientation and molding processes (see Sec. 2.5).

Advanced composite materials deserve attention because of their potential future importance. However, their high cost has thus far prevented their adoption in all but specialty applications, such as sports equipment. Graphite reinforced tennis rackets and archery bows, for example, have begun to

Table 2.3 Relationship between Fiberglass Orientation, Form, and Fabricating Process

Orientation	Form	Fabricating Process
Unidirectional	Continuous strand Continuous strand roving Spun strand roving	Continuous pultrusion Filament winding Hand lay-up
Bidirectional	Woven roving Woven fabrics	Hand lay-up Filament winding
Multidirectional	Chopped strand or roving Reinforced mat Milled fibers	Hand lay-up Spray-up Compression Injection Stamping Laminating

be popular.* Additional situations may be expected to develop in the future where ACM performance benefits outweigh cost considerations. An extremely important instance where this may occur is in automobile materials usage. Standard FRP are already being introduced at a rapid rate in order to achieve improved fuel economy. If rigorous regulatory standards are imposed for the years beyond 1985,** ACM may have to be employed regardless of cost. With this in mind, Ford Motor Company built and exhibited at the 1979 SAE Exposition in Detroit an experimental car that uses ACM as much as possible. The car was designed to match the appearance and performance characteristics of the intermediate-sized Ford Granada. The impressive weight reductions achieved by displacing steel components with ACM are shown in Table 2.4.

Different kinds of ACM have been developed, including silicon carbide whiskers, carbon/graphite fibers, and aramids.[7] Whiskers are the ultimate reinforcement in that they have mechnical strengths equivalent to the forces between adjacent atoms. Their strength stems from their essentially perfect crystalline structure and their extremely small diameter. These characteristics allow little room for the defects that weaken larger crystals. Figure 2.4 shows how whisker strength increases with decreasing in diameter. Test data on sapphire whiskers have demonstrated tensile strengths greater than 4×10^6 psi and a Young's modulus greater than 100×10^6 psi. This compares with steel's tensile strength of 50×10^3 psi and Young's modulus of 28×10^6 psi. However, whiskers have not been produced commercially and their projected price is quite high.

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*The costs of ACM are expected to decrease as increased production leads to economies of scale. For example, graphite fibers now costing $20/lb are projected to decrease to less than $10/lb when annual output reaches 1×10^6 lb. Even that price, however, greatly exceeds the $0.60-0.70/lb cost of fiberglass. For this reason, hybrid systems of graphite and glass fibers have the greatest potential for high-strength applications.

**Congress has debated standards of 35-40 mpg in the 1990s. General Motors Corporation has indicated they can attain such levels.[8]

Table 2.4 Component Weight Savings in the Ford Motor Company Lightweight Vehicle Program

	Component Weight (lb)				
Component	Steel	Graphite Composite	Reduction (lb)	Reduction (%)	Weight Ratio[a]
Frame	282.8	207.2	75.6	55	0.73
Front end	96.0	29.3	66.7	27	0.31
Hood	49.0	16.7	32.3	69	0.34
Deck lid	42.8	13.9	28.9	66	0.32
Bumpers	123.1	44.4	78.7	68	0.36
Wheels	92.0	49.3	42.7	64	0.54
Doors	155.6	61.1	94.5	46	0.39
Miscellaneous[b]	69.3	35.8	33.5	61	0.52
Body-in-white[c]	461.0	208.0	253.0	48	0.45

[a] $\text{Weight ratio} = \frac{\text{ACM component weight}}{\text{steel component weight}}$.

[b] Bracketry, seat frame, and other items.

[c] Complete body structure without closure panels (e.g., doors) and trim (e.g., seats).

Source: Ref. 9.

Most discussion of ACM centers on carbon/graphite and aramid fibers. Carbon/graphite fibers have a matrix of amorphous carbon filled with acicular microcrystallite fibrils. Aramid fibers, such as Kevlar™,* consist of lightly bound bundles of relatively long polymer chains in a semiparallel array. A comparison of the tensile properties of whiskers and carbon/graphite, aramid, and glass fibers is shown in Fig. 2.5. Each ACM has a larger Young's modulus than glass fiber and, except for whiskers, has approximately the same yield strength.

2.3 FILLERS

Historically, fillers have been employed in FRP systems to reduce costs and to achieve desired flow properties. The most widely used fillers cost less than $0.20/lb, compared to $0.55-0.70/lb for the fiberglass or resin that they displace. For example, UPE resin costs $0.56-0.59/lb. Approximately 55% (by volume) resin is required to achieve the necessary wetting of fiber and filler under most conditions. During processing, the granular or platelet filler particles flow more easily than the rodlike

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*Kevlar is a registered trademark of E.I. DuPont de Nemours & Company.

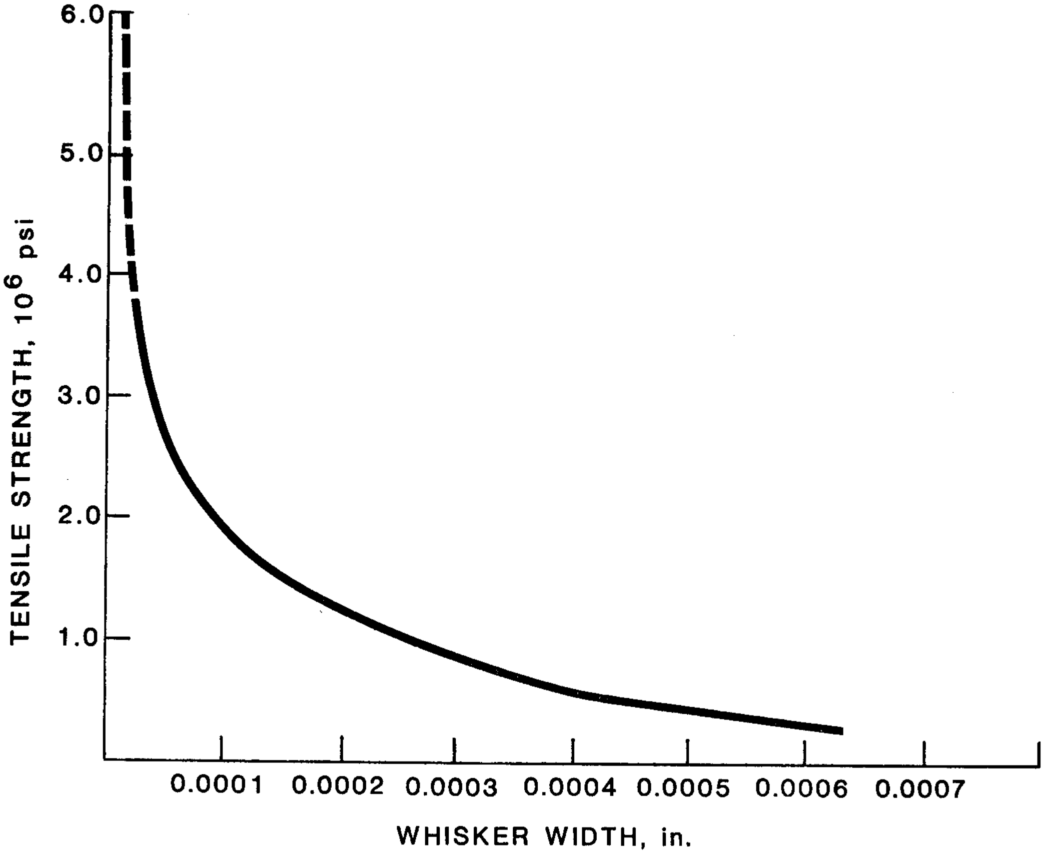

Fig. 2.4 Whisker Tensile Strength as a Function of Diameter (Source: Adapted from Ref. 7)

reinforcement fibers. Therefore, fillers reduce the pressure necessary for molding and permit more complex shapes.

The quantities of fillers consumed in 1979 and estimated consumption for 1980 are shown in Table 2.5. Calcium carbonate represents by far the largest usage, with talc minerals and clays a distant second and third. These three fillers account for 87% of total usage. An important filler, which is included under "Miscellaneous" in Table 2.5, is hydrated alumina. It furnishes good electrical properties and flame resistance.

A property of calcium carbonate that leads to its extensive usage is its low oil absorptivity. This property is a function of the specific surface of the particles, with nonporous particles absorbing less oil than porous particles of the same size. Since low oil absorptivity permits more filler to be used, other fillers often are used in conjunction with calcium carbonate to achieve a desired property. Clay, for example, provides better flow and molding properties than calcium carbonate, but is poor with regard to color. The clay usually comprises only 10-20% of the filler.

Another capability of fillers has been recently recognized, i.e., when properly matched to the resin and reinforcement system, fillers themselves provide significant reinforcement.[11] Filler manufacturers have been pursuing an active research and development program in this area in order to

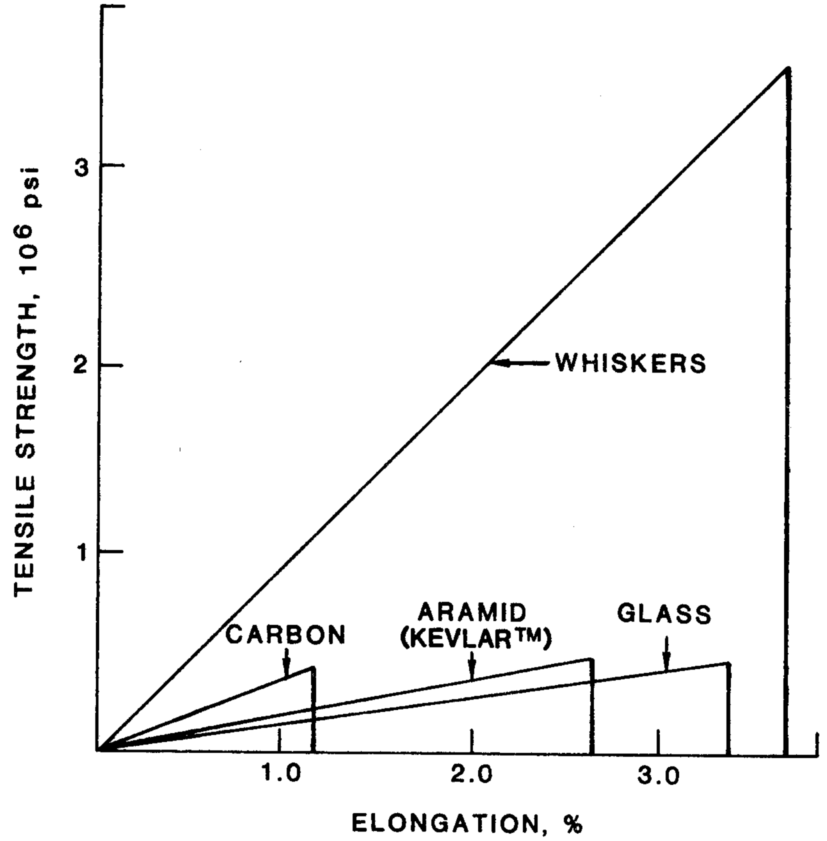

Fig. 2.5 Tensile Strength of Whiskers and Carbon, Aramid, and Glass Fibers (Source: Adapted from Ref. 7)

capitalize on the cost advantage they now have over both resin and reinforcing materials. The primary focus has been on TP resin applications, including RTP, but the results apply to TS systems as well.

The nature of the findings obtained for filler reinforcement is illustrated in Fig. 2.6. The top curve in this figure is for glass-fiber-reinforced PP, with no filler. The bottom curve is for PP with inorganic filler, but no glass reinforcement. Each of the intermediate curves represents PP with a mixture of glass-fiber reinforcement and inorganic filler. For example, the curve labeled 20% glass fiber also contains 10% filler at a total reinforcement of 30%, 20% filler at 40% reinforcement, and so on. The figure shows that a substantial fraction of the flexural strength at 40% total reinforcement can be obtained by a system containing equal parts of glass and filler. This represents a considerable cost reduction relative to the glass-only system.

2.4 MOLDING COMPOUNDS

The resin, filler, and reinforcement can be joined together during the molding operation, as is done in hand lay-up and spray-up molding. In high throughput operations, however, as is the case for most automotive

Table 2.5 Filler Consumption (10^6 lb)

Material	Consumption 1979	 1980[a]
Carbonates[b]	2805	3366
Clays	264	316.8
Cork	2.2	4.4
Glass[c]	24.2	28.6
Mica	26.4	33
Perlite	8.8	11
Shell flours[d]	11	13.2
Silicas[e]	101.2	121
Starch and cellulosics	147.4	176
Talc minerals	330	396
Wood flour	112.2	132
Miscellaneous[f]	77	92.4
Total	3909.4	4690.4

[a] Estimated.

[b] Calcium carbonate, chalk, limestone, etc.

[c] Bubbles, spheres, ground glass, etc. Does not include fiber reinforcements.

[d] Walnut shells, peanut and rice hulls, soybeans, etc.

[e] Novaculite, sand, quartz, etc.

[f] Plastic spheres, various inorganic compounds, etc.

Source: Ref. 10.

applications, a molding compound containing all the necessary chemical, filler, and reinforcement constituents is formulated at an earlier stage in the production sequence. The molding operation then consists of pressing the compound into the desired shape, holding it in position until the cure is complete, and removing the heat released during curing. Uniform heat removal is essential as the product cools from a maximum polymerization temperature slightly above 350°F. Otherwise, sink marks and surface cracks appear on the finished product.

There are three main types of molding compound: preforms, bulk molding compounds (BMCs), and sheet molding compounds (SMCs). Preforms are

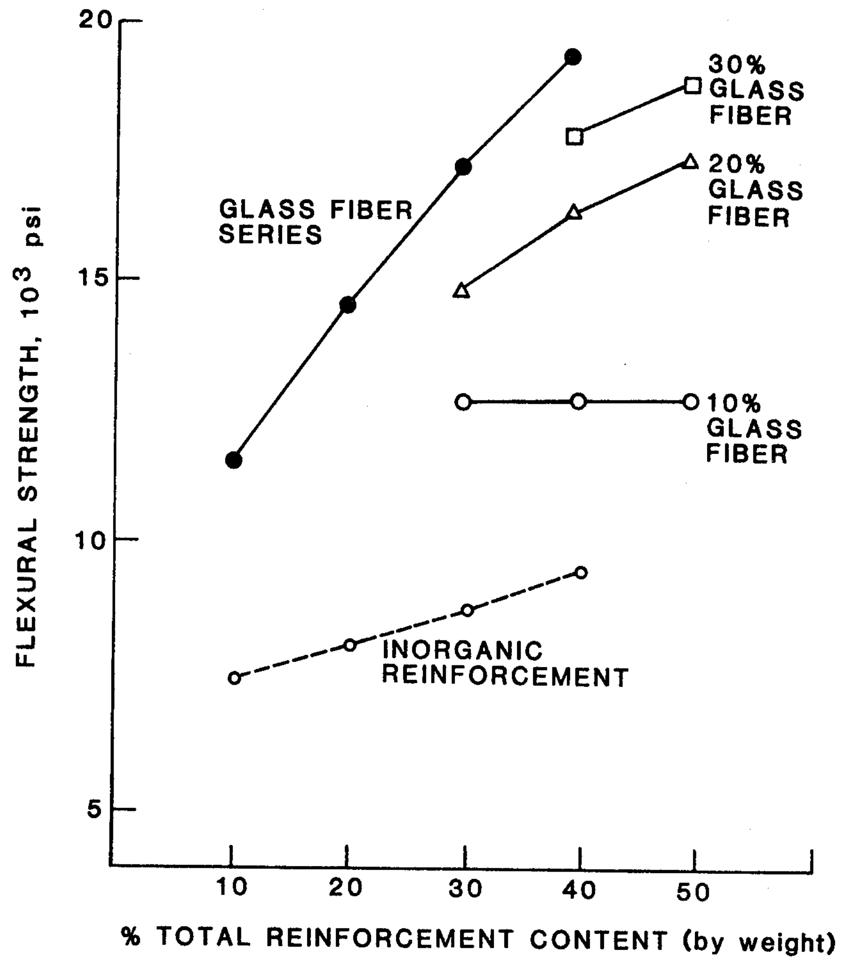

Fig. 2.6 Flexural Strength of Polypropylene as a Function of Total Reinforcement (Source: Adapted from Ref. 11)

mats of chopped strands held together by binder and formed into the approximate shape of the part to be molded. The use of preforms is gradually being phased out in most automotive applications. Bulk molding compounds are modeling-clay-like mixtures provided in bulk form or extruded into ropelike shapes to facilitate handling. The glass fibers are from 1/8 in. to 1-1/4 in. in length. As their name indicates, SMCs are assembled in sheet form. Sheet molding compounds can accommodate fiberglass lengths up to 2 in., which enhances their mechanical properties relative to BMCs. Sheet molding compounds must be layered before molding if parts of greater than 1/4 in. thickness or of variable cross section are to be formed. Recently, a thick molding compound, TMC™,* version of SMC has been developed that reduces the need for layering, thereby avoiding the internal weaknesses that such joints involve. This compound can be molded in thickness up to 2 in. However, SMC thickness suffices for most automotive needs.

The process sequence for producing SMCs is shown in Fig. 2.7. The resin mix is spread on two carrier films (e.g., polyethylene or nylon) by

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*TMC is a registered trademark of USS Chemicals.

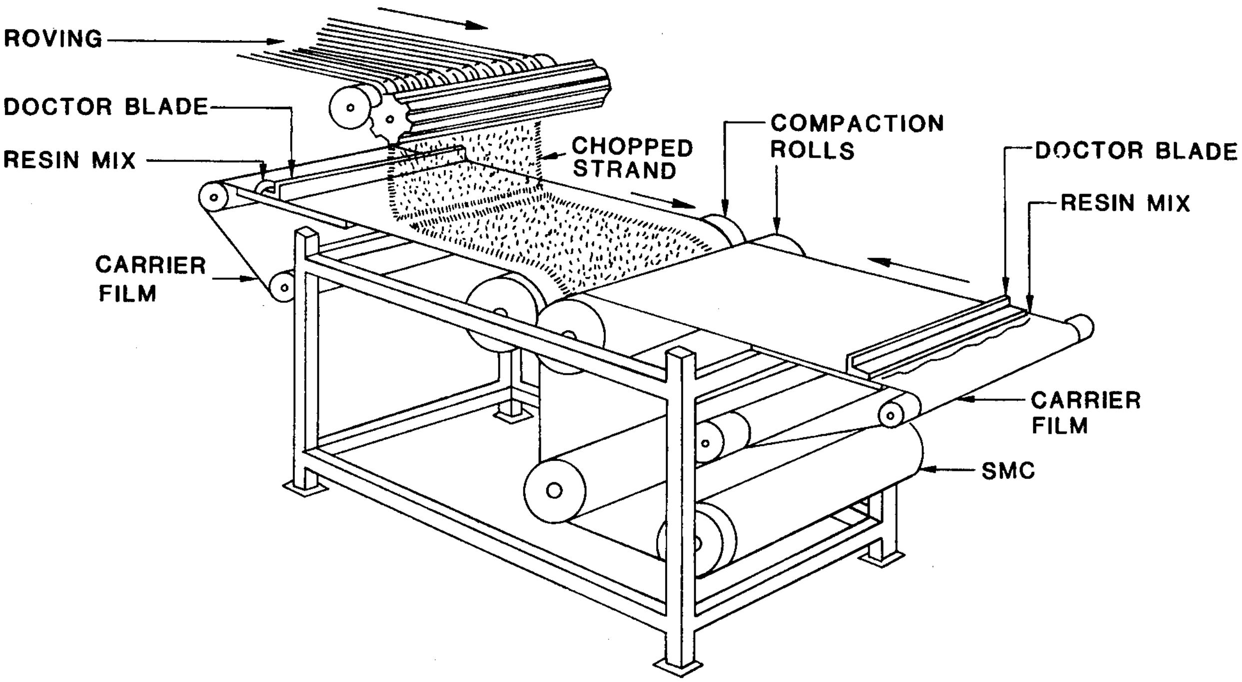

Fig. 2.7 Sheet Molding Compound Process (Source: Adapted from Ref. 6)

doctor blades. As the two films move together, chopped roving fiberglass strands are dropped in a random pattern onto one of the resin films. The two films are pressed together by compaction rolls to wet out the fiberglass and form the SMC product. The SMC is then rolled or cut up into sections and stacked in a maturation room having controlled temperature and humidity. Its apparent viscosity increases dramatically over time from 7000 cp after mixing to 15-80 x 10^6 cp. A thickening agent, such as magnesium oxide, is usually added to facilitate the thickening process. At the end of the treatment period, the SMC can be handled and shipped easily. During molding, the viscosity is initially reduced by heating; then, being pseudoplastic, the viscosity adjusts further under mold pressure so that the material flows readily.*

2.5 MOLDING PROCESSES

The second, or curing, stage of the chemical reaction sequence described in Sec. 2.1.1 takes place during the molding process. The reactive monomer participates in the development of cross-linkages between the unsaturated dibasic anhydride groups. The reaction takes place under pressure in the mold and is initially energized by heat. In addition, a catalyst, or curing agent, is usually added to the SMC formulation to insure that the reaction proceeds rapidly. Typical curing agents are benzoyl peroxide,

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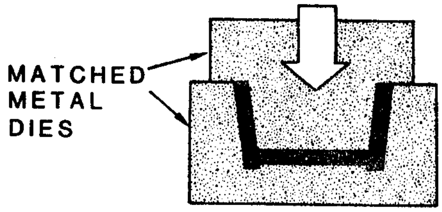
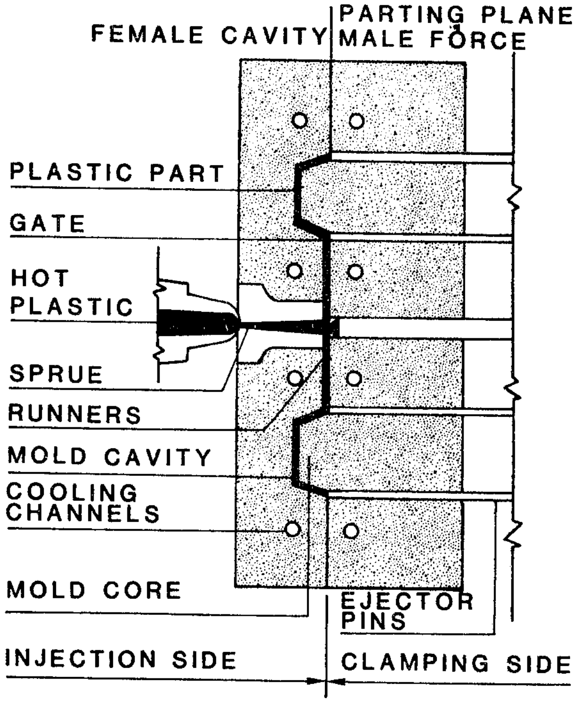
*The viscosity of pseudoplastic materials decreases as stress is increased. Thus, resistance to flow is greatest at low stress and decreases steadily as greater stress (molding pressure) is applied.

MEK-peroxide, di-t-butyl peroxide, and dicumyl peroxide. Rapid curing is extremely important. Although the actual molding operation can be completed in about 20 s, the part must remain in the mold for nearly 2 min until curing is complete. This 2-min requirement increases capital cost, because a number of molds must be operated in parallel in order to achieve the large throughputs desired in the automobile industry. For example, if the molding time were reduced to 1 min, the number of molds required for a given throughput could be nearly cut in half. The time required for curing can be contrasted with the few seconds required for a steel or aluminum stamping operation. Manufacturers of FRP have attempted to counteract this disadvantage by achieving parts consolidation, so that a single molding operation accomplishes the same function as a number of stamping and joining operations.



(a) COMPRESSION MOLDING



(b) INJECTION MOLDING

Fig. 2.8 Compression and Injection Molding, the Two Most Important Automobile Molding Processes (Source: Adapted from Refs. 12 and 13)

The two molding processes most widely used for FRP applications in the automotive industry are shown in Fig. 2.8. In compression molding, a measured amount of molding compound is placed in the heated mold, and the mold sections are forced together to form the part. After the approximately 2-min curing period, the mold is opened and the part ejected. In injection molding, on the other hand, the heated plastic is forced into a closed mold. If the FRP is based on a TP resin, the resin is heated before entering the mold, which is then cooled. For TS-resin FRP, cool material is forced into a heated mold. Compression molding is usually used for TS-resin FRP, and injection molding for TP-resin FRP. The advantages of compression molding are its ability to accommodate longer, oriented fibers and its lower scrap rate. The advantage of injection molding is higher throughput.

Additional closed-mold approaches for FRP are resin transfer and rotational molding. Pultrusion is used when continuous cross-sectional shapes are desired and is a semi-closed mold technique, whereby the filament is pulled through the die. Finally, a number of open-mold techniques are used, including hand lay-up, spray-up, and filament winding. Hand lay-up and spray-up were the earliest methods used in FRP applications. Highly labor intensive, these open-mold techniques continue to be used in special applications, such as large boat hulls. Filament winding is employed when large, symmetrical shapes with continuous, oriented fibers are desired, such as aerospace fuel tanks.

3 ENERGY REQUIREMENTS

As discussed in Sec. 2, FRP systems consist of three principal components: plastic resin, reinforcement, and filler. The relative types and quantities of each component depend on the material characteristics desired. From an energy viewpoint, the plastic resins are of greatest interest because they involve substantially larger amounts of energy and because a wide variety of alternative processes and material combinations are possible. In addition, plastic resins are the only component requiring hydrocarbon feedstocks in their manufacture.

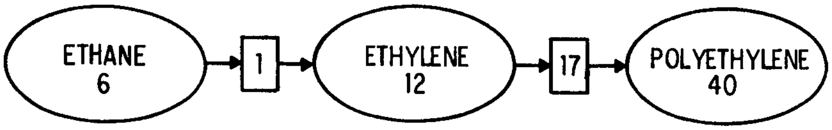
3.1 PLASTIC RESINS

3.1.1 Chemical Process Sequences

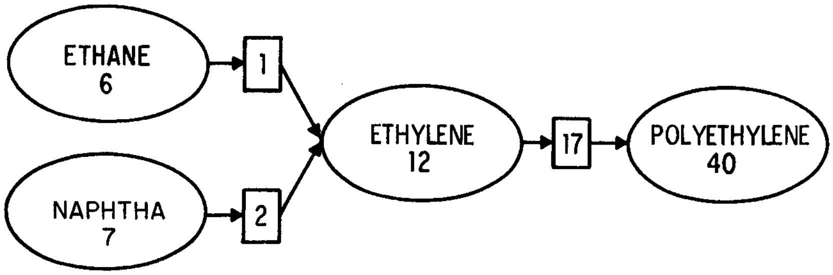
Each plastic resin is the end product of a process sequence derived from one or more hydrocarbon feedstocks. The nature of such process sequences can be most easily described by considering a specific example, polyethylene manufacture. Figure 3.1(a) indicates that polyethylene can be manufactured via a two-step process sequence starting with ethane as the feedstock. In order to determine the feedstock and process energies attributable to polyethylene production via this sequence, it is necessary to trace back along the sequence, accumulating the relevant energies at each step. Thus, process energy includes the energy consumed in processes 17 and 1, the latter being weighted for level of participation. (The manner of weighting process and feedstock participations is described in Sec. 3.1.2.) The feedstock energy is the combustion energy of the amount of ethane required to produce 1 lb of polyethylene.

Ethylene also can be manufactured from alternative sets of raw materials via different process sequences as illustrated in Fig. 3.1(b). This diagram indicates that ethylene can be manufactured by two alternative process sequences, from naphtha as well as from ethane. Other feedstocks include propane, butane, refinery gas, and gas oils (atmospheric and vacuum gas oil). In fact, approximately 50% of the ethylene manufactured in the United States is derived from naphtha and gas oils. For the sequences illustrated by Fig. 3.1(b), it is necessary to allocate the energy requirements between the two branches in proportion to the relative participation of each. These participations, termed process splits, must be determined before the sequence energies can be calculated.

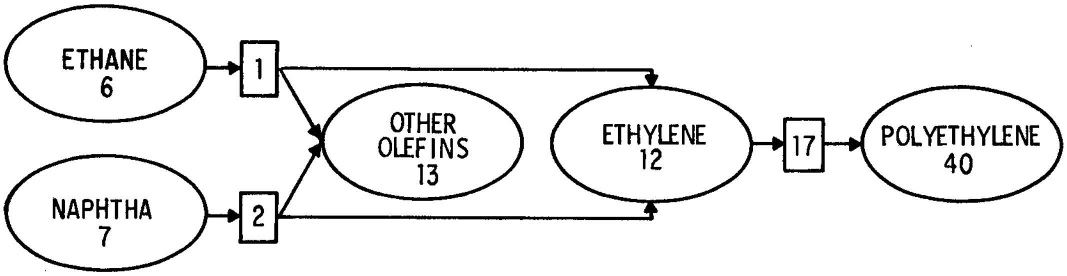
An additional complexity is that chemical processes frequently produce more than one marketable product. This is illustrated in Fig. 3.1(c). Other olefins (e.g., propylene and butadiene) are produced in processes 1 and 2. If the additional products are of equivalent value, they are termed coproducts. If they are of significantly less value, the economics of the process are dominated by the main product and the additional products are known as by-products. In either case, it is important that the energy costs of the process be allocated among all products. The energy costs could be allocated in a number of ways, e.g., by the economic value or by the embodied energy of the various outputs. However, allocation usually is made on the



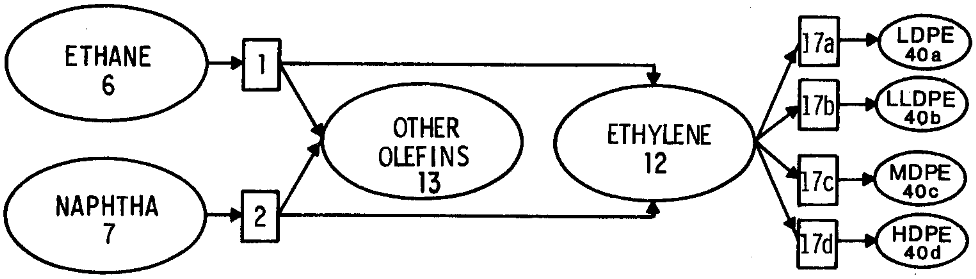
(a) TWO-STEP PROCESS SEQUENCE



(b) PROCESS AND RAW MATERIAL ALTERNATIVES



(c) COPRODUCTS



(d) CLOSELY RELATED PRODUCTS

OVALS DENOTE MATERIALS;
BOXES DENOTE PROCESSES

Fig. 3.1 Chemical Process Sequences

basis of weight shares of the product output. Thus, if α lb of product A and β lb of product B are produced from a process requiring P_c units of process energy, the energy cost to A is specified as $[\alpha/(\alpha + \beta)]P_c$ and that of B as $[\beta/(\alpha + \beta)]P_c$. Feedstock energy allocations are made in the same way.

Another aspect of process sequences is shown in Fig. 3.1(d). In this case, four different, but closely related, plastic resins can be produced from ethylene. The four products are LDPE, linear-low-density polyethylene (LLDPE), medium-density polyethylene (MDPE), and HDPE. These products require different catalyst systems and reaction conditions (e.g., temperature and pressure) and have significantly different characteristics. In addition, the energy requirements can be quite different, even for the same product. For example, a recent development in LLDPE manufacture has reduced the process energy requirements for process 17b by 45%. However, most of the process energy rquirements for processing LLDPE occur at earlier steps in the process sequence. This highlights the fact that energy analyses of chemical production processes must be made within the context of the overall process.

An additional property of petrochemicals necessitating that their economic and energy aspects be appraised within the process sequence context is shown in Fig. 3.2. This diagram illustrates how: (1) ethylene acts as a full participant in process sequences leading to three competing plastic end products (HDPE, PS, and PVC), and (2) propylene, which is produced as a coproduct to ethylene in processes 1 and 2, acts within another process sequence leading to a fourth plastic end product, PP. In fact, ethylene participates in many other process sequences leading to both plastic and nonplastic end products. A comparable situation with respect to metals would be if steel and aluminum were produced as coproducts in several processes and then were employed as key ingredients in the manufacture of other metallic products, such as copper and zinc. Metal alloys are produced, of course, but in most instances one metal plays the dominant role. Petrochemicals are unique in the diversity of products that can be obtained from a single feedstock. In a way, this has a simplifying effect. No matter which chemical end product wins out, the demand for olefins (ethylene, propylene, and butylenes) will be generally maintained. Although there are several other important chemicals, especially the aromatics (benzene, toluene, and xylene), olefins are the central participants in the petrochemical industry. Thus, energy conservation achieved in their manufacture reduces the energy/product ratio for nearly all petrochemicals.

Figures 3.1 and 3.2 illustrate what must be taken into account in determining plastic resin energy requirements. However, the sequence examined in Fig. 3.1 is one of the simplest to be encountered for plastic resins. The more complex sequences will be illustrated through an examination of the

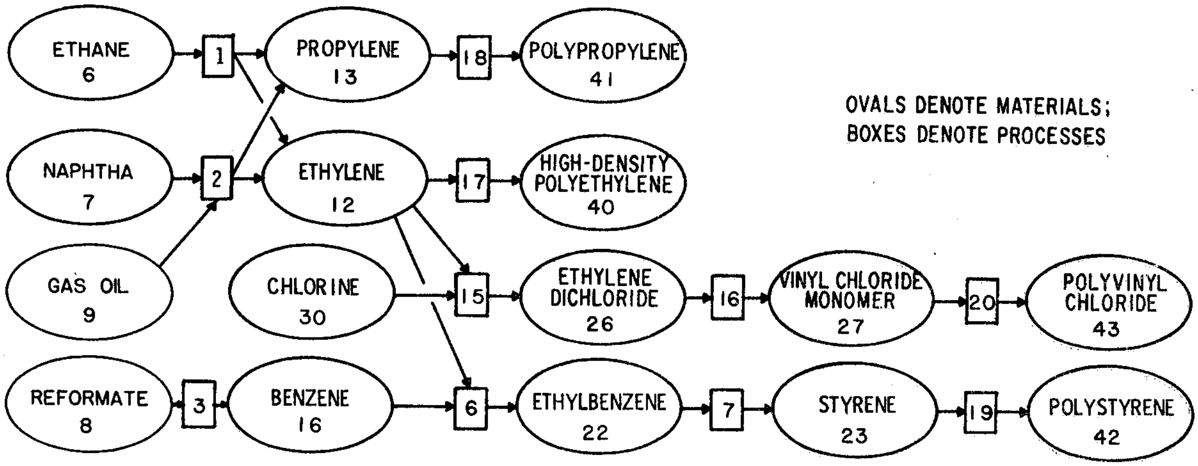


Fig. 3.2 Interrelationships among Market-Competitive Plastic Resins

process sequences involved in UPE manufacture. First, though, a general set of equations will be developed to enable systematic evaluation of process and feedstock energies, even for the more complex situations.

3.1.2 Sequence Energy Computations

To evaluate sequence energies, it is necessary to establish nomenclature regarding the participating materials, processes, and their interrelationships. Figure 3.3 depicts a generic sequence configuration that includes the major parameters. Here, material 4 is made from material 3 via process 3. The pounds of material 3 required to produce 1 lb of material 4 via process 3 is given by $a^3_{4,3}$, where the superscript denotes the process and the two subscripts denote, respectively, the output and input materials. This variable is known as an input coefficient, since it identifies the necessary input quantity for a unit output.* The process energy of process 3 is designated as P_3.

Moving back along the process sequence, material 3 can be made from either material 1 or material 2. In any given year, the fraction of material 3 made from material 1 via process 1 is given by x^3_1. This variable is known as the process split. Likewise, the fraction of material 3 made via process 2 is designated x^3_2; the superscript denotes the output material and the subscript denotes the process. Since the two processes encompass all contributions to production of material 3, $x^3_1 + x^3_2 = 1$. The other variables shown for processes 1 and 2 have the same meaning as the equivalent variables defined for process 3.

The final variables in Fig. 3.3 are the feedstock energies, f_1 and f_2. These represent the combustion energies of materials 1 and 2. In most

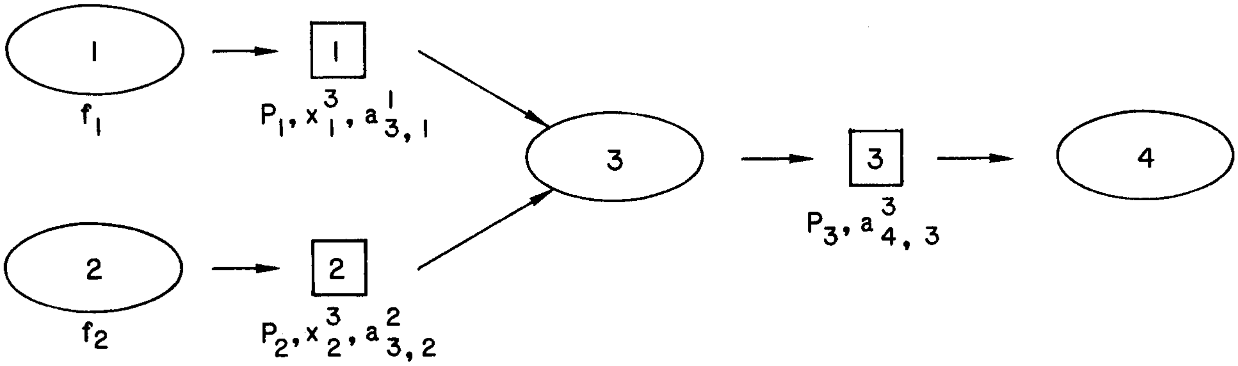


Fig. 3.3 Configuration and Parameters of a Generic Process Sequence

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*Output coefficients, on the other hand, designate where the outputs of a given material go. For example, if material 3 contributes to production of materials 4, 10, and 12, its output coefficients would identify for each pound of material 3, what fraction of the pound enters into production of each of the three materials.

evaluations, the convention is to take the higher heating value (HHV) as the representative combustion energy. Higher heating value is defined as the total heat released when the hydrocarbon is completely converted to carbon dioxide and water at 25°C and constant pressure and when the water is condensed to release its latent heat of vaporization. Lower heating value (LHV) is obtained by subtracting water's latent heat of vaporization from the HHV.

As Fig. 3.3 shows, the first step in evaluating the energies associated with process sequences leading to plastic end products is to characterize the individual participating processes. Each process must be defined as to the quantity of inputs -- materials and energy -- required to produce the desired output. For example, consider the production of ethylene from ethane, shown as process 1 of Fig. 3.1(c). Ethylene is produced as the principal product, accompanied by a set of olefin coproducts. The material and energy requirements of this and related processes are examined in Refs. 14 and 15. Using the nomenclature just defined, the material and energy requirements of process 1 were found to be:

$$a^1_{12,6} = 1.27 \tag{3}$$

$$f_6 = 22.3 \times 10^3 \text{ Btu/lb}$$

$$P_1 = 3.76 \times 10^3 \text{ Btu/lb (fuel)}$$

Feedstock requirements cannot generally be assigned to a specific process, because they also depend on the preceding steps in the process sequence. In this case, however, ethylene production acts as the first step in the sequence. As a result, the feedstock energy requirement can be directly determined:

$$\begin{aligned} f^s_{12} &= a^1_{12,6}(f_6) \\ &= 1.27(22.3 \times 10^3) \\ &= 28.3 \times 10^3 \text{ Btu/lb} \end{aligned} \tag{4}$$

where f^s_{12} is the sequence feedstock energy of producing material 12 (ethylene) from material 6 (ethane) via the one-step process sequence (process 1). The sequence process energy of the one-step sequence is:

$$\begin{aligned} P^s_{12} &= P_1 \\ &= 3.76 \times 10^3 \text{ Btu/lb} \end{aligned} \tag{5}$$

More generally, process energy can be aggregated into three overall categories: fuels, electric power, and steam. Fuels are usually expressed directly in thousand British thermal units required. Electric power is expressed in kilowatt hours required. Electric power can be converted into fuel equivalents by specifying the thermal factor, e.g., British thermal units per kilowatt hour. If the overall efficiency of electricity generation is taken to be 34.12%, the thermal value of the electric power requirements is obtained in thousand British thermal units per pound by multiplying kilowatt hours by 10. Steam requirements are usually expressed in terms of the pressure required. This suffices to designate both the steam temperature and energy content at saturation. Saturated steam between pressures of 100 psi and 3000 psi has an enthalpy ranging from 1000 Btu/lb to 1200 Btu/lb, while typical steam generation efficiency ranges from 85% to 90%. A reasonable estimate can be made by assigning steam the average energy value of 1.2×10^3 Btu/lb, as its energy does not vary widely over the usable pressure range. Process energy can then be calculated by the formula:

$$P_\alpha = F_\alpha + (10)(K_\alpha) + (1.2)(S_\alpha) \qquad (6)$$

where:

P_α = process energy per unit output of process α (10^3 Btu/lb),

F_α = fuel requirements per unit output of process α (10^3 Btu/lb),

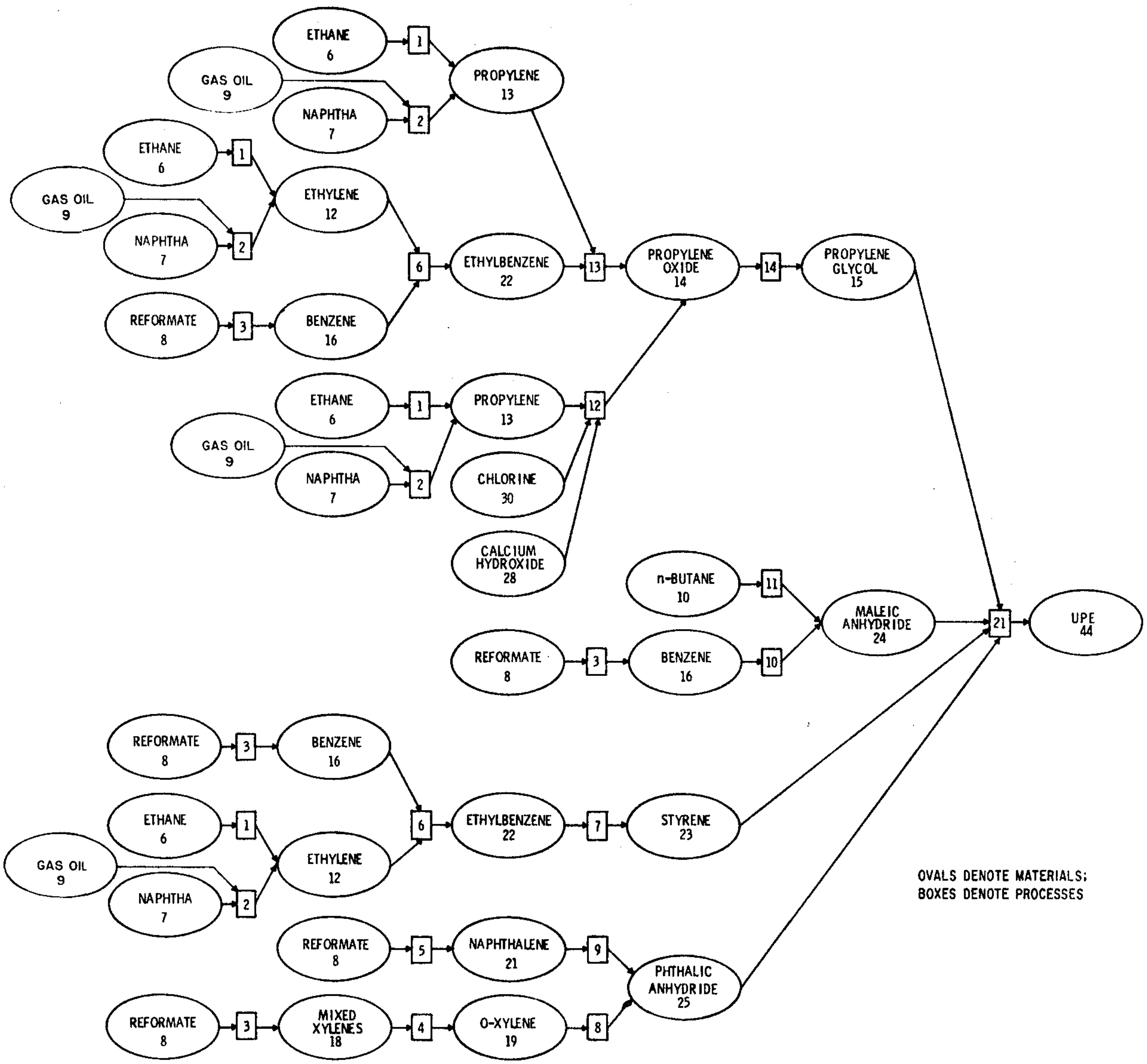
K_α = electricity requirements per unit output of process α (kWh/lb), and

S_α = steam requirements per unit output of process α (lb/lb).

As illustrated by the polyethylene example, calculation of sequence energies -- process and feedstock -- requires knowledge of the materials requirements of each process, the process splits, the individual process energies, and the feedstock energies. The approach to computing sequence energies will now be developed for specific plastic end products. Five plastic resins widely used in the automobile industry will be considered: HDPE, PP, PS, PVC, and UPE resins. The UPE resins are of greatest interest since, as discussed in Sec. 2, these TS resins are by far the most widely employed for FRP. The other four, which are TP resins, are more extensively used in general, and their use in FRP is increasing.

The first step in assessing the sequence energies of each resin is to identify the specific pathways leading from feedstock to resin. This is done for the four TP resins in Fig. 3.2 and for UPE in Fig. 3.4. The nomenclature used in these figures will facilitate later computation of sequence energies. The descriptive names and numerical designations used in these figures are listed for the materials and processes in Tables 3.1 and 3.2, respectively.

Examination of the five plastics process sequences in Figs. 3.2 and 3.4 shows that the complexity of the sequences varies considerably. Polyethylene and PP are both relatively simple sequences, involving only three processes. Polystyrene and PVC are of intermediate complexity, involving six and five processes, respectively. Unsaturated polyester resins are of significantly greater complexity, involving 25 processes. In addition, each of these process sequences involves even greater variety or complexity than is shown in the figures. For example, ethylene can be made from ethane, propane, liquid petroleum gas (LPG), naphtha, gas oil, and coal. Commercial processes already exist for each of these raw materials, except coal, and coal processes are being developed. Energy requirements vary among processes using different raw materials and among different commercial processes. Thus, while the two processes shown for olefin manufacture (processes 1 and 2) are representative of the range of processes employed, they are not the complete set.



OVALS DENOTE MATERIALS;
BOXES DENOTE PROCESSES

Fig. 3.4 Unsaturated Polyester Resin Process Sequence

Having identified the process sequence pathways, sequence energies can be determined. The formulas for doing this for a three-step sequence (processes α, β, and γ) are:

$$P_i^s = \sum_\alpha x_\alpha^i \left[P_\alpha + \sum_j a_{i,j}^\alpha \left(\sum_\beta x_\beta^j \left\{P_\beta + \sum_k a_{j,k}^\beta \left[\sum_\gamma x_\gamma^k \left(P_\gamma\right)\right]\right\}\right)\right] \qquad (7)$$

for process energy and

$$f_i^s = \sum_\alpha x_\alpha^i \left[\sum_j a_{i,j}^\alpha \left(\sum_\beta x_\beta^j \left\{\sum_k a_{j,k}^\beta \left[\sum_\gamma x_\gamma^k \left(\sum_i a_{k,l}^\gamma\ f_\theta\right)\right]\right\}\right)\right] \qquad (8)$$

for feedstock energy where:

P_i^s = sequence process energy of chemical i,

x_α^i = fraction of chemical i manufactured via process α,

a^{α}_{ij} = weight of chemical j used in the production of 1 lb of chemical i via process α,

P_{α} = process energy of process α,

f^{s}_{i} = sequence feedstock energy of chemical i, and

f_{θ} = heat of combustion of feedstock θ.

Equation 7 solves for the sequence process energy given the process splits, individual process energies, and chemical inputs for each process. Equation 8 solves for the sequence feedstock energy given the process splits, chemical inputs, and feedstock heats of combustion. The formulas for longer or shorter sequences can be easily established by extending or contracting the repeating elements of Eqs. 7 and 8.

In order to proceed with the sequence energy computations for the five plastics, the data specified in Eqs. 6–8 must be assembled for the 21 processes listed in Table 3.2. These data are available in Refs. 11 and 12, and are summarized in Tables 3.3 and 3.4. Table 3.3 lists the chemical inputs in rows and the processes in columns. Thus, the entry 0.741 in row 16, column 6 indicates that 0.741 lb of chemical 16 (benzene) are used in process 6 (ethylbenzene production). Using the nomenclature defined for Eqs. 7 and 8, $a^{6}_{22,16} = 0.741$. Row 4 gives the individual process energies computed using Eq. 6. The combustion energy (HHV) of each feedstock is shown in brackets beside its name. The process splits (see Table 3.4) are given separately because, in the case of coproducts, the process participations may

Table 3.1 Utilities and Materials Participating in Plastics Manufacture

Utilities	
1	Fuel
2	Electricity
3	Steam
4	Process energy
Feedstocks	
6	Ethane
7	Naphtha
8	Reformate
9	Gas oil
10	n-Butanes
Plastic resins	
40	High-density polyethylene
41	Polypropylenes
42	Polystyrene
43	Polyvinyl chloride
44	Unsaturated polyester
Chemical intermediates	
12	Ethylene
13	Propylene
14	Propylene oxide
15	Propylene glycol
16	Benzene
18	Mixed xylenes
19	o-Xylene
21	Naphthalene
22	Ethylbenzene
23	Styrene
24	Maleic anhydride
25	Phthalic anhydride
26	Ethylene dichloride
27	Vinyl chloride monomer
28	Calcium hydroxide
30	Chlorine

Table 3.2 Processes Participating in Plastics Manufacture

1. Olefins from ethane and propane via fired tubular reactor
2. Olefins from naphtha and gas oil via fired tubular reactor
3. Benzene-toluene-xylene from reformate via solvent extraction
4. o- and p-Xylene from mixed xylenes via distillation and molecular sieves
5. Naphthalene from reformate via dealkylation
6. Ethylbenzene from ethylene and benzene via catalytic alkylation
7. Styrene from ethylbenzene via dehydrogenation
8. Phthalic anhydride from o-xylene via tubular reactor
9. Phthalic anhydride from naphthalene via tubular reactor
10. Maleic anhydride from benzene via catalytic oxidation
11. Maleic anhydride from n-butanes via catalytic oxidation
12. Propylene oxide from propylene, chlorine, and calcium hydroxide via chlorohydrin process
13. Propylene oxide from propylene and ethylbenzene via hydroperoxide process
14. Propylene glycol from propylene oxide via hydration
15. Ethylene dichloride from ethylene and chlorine via oxychlorination
16. Vinyl chloride monomer from ethylene dichloride via pyrolysis
17. High-density polyethylene from ethylene via Ziegler catalysis in bulk polymerization
18. Polypropylene from propylene via Ziegler catalysis in solution polymerization
19. Polystyrene from styrene via bulk polymerization
20. Polyvinyl chloride from vinyl chloride monomer via suspension polymerization
21. Unsaturated polyester from maleic anhydride, phthalic anhydride, propylene glycol, and styrene via batch polymerization

Table 3.3 Input Coefficients and Process Energies for Selected Plastic Resin Sequences

Utilities and Materials	1 Olefins from Ethane/ Propane	2 Olefins from Naphtha/ Gas Oil	3 BTX (reformate)	4 o-Xylene/ p-Xylene (mixed xylenes)	5 Naphthalene (reformate)	6 Ethylbenzene	7 Styrene	8 Phthalic Anhydride from o-Xylene
Utilities								
1 Fuel (10^3 Btu)	3.76			7.57	6.96	(-)0.30	1.55	
2 Electricity (kWh)			0.006	0.016	0.074		0.039	0.41
3 Steam (lb)			1.57	0.35	0.70		4.0	
4 Process energy (10^3 Btu)	3.76		1.95	8.13	8.50	(-)0.30	6.43	4.10
Feedstocks								
6 Ethane/propane (22.3 x 10^3 Btu)	1.27							
7 Naphtha (20.4 x 10^3 Btu)		0.59						
8 Reformate (19.6 x 10^3 Btu)			1.0		1.053			
9 Gas oil (19.6 x 10^3 Btu)		0.69						
10 n-Butanes (21.2 x 10^3 Btu)								
Chemical intermediates[a]								
12 Ethylene						0.266		
13 Propylene								
14 Propylene oxide								
15 Propylene glycol								
16 Benzene						0.741		
18 Mixed xylenes				1.01				
19 o-Xylene								0.97
21 Naphthalene								1.09
22 Ethylbenzene							1.12	
23 Styrene								
24 Maleic anhydride								
25 Phthalic anhydride								
26 Ethylene dichloride								
27 Vinyl chloride monomer								
28 Calcium hydroxide								
30 Chlorine								

Table 3.3 (Cont'd)

Utilities and Materials	9 Phthalic Anhydride from Naphthalene	10 Maleic Anhydride from Benzene	11 Maleic Anhydride from n-Butanes	12 Propylene Oxide via Chlorohydrin	13 Propylene Oxide via Hydroperoxide	14 Propylene Glycol	15 Ethylene Dichloride via Oxychlorination
Utilities							
1 Fuel (10^3 Btu)				18.7	8.0		
2 Electricity (kWh)	0.41	0.79	0.72			0.07	0.013
3 Steam (lb)							
4 Process Energy (10^3 Btu)	4.10	7.90	7.20	18.7	8.0	0.7	0.13
Feedstocks							
6 Ethane/propane (22.3×10^3 Btu)							
7 Naphtha (20.4×10^3 Btu)							
8 Reformate (19.6×10^3 Btu)							
9 Gas oil (19.6×10^3 Btu)							
10 n-Butanes (21.2×10^3 Btu)			1.21				
Chemical intermediates							
12 Ethylene							0.294
13 Propylene				0.94	0.229		
14 Propylene oxide						0.75	
15 Propylene glycol							
16 Benzene		1.16					
18 Mixed xylenes							
19 o-Xylene							
21 Naphthalene							
22 Ethylbenzene							
23 Styrene					1.18		
24 Maleic anhydride							
25 Phthalic anhydride							
26 Ethylene dichloride							
27 Vinyl chloride monomer							
28 Calcium hydroxide				1.09			
30 Chlorine				1.59			0.387

Table 3.3 (Cont'd)

Utilities and Materials	16 Vinyl Chloride Monomer	17 High-Density Polyethylene	18 Polypropylene	19 Polystyrene	20 Polyvinyl Chloride	21 Unsaturated Polyester
Utilities						
1 Fuel (10^3 Btu)	3.7					0.30
2 Electricity (kWh)	0.03	0.375	0.27	0.119	1.04	0.025
3 Steam (lb)		2.5	2.1	0.38	0.082	0.243
4 Process Energy (10^3 Btu)	4.0	6.60	5.20	1.63	1.86	0.83
Feedstocks						
6 Ethane/propane (22.3 x 10^3 Btu)						
7 Naphtha (20.4 x 10^3 Btu)						
8 Reformate (19.6 x 10^3 Btu)						
9 Gas oil (19.6 x 10^3 Btu)						
10 n-Butanes (21.2 x 10^3 Btu)						
Chemical intermediates						
12. Ethylene		1.02				
13. Propylene			1.045			
14. Propylene oxide						
15. Propylene glycol						0.28
16. Benzene						
18. Mixed xylenes						
19. o-Xylene						
21. Naphthalene						
22. Ethylbenzene						
23. Styrene				0.983		0.35
24. Maleic anhydride						0.16
25. Phthalic anhydride						0.21
26. Ethylene dichloride		1.61				
27. Vinyl chloride monomer					1.02	
28. Calcium hydroxide						
30. Chlorine						

[a] Numbers are not consecutive.

Table 3.4 Process Splits

	Material	1 Olefins from Ethane/ Propane	2 Olefins from Naphtha/ Gas Oil	8 Phthalic Anhydride from o-Xylene	9 Phthalic Anhydride from Naphthalene	10 Maleic Anhydride from Benzene	11 Maleic Anhydride from n-Butanes	12 Propylene Oxide via Chlorohydrin	13 Propylene Oxide via Hydroperoxide
12	Ethylene	0.55	0.45						
13	Propylene	0.25	0.75						
14	Propylene oxide							0.6	0.4
24	Maleic anhydride					0.8	0.2		
25	Phthalic anhydride			0.7	0.3				

differ among products. In olefins manufacture, for example, more ethylene is produced from ethane and more propylene from naphtha.

Use of Eqs. 7 and 8 and the data in Tables 3.3 and 3.4 can be illustrated by considering HDPE and UPE, which lie at opposite ends of the sequence complexity spectrum. From Eq. 7, the sequence process energy of HDPE is given by:

$$P^{s}_{40} = P_{17} + a^{17}_{40,12}(x^{12}_{1}P_{1} + x^{12}_{2}P_{2}) \tag{9}$$

where $x^{40}_{17} = 1$. Inserting the values given in Tables 3.3 and 3.4 for process energies, chemical inputs, and process splits (with energies expressed in 10^3 Btu/lb.

$$p^{s}_{40} = 6.60 + 1.02(0.55)(3.76) \tag{10}$$

In this case, $P_2 = 0$ because all the fuel energy requirements are satisfied by combustion by-products generated during feedstock conversion. Proceeding in the same manner, Eq. 7 can be used to calculate sequence feedstock energy:

$$\begin{aligned} f^{s}_{40} &= a^{17}_{40,12}\Bigl[x^{12}_{1}a^{1}_{12,6}\ f_{6} + x^{2}_{12}(a^{2}_{12,7}\ f_{7} + a^{2}_{12,9}\ f_{9})\Bigr] \\ &= 1.02[(0.55)(1.27)(22.4) + (0.45)(0.59)(20.2) \\ &\quad + (0.45)(0.69)(19.6)] \\ &= 27.64 \text{ x } 10^{3} \text{ Btu/lb} \end{aligned} \tag{11}$$

The total sequence energy required to manufacture HDPE resins is then:

$$\begin{aligned} t^{s}_{40} &\equiv P^{s}_{40} + f^{s}_{40} \\ &\equiv 36.35 \text{ x } 10^{3} \text{ Btu/lb} \end{aligned} \tag{12}$$

Computations for UPE proceed in the same manner, but are substantially more complex. Equation 7, yields for sequence process energy:

$$\begin{aligned} P^{s}_{44} = P^{44}_{21} &+ a^{21}_{44,15}\Biggl[P_{14} + a^{14}_{15,14}\Biggl(x^{14}_{12}\Bigl\{P_{12} \\ &+ a^{12}_{14,13}\Bigl[x^{13}_{1}\ P_{1} + x^{13}_{2}\ P_{2}\Bigr]\Bigr\} + x^{14}_{13}\Bigl\{P_{13} \\ &+ a^{13}_{14,13}\Bigl[x^{13}_{1}\ P_{1} + x^{13}_{2}\ P_{2}\Bigr] + a^{13}_{14,22}\Bigl[P_{6} \\ &+ a^{6}_{22,12}\Bigl(x^{12}_{1}\ P_{1} + x^{12}_{2}\ P_{2}\Bigr) + a^{6}_{22,16}\ P_{3}\Bigr]\Bigr\}\Biggr)\Biggr] \\ &+ a^{21}_{44,23}\Biggl[P_{7} + a^{7}_{23,22}\Biggl(P_{6} + a^{6}_{22,12}\Bigl\{x^{12}_{1}\ P_{1} \\ &+ x^{12}_{2}\ P_{2}\Bigr\} + a^{6}_{22,16}\ P_{3}\Biggr)\Biggr] + a^{21}_{44,24}\Biggl[x^{24}_{10}\Biggl(P_{10} \end{aligned} \tag{13}$$

$$+ a_{24,16}^{10} P_3\Bigr) + x_{11}^{24} P_{11}\Bigr] + a_{44,25}^{21} \Bigl[x_8^{25} \Bigl(P_8$$

$$+ a_{25,19}^{8} \Bigl\{P_4 + a_{19,18}^{4} P_3\Bigr\}\Bigr) + x_9^{25} \Bigl(P_9 + a_{25,21}^{9} P_5\Bigr)\Bigr]$$

Clearly, the number of terms required for the UPE sequence process energy computation is much greater than for HDPE. Nevertheless, all of the necessary information is contained in Tables 3.3 and 3.4, and the evaluation procedure remains the same. The result for UPE sequence process energy is 12.47 x 10^3 Btu/lb.

The comparable equation for the UPE sequence feedstock energy is:

$$f_{44}^{s} = a_{44,15}^{21} a_{15,14}^{14} \Bigl(x_{12}^{14} \Bigl\{a_{14,13}^{12} \Bigl[x_1^{13} a_{13,6}^{1} f_6 \tag{14}$$

$$+ x_2^{13} \Bigl(a_{13,7}^{2} f_7 + a_{13,9}^{2} f_9\Bigr)\Bigr] + a_{14,28}^{12} f_{28}$$

$$+ a_{14,30}^{12} f_{30}\Bigr\} + x_{13}^{14} \Bigl\{\Bigl[a_{14,13}^{13} + a_{22,12}^{6}\Bigr]$$

$$\Bigl[x_1^{13} a_{13,6}^{1} f_6 + x_2^{13}\Bigl(a_{13,7}^{2} f_7 + a_{13,9}^{2} f_9\Bigr)\Bigr]$$

$$+ a_{22,16}^{6} a_{16,8}^{3} f_8\Bigr\}\Bigr) + a_{44,23}^{21} a_{23,22}^{7} \Bigl\{a_{22,12}^{6}$$

$$\Bigl[x_1^{12} a_{12,6}^{1} f_6 + x_2^{12}\Bigl(a_{12,7}^{2} f_7 + a_{12,9}^{2} f_9\Bigr)\Bigr] + a_{22,16}^{6}$$

$$a_{16,8}^{3} f_8\Bigr\} + a_{44,24}^{21} \Bigl(x_{10}^{24} a_{24,16}^{10} a_{16,8}^{3} f_8$$

$$+ x_{11}^{24} a_{24,10}^{11} f_{10}\Bigr) + a_{44,25}^{21} \Bigl(x_8^{25} a_{25,19}^{8}$$

$$a_{19,18}^{4} a_{18,8}^{3} f_8 + x_9^{25} a_{25,21}^{9} a_{21,8}^{5} f_8\Bigr)$$

Substituting the data from Tables 3.3 and 3.4 into this equation, the UPE sequence feedstock energy is 22.16 x 10^3 Btu/lb. The total sequence energy for UPE is:

$$t_{44}^{s} = P_{44}^{s} + f_{44}^{s} \tag{15}$$

$$= 34.63 \times 10^3 \text{ Btu/lb}$$

The sequence energies for UPE, HDPE, and the other three TP resins are given in Table 3.5. The values are expressed in both unit weight and unit volume terms. Both are important because energy comparisons (e.g., between plastics and steel) depend on the specific application. Since plastics are approximately seven times lighter than steel (0.040 lb/in.^{3} for UPE versus 0.284 lb/in.^{3} for steel), the volume of each product for a given function has a significant impact on the comparison. The energy required to fabricate a typical steel product is 24.8 x 10^3 Btu/lb, or 7.04 Btu/in.^{3}. Thus, relative

Table 3.5 Plastic Resin Sequence Energies

Plastic	Density (lb/in.^{3})	Energy/Weight: Process Energy (10^3 Btu/lb)	Energy/Weight: Feedstock Energy (10^3 Btu/lb)	Energy/Weight: Total Energy (10^3 Btu/lb)	Total Energy/Volume (10^3 Btu/in.^{3})
High-density polyethylene	0.0343	8.71	27.64	36.35	1.25
Polypropylene	0.0325	6.18	27.24	33.42	1.09
Polystyrene	0.0379	8.17	23.94	32.11	1.22
Polyvinyl chloride[a]	0.0433	15.50	13.11	28.61	1.24
Unsaturated polyester[a]	0.0404	12.47	22.16	34.63	1.40

[a] The sequence process energies for polyvinyl chloride and unsaturated polyester include the process energy contribution from chlorine manufacture, although this process is not shown in Figs. 3.2 and 3.4. Process energy for chlorine is estimated to be 9.75 x 10^3 Btu, based on 26% mercury cell and 74% diaphragm cell participation and energy allocation by weight between coproduct chlorine and caustic soda.

to steel, all of the plastics listed in Table 3.5 are at an energy disadvantage on a weight basis, yet have a fivefold advantage on a volume basis.*

3.2 REINFORCEMENTS

3.2.1 Glass Fibers

The principal aspects of the fiberglass manufacturing sequence are schematically depicted in Fig. 3.5. The three process steps are: (1) mixing the mainly inorganic raw materials to form the glass batch, (2) heating the batch to approximately 2700°F in order to melt and refine the mixture, and (3) extruding the glass through platinum bushings in order to form the 0.1-0.75 mil glass fibers. Sand and limestone represent 75% of the raw materials for type-E glass. It is estimated that 1.2 lb of glass batch are necessary to make 1 lb of glass product. Total energy for this process, including binder application, high-speed winder, job efficiencies, heating, and lighting, is 21,805 Btu/lb. The energy resources used are 14.97 x 10^3 Btu natural gas and 0.68 kWh electricity. Most of the energy is consumed in the melting and refining step.

The only other energy contribution to the fiberglass sequence is mining the raw materials. Mining energy requirements are 300 Btu/lb of fiberglass. The energy resources employed are 110 Btu diesel fuel and 0.02 kWh electricity. Total process energy for fiberglass manufacture is 22.10 x 10^3 Btu/lb. No feedstock energy is involved.[16]

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*The plastic resins must be fiber reinforced in order to compete with steel in structural applications. The density of the composite is somewhat greater than that of the resin. Glass fiber density is 0.092 lb/in.^{3} and calcium carbonate filler density is 0.100 lb/in.^{3} Nevertheless, composite density remains less than 25% that of steel.

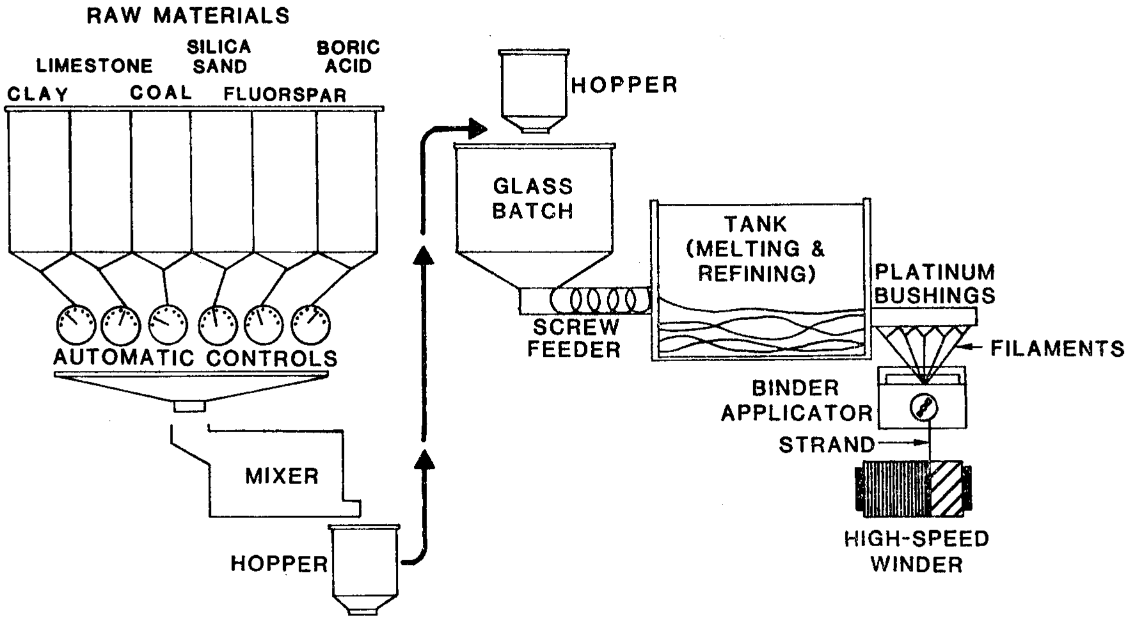

Fig. 3.5 Fiberglass Process Sequence (Source: Adapted from Ref. 6)

3.2.2 Graphite Fibers

In terms of molecular structure, graphite consists of a series of parallel planes, each plane being composed of an interconnecting matrix of hexagonally linked carbon atoms. The atoms are strongly bonded within each plane, but relatively weak bonds exist between planes. As a result, graphite's mechanical properties vary by 100-1000, depending on whether the stress is exerted parallel or perpendicular to the layer planes. For this reason, a principal objective of graphite fiber manufacturing is to orient the layer planes parallel to the fiber axis. This is done by starting with a precursor fiber having the desired orientation, then systematically driving off the noncarbon atoms.

Rayon was the precursor material for the first graphite fibers. Since research on graphite fibers and suitable precursors was initiated in 1964, fibers based on polyacrylonitrile (PAN) precursors have become the dominant commercial variety. A disadvantage of PAN-based fibers is that PAN costs \$3/lb.* Research is underway on the use of petroleum pitch as a lower cost alternative.

Graphite fibers are manufactured in a two-step sequence. First, the precursor PAN is heated to 480-750°F while the fiber is held under tension. The PAN molecules are oxidized at this temperature to produce a stable state. In the second step, the temperature is increased to 2730-4530°F in order to pyrolyze all atoms except the carbon ladder backbone. Tension is maintained on the fiber throughout the process to maintain the desired orientation of the carbon basal plane. The temperature employed also contributes to the degree

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*Glass fibers cost only \$0.60-0.70/lb.

of basal plane orientation and determines the degree of graphitization attained.

The high temperatures needed to convert the precursor material into graphite fiber translates into large process energy requirements. The production sequence from raw materials through PAN to graphite fiber is estimated to require 88.8 x 10^3 Btu/lb.[3] This high energy intensity can be partially offset by the lighter weight of the graphite component.

3.3 FILLERS

Filler energy requirements are related to mining and beneficiating the inorganic material. In the case of calcium carbonate, which is used for most automotive applications, this energy requirement is 0.35 x 10^3 Btu/lb.[16] The energy resources employed are 233 Btu diesel fuel and 0.0117 kWh electricity per pound of calcium carbonate. Filler energy requirements are considerably smaller than the 34.63 x 10^3 Btu/lb for UPE resin and 22.10 x 10^3 Btu/lb for glass fibers. Use of 40% filler, therefore, greatly reduces the aggregate embodied energy of the FRP.

3.4 FIBER-REINFORCED PLASTIC PRODUCTS

The final two steps in the FRP manufacturing sequence are to assemble the molding compound and perform the molding operation. Sheet molding compound with 30% fiberglass content is the most widely used type of FRP in the automobile industry. A schematic diagram of the SMC manufacturing sequence is given in Fig. 2.7, and the molding operation was described in Sec. 2.5.

Materials efficiency in SMC manufacture is 96-97%. The energy required for SMC manufacture and molding is 0.42 kWh/lb for electricity and 80 Btu/lb for fuel, yielding a total energy requirement of 4.28 x 10^3 Btu/lb.[6] This amount of energy is substantially less than the embodied energy requirements of the resin and fiberglass. In fact, the overall molding process is exothermic. The small fuel requirements are needed to initiate the reaction and to soften the SMC for molding; the electrical energy powers the equipment that forms the SMC and the presses that mold the product.

The aggregate energy for manufacturing the FRP product includes: (1) the embodied energies of the resin, fiberglass, and filler; (2) the energy for SMC manufacture; (3) the transportation energy associated with SMC (estimated to be 218 Btu/lb); and (4) the molding energy. Materials losses are estimated to be 4% during SMC manufacture and 10% during product molding. The process, feedstock, and total energies are given in Table 3.6.

Table 3.6 Energy Requirements for Fiber-Reinforced Plastics (10^3 Btu/lb)

Material	Process Energy	Feedstock Energy	Total Energy
Unsaturated polyester resin (30%)	12.47	22.16	34.63
Fiberglass (30%)	22.10	-	22.10
Calcium carbonate filler (40%)	0.35	-	0.35
Fiber-reinforced plastic[a]	16.46	7.69	24.15[b]

[a] Includes molding compound assembly and molding operation energies. Assumes a nonrecyclable 10% scrap rate.

[b] Feedstock requirements represent 31% of the total energy.

4 AUTOMOBILE MATERIALS COMPETITION AMONG FIBER-REINFORCED PLASTICS, STEEL, AND ALUMINUM

4.1 BACKGROUND

Cost has historically dominated decision making in the automotive industry. Although attributes like performance, appearance, durability, and safety have been important considerations, great emphasis has been placed on achieving a given design at minimum production cost. In fact, the automotive industry has gone beyond other industries in their cost planning. Because the industry's product is complex and expensive, an extremely large number of design decisions are necessary. By systemizing their entire planning and production sequence, automobile manufacturers have been able to achieve significant economies of scale.

The automotive industry's use of materials has reflected the importance given to cost. Figure 4.1 shows the relationship between the amounts of different materials consumed in 1976 and their prices in that year. The five materials having the largest tonnages were shown in Table 1.1 to be among the principal components of automobiles. Iron and steel, the lowest cost materials, for example, constitute 70% of automobile weight. There is a certain chicken-or-egg aspect to this situation in that the automotive industry in 1978 consumed: 53.3% of malleable iron, 29.9% of zinc, 21.7% of steel, 16.5% of aluminum, and 12.0% of copper.[18] In other words, selection by the automotive industry guarantees that a material will be used in large quantity, thereby insuring cost reductions based on economies of scale.

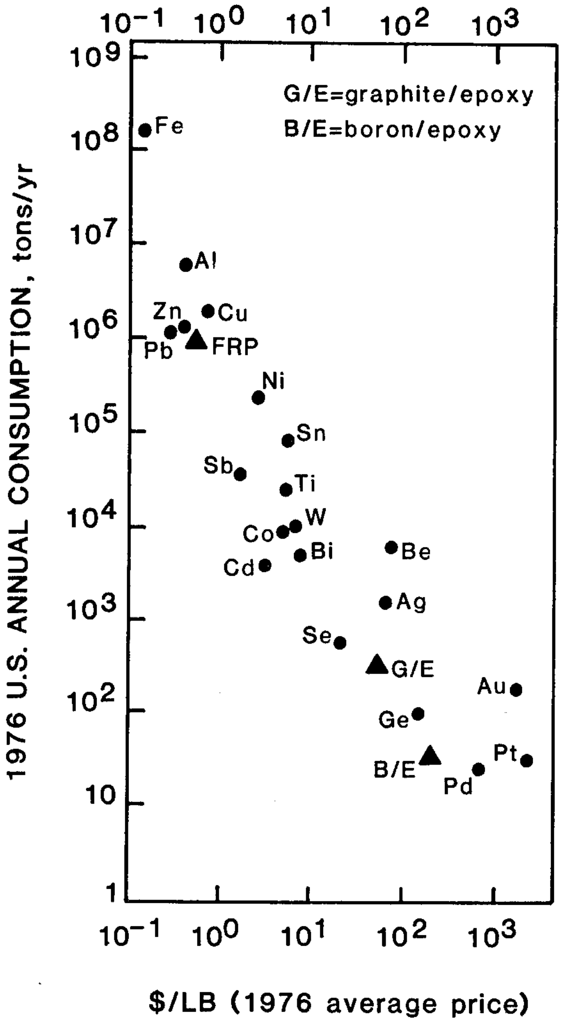

Fig. 4.1 Materials Usage as a Function of Price (Source: Ref. 17)

Another historical aspect of the automotive industry had been a trend toward more spacious and luxurious cars; Table 1.1 shows steadily increasing vehicle weight from 1965 to 1971. The oil embargo of 1973-1974 put a halt to this trend. Sales of smaller cars reduced average vehicle weight by 4% in 1974, even though manufacturers had not yet had the opportunity to introduce weight-saving design changes. Since then, consumer preferences have fluctuated with the price of gasoline. However, a downward trend in preferred vehicle size has persisted and has been expressed to some extent through the purchase of small, imported cars.

The need for automobile manufacturers to produce lighter, fuel-efficient cars was given the force of law by passage of the Energy Policy and Conservation Act in December, 1975. The CAFE standards established by this act require each automobile manufacturer to achieve specified levels of fuel economy in given years. The standards are based on combined city and highway results for a composite fleet. The average fuel economy of all vehicles sold by each manufacturer had to be 18 mpg in 1978 and will have to increase to 27.5 mpg in 1985. The manufacturers have introduced a number of design changes to improve vehicle fuel economy, including reducing the overall size of the vehicle (downsizing), adding more diesel engines to the fleet, and reducing vehicle weight. Since FRP and aluminum, even though much lighter, can perform many of the same functions as steel, they are being used for applications that have usually been reserved for lower cost steel.

Table 4.1 shows how materials usage is being adjusted to achieve lighter weight cars. The participation of iron and steel will have decreased from 74.3% in 1971 to 68.8% in 1985. Over the same period, use of plastics and aluminum will have increased from 4.5% to 18.1%. Overall vehicle weight in 1985 will be 35% less than that in 1971. The trend in average weight over the period 1965-1985 is shown in Fig. 4.2. The average weight shown for 1985 represents a mix of heavier diesel vehicles and lighter gasoline vehicles, which reflects projected sales in the various vehicle size categories. After 1985 it is anticipated that fuel economy goals will be set even higher. Standards of 40 mpg for 1990 have been discussed in Congress, and an 80-mpg standard has been suggested as an eventual goal. The latter standard will require some members of the fleet to be two-passenger cars having two or three cylinders. From a FRP standpoint, such stringent standards may require use of the more expensive ACM.

Table 4.1 Adjustments in U.S. Automobile Materials Usage Motivated by Efforts to Improve Fuel Economy

	1971		1977		1985	
Material	lb	%	lb	%	lb	%
Cast iron	572	14.3	640	17.1	260	10.0
High-strength steel	-	-	110	2.9	260	10.0
Other steels	2400	60.0	2210	58.9	1270	48.8
Aluminum	76	1.9	110	2.9	210	8.1
Plastics	104	2.6	190	5.1	260	10.0
Other materials[a]	848	21.2	490	13.1	340	13.1
Dry weight	4000	100	3750	100	2600	100
Inertia weight	4500	-	4200	-	3000	-

[a] Includes but is not limited to zinc, copper, lead, glass, and rubber.

Sources: Refs. 1 (1971) and 2 (1977 and 1985).

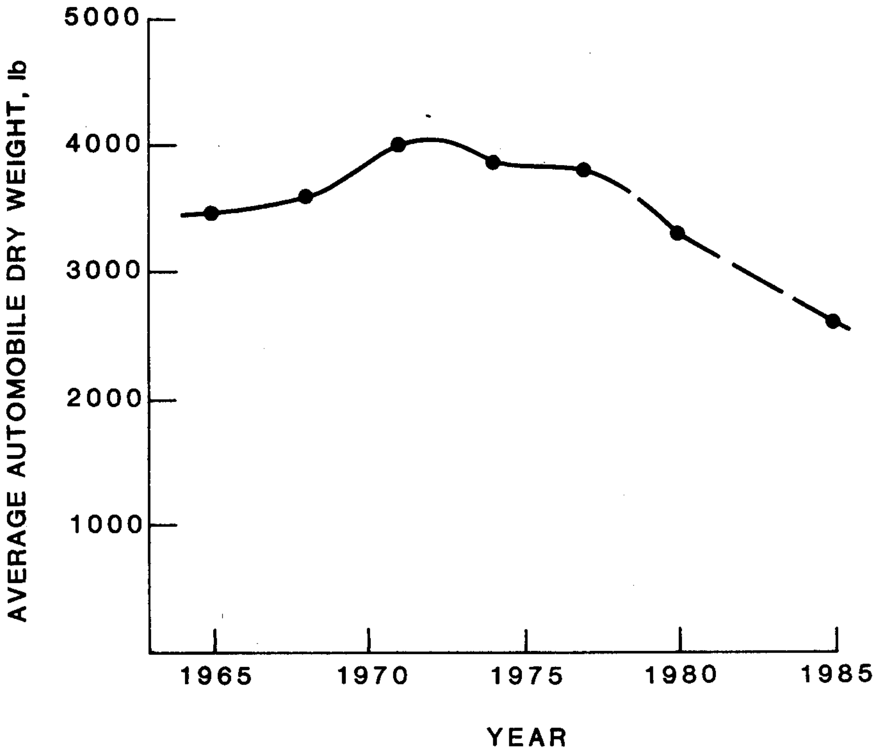

Fig. 4.2 Trend in Average Automobile Weight (Sources: Refs. 1 (1965, 1968, and 1971) and 2 (1977 and 1985)

One potentially important aspect of the materials competition that has not yet played a major role is corrosion resistance. The National Bureau of Standards (NBS) has estimated that automobile corrosion costs $6-14 billion annually in the United States and that $2-8 billion of these costs are avoidable. Since applications requiring corrosion-resistant products already account for over 10% of FRP shipments (see Table 2.1), a trend to improve corrosion resistance in automobiles should favor increased use of plastics. Although aluminum also offers some corrosion protection, penetration of the protective aluminum oxide film leads to pitting. Galvanized steel also provides corrosion protection. Two-sided, hot-dip galvanized sheet is widely used, and one-sided galvanized sheet or zinc-rich, primer-coated sheet are increasingly being used as sheet thickness is decreased to save weight.

4.1.1 Steel

The overall weight reduction shown in Fig. 4.2 means that all materials must expand their market share in order to maintain the same sales volume. For example, iron and steel's projected 10.1% reduction in share between 1977 and 1985 translates into a 40% loss in sales volume (1170 lb/vehicle). Given such potentially large dislocations, market competition is intense. The most promising developments in steels are the high-strength steels (HSS) that offer weight savings of 10-25%. Although more expensive than low-carbon steel, HSS capitalize on the automotive industry's experience with and confidence in steel components. Since steel parts have excellent surface properties and high production throughput, HSS are projected to more than triple their market share between 1977 and 1985. This rate of growth would exceed that of either plastics or aluminum, even though the use of steel as a whole would be declining.

Dual-phase steels, so named because they consist of a dispersion of martensite in a ferrite matrix, are the most promising of the HSS. They offer the best combination of ductility and strength. They can be employed in applications requiring tensile strengths of 60,000-145,000 psi and avoid the formability problems encountered with conventional high-strength/low-alloy (HSLA) steels. The chief impediment to their broader use is developing market demand sufficient to justify substantial capital investment by the steel industry for the necessary continuous annealing facilities.

4.1.2 Fiber-Reinforced Plastics

Plastics possess significant marketing advantages based on their light weight and the opportunities they present for parts consolidation. These two aspects account for the automobile market penetration that plastic components have already achieved. Only about 8% of the plastics usage shown for 1977 in Table 4.1 was in the form of FRP, and this usage was confined primarily to body fascia and other nonstructural body panels.* To expand their market further, plastics must begin to compete successfully against steel and aluminum in structural applications. As Table 4.1 indicates, the total weight of plastics used per vehicle is not expected to increase substantially from 1977 to 1985. This projection assumes that FRP will not be able to displace steel in structural applications over that period. Two considerations argue for this result: (1) vehicle downsizing and associated engine redesign will receive primary emphasis over the next two to three years and (2) it will take at least three to five years for the industry to resolve concerns regarding FRP usage. The 1985 estimate for plastics usage given in Table 4.1 was developed by Ford Motor Company and was widely supported in a series of meetings with other automobile and FRP manufacturers.

Concerns have been expressed regarding FRP usage, including: (1) inadequate surface quality, (2) low production rates because of the 2-min cure constraint,** (3) undeveloped assembly techniques, (4) uncertain energy absorption characteristics, (5) lack of information on basic material properties like fatigue behavior, and (6) lack of recyclability. Substantial progress has been made with respect to achieving Class A surface quality. Up to 40% TP resin has been employed in conjunction with the basic TS-resin FRP to reduce shrinkage during cooling. In addition, an in-mold urethane coating has been used to deal with surface irregularities. In this process, the press is opened briefly after forming and partial cure to inject a layer of urethane. The final surface finish forms during the remainder of the curing cycle.

With regard to production limitations, partial alleviation is expected through use of a rotating jig that ties up the large press only for the 20-s

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*Fiber-reinforced plastics also were used in heater and air-conditioning housings, where surface appearance was not a consideration.

**Open-mold time is 1-2 min, for an overall cycle time of 3-4 min.

molding operation and then rotates the clamped mold into a standby position for the remainder of the curing cycle. A representative assembly problem concerns making and testing bonds between parts. Steel components can be spot welded, with 20 or more welds done at once, and then visually inspected. Fiber-reinforced plastics, on the other hand, require adhesive or mechanical joining techniques. Adhesive bonds take time to cure, and a rapid, nondestructive test to insure bond integrity needs to be developed. Since mechanical attachments lead to point stresses, the material must be strengthened at that point. The concern with regard to energy absorption is that FRP (and HSS) can fail by "popping" and then letting go. This is in contrast to low-carbon steels, which absorb energy continuously throughout the buckling process. This difference is reflected in the reduced area under the stress-strain curve of FRP and HSS as compared to low-carbon steels. Work underway at Ford Motor Company, however, indicates that FRP can be configured so that delamination occurs continuously throughout the crushing phase.[19]

Lack of information on basic material properties was identified consistently by workers in the field as the most pressing area for research. Because FRP are anisotropic materials and their properties are influenced by more than 150 variables in the production cycle,* the amount of data that must be gathered and systematically evaluated is immense. Because this process has barely begun, insufficient data are available to develop more than rough generalizations, such as the mixture rule expressed in Eq. 2. As for recyclability, little progress is expected. Fiber-reinforced plastics could be ground up and used as filler, but this is an extremely low value application. Alternatively, FRP resins could be pyrolyzed to produce fuel oils. Ford Motor Company has been investigating this possibility with the University of Tennessee but has not yet reported on the results. Although incineration would recover at least the heat of combustion, the resin represents only about 30% of the weight and the inorganic ash formed would retain much of the thermal energy.

To summarize, FRP have a number of significant hurdles to overcome before these materials can compete effectively against steel, including the new HSS. If FRP do prevail, one designer estimated that 2000-lb cars will be produced by the mid-1990s that utilize 45% plastic. The resulting 640-lb increase in plastics usage beyond the 260 lb estimated for 1985 will come mainly from hanging FRP body panels on a steel space frame. At 10×10^6 cars per year, the 640 lb/vehicle translates into 6.4×10^9 lb/yr FRP, more than three times the total FRP consumption shown for 1979 in Table 2.1.

4.1.3 Aluminum

Aluminum is a well-known, lightweight material used in many diverse applications. In the automotive industry, aluminum has the added advantage that it can be handled in the same types of equipment as steel. Hence, assembly techniques for aluminum parts are well established, and aluminum and steel products are easily interchanged. There are a number of disadvantages to aluminum, however, that have limited its use in automobiles. Foremost

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*Owens Corning Fiberglas has identified more than 150 significant process variables as part of their SMC-1982 program.[16]

among these is cost. The current price of aluminum sheet is $0.90-1.40/lb, more than four times that of steel sheet.[20] In addition, its advantage in being three times lighter than steel is offset, in applications where stiffness is the main design criterion, by having a tensile modulus only one-third that of steel. As a result of these two disadvantages, more than 50% of the aluminum usage projected for 1985 will be in the form of lower cost cast aluminum for engine heads, manifolds, and other structural housings. In general, the high cost of aluminum sheet has caused it to be used as a "Band-aid™" material in achieving improved vehicle efficiency. It is employed where necessary to meet specified weight objectives on selected product lines and is replaced as soon as possible by an improved (and less expensive) steel component. Here, the ease with which steel and aluminum components can be interchanged acts to the detriment of aluminum.*

Because aluminum is a soft material and easily scratched, it requires special handling. Also, it is extremely energy intensive to produce, mainly because of the energy required for the electrolysis of alumina. Historically, the aluminum industry has been able to capitalize on the relatively low cost of hydropower, but access to this energy source is gradually being curtailed. Future additions to aluminum capacity will have to rely on thermal plants. However, recycle of aluminum is much less energy intensive, requiring only about 10% of the energy needed for production from virgin materials. About 53% of the aluminum used in cars is already being recycled.[21] This material is used mainly to produce cast aluminum and not the aluminum sheet being considered in this assessment. Nevertheless, recycling represents an important mode of energy recovery that can be expected to increase in the future.

4.2 WEIGHT REDUCTION

Comparative mechanical properties of two steels, aluminum, fiberglass, graphite fiber, and three types of FRP are given in Table 4.2. The density of the competing materials is one-third or less that of steel. In addition, the graphite and glass fibers, respectively, have 5-10 times conventional cold-rolled, low-carbon (CRLC) steel's tensile strength. Graphite fiber has a tensile modulus equal to that of steel, while the modulus for fiberglass is one-third as great. Fiberglass and graphite fibers are lighter than steel but have comparable mechanical properties, which leads to much greater specific strengths (25-fold) and somewhat greater specific moduli. When glass fibers are dispersed as random 1-in. fibers in conventional 30% SMC, the specific strength of the composite is approximately the same as steel, while the specific modulus is only one-third as great. If greater strength is required, the quantity of glass fibers can be increased. For example, XMC™** composite contains 65-80% (by weight) unidirectionally oriented glass fibers and 20-35% TS resin (no filler). Its specific strength is nearly seven times as great as that of steel, while its specific modulus is comparable. The epoxy/graphite (EG) composite offers a further threefold increase in specific properties over that of XMC. Aluminum achieves specific properties comparable to those of

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*Fiber-reinforced plastics, on the other hand, usually introduce parts consolidation to help justify their use. Thus, once the adaptations necessary for the FRP components have been made, the manufacturer is unlikely to switch back to the steel component.

**XMC is a registered trademark of PPG Industries, Inc.

Table 4.2 Comparative Mechanical Properties

Material	Orientation	Density (lb/in.^{3})	Tensile Strength (10^3 psi)	Tensile Modulus (10^6 psi)	Specific Strength (10^5 in.)	Specific Modulus (10^6 in.)
Steel (CRLC/1015)	Isotropic	0.284	50	28	1.8	98
High-strength steel (dual phase)	Isotropic	0.284	100	28	3.5	98
Aluminum (5052)	Isotropic	0.097	28	10	2.9	103
Fiberglass (Type E)[a]		0.092	500	10.5	54	114
Graphite-HS[b] fiber		0.063	400	32-34	64	524
Fiber-reinforced plastics						
Sheet molding compound (30% reinforcement)	Multidirectional	0.067	14	2.0	2.1	30
XMC/3™[c] (70% reinforcement)	Unidirectional	0.071	80	5.2	12	73
Epoxy/graphite (50% reinforcement)	Unidirectional	0.054	186	22	34	408

[a] Type-E fiberglass is a lime-alumina-borosilicate glass designed primarily for electrical applications.

[b] Graphite-HS is a PAN-based high-strength graphite fiber.

[c] XMC/3™ is a registered trademark of PPG Industries, Inc.

Sources: Refs. 6 (XMC/3™), 16 (sheet molding compound), 22 (steel and aluminum), 23 (high-strength steel), and 24 (type-E fiberglass, graphite-HS, and epoxy/graphite).

steel by offsetting lesser mechanical properties with substantially lower density.

The implications of the differences in material mechanical properties can be approximately evaluated with regard to vehicle weight reduction by the following empirical formula:

$$\frac{W_c}{W_s} = \frac{\rho_c}{\rho_s}\left(\frac{E_s}{E_c}\right)^m \tag{16}$$

where:

W_c = weight of the competitive material component,

W_s = weight of the steel component,

ρ_c = density of the competitive material,

ρ_s = density of steel,

E_c = Young's modulus of the competitive material component,

E_s = Young's modulus of the steel component, and

m = empirical exponent depending on the shape of the component.

This formula estimates the relative weights of two materials of the same geometrical configuration used to perform the same structural function. It provides an approximate guide to the relationship between their material properties, but the actual weight comparison depends on the specifics of the part design. Since FRP usage is frequently accompanied by parts consolidation, estimates provided by Eq. 16 tend to be conservative with regard to FRP.* Nevertheless, the equation provides a useful first approximation, especially since manufacturers may begin by introducing similarly shaped FRP components on some of the first year's output. The ratio of the Young's moduli is used, because stiffness is the most restrictive structural requirement in the majority of automotive applications.[25] The empirical factor ranges from 0.33 to 1.0. Representative values are: 1.0 for thin-walled beams, such as chassis, pillars, and rocker panels; 0.5 for panels, such as hoods, roofs, and door panels; and 0.33 for solid sections, such as reinforcement brackets and hinges. Most of a vehicle's weight is in the form of sheet stock used for thin-walled beams and panels.

Using Eq. 16 and the mechanical properties given in Table 4.2, aluminum and FRP composites can be compared to steel for various component shapes (see Table 4.3). In all cases, the competing materials perform best against steel in the solid sections, which contribute little to overall vehicle weight. In thin-walled beams, only the EG composite offers significant weight reduction. Therefore, it is in body panels that FRP and aluminum have the greatest potential for market penetration. The weight reductions predicted by Eq. 16 for body panels are: 43% for aluminum, 12% for SMC, 42% for XMC™, and 80% for EG.

As noted previously, the results predicted by Eq. 16 are conservative with respect to FRP, because parts consolidation increases their competitive

Table 4.3 Weight Comparisons for Alternative Materials by Component Shape

Material	Weight Ratio[a]		
	Thin-Walled Beams (m = 1.0)	Panels (m = 0.5)	Solid Sections (m = 0.33)
Steel[b]	1.0	1.0	1.0
Aluminum	0.96	0.57	0.48
Fiber-reinforced plastics			
Sheet molding compound	3.30	0.88	0.57
XMC/3™	1.34	0.58	0.43
Epoxy/graphite	0.19	0.20	0.21

[a] The weight ratio values are the weight of the composite material component divided by the weight of the comparable steel component. Values less than one indicate that weight reduction is achieved when the composite material is employed.

[b] Steel serves as the basis for comparison.

Source: This analysis is patterned after that presented in Ref. 17.

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*Steel and aluminum parts also are being redesigned in light of current needs to reduce vehicle weight. This could reduce the relative advantage gained in FRP parts consolidation.

position. Manufacturers of FRP emphasize that it is function, not shape, that must be satisfied. For comparison, Table 4.4 identifies weight reductions actually achieved using SMC, XMC™, and EG composites for various components. The reductions achieved in the two body panels using SMC are 35% and 53%, considerably better than the 12% predicted by Eq. 16. Likewise, HMC™ and XMC™ (see Table 4.4, footnote a) perform considerably better than predicted in the two thin-walled beam and the solid section applications, achieving 50-54% weight reductions. The EG composite achieves the greatest weight savings (66% and 68%), which is somewhat less than the 80% predicted by Eq. 16. This discrepancy may be attributable to use of a different graphite fiber or to additional constraints placed on the part.

Based on Table 4.4, aluminum is assumed to offer a weight reduction relative to steel of approximately 50%, while SMC offers 40% and EG offers 70%. As noted previously, the high cost of graphite fibers precludes their extensive use. Therefore, subsequent comparisons focus on the competition among steel, aluminum, and SMC in body panel applications. However, hybrid FRP composites using both glass and graphite fibers could achieve substantial weight reductions at intermediate cost.

The discussion to this point has focused on primary weight reductions, i.e., those attained by substituting one material for another in a specific component. If the materials substitution takes place within the context of an overall weight reduction effort, however, a number of secondary weight reductions can be achieved. These consist of opportunities to reduce the weights of the support structure, engine, braking system, and drive train as overall vehicle weight is reduced. For example, Ford Motor Company was able to demonstrate the potential for a 706-lb primary weight reduction in their 1979 Ford LTD by constructing a concept vehicle that made use of graphite-based composites. The composites were employed in a variety of applications for which, though technically suited, they cannot presently be economically justified. The design achieved 540 lb in secondary weight

Table 4.4 Representative Weight Savings

Unit	FRP Type	Steel Component Weight (lb)	FRP Component Weight (lb)	Weight Reduction (%)
Ford Econoline van hood	SMC	29	19	35
GMC truck door	SMC	75	35	53
Corvette bumper backup unit	HMC™[a]	22	10	54
Door beam	XMC™[a]	17	8.5	50
GMC Phoenix transmission support	XMC™	8.5	4	53
Hood	EG	49	17	66
Deck lid	EG	43	14	68

[a] HMC and XMC are registered trademarks of PPG Industries, Inc.

savings, which included an adjustment from a 5.0-L to a 2.3-L engine, while maintaining vehicle performance.[9]

Values given in the literature for the ratio of secondary to primary weight savings vary from 0.4 to 1.6.[26] The exact value achieved depends on the part or parts being replaced, the weight efficiency of the vehicle being modified, and the extent of redesign being undertaken. Significant secondary weight savings can be achieved for parts located on the upper body of the vehicle, while minimal secondary weight savings can be achieved for lower body or structural parts, such as wheels. The ratio achieved by the numerous changes introduced in the Ford concept vehicle was 0.76, starting from the relatively weight inefficient LTD vehicle. It is estimated that 0.5 is representative of the general potential for secondary weight reduction in present-day vehicles, i.e., 0.5 lb of secondary weight is removed for each pound of primary weight reduction. In view of the great emphasis being placed on vehicle weight reduction, this level of secondary weight reduction should generally be achievable.

4.3 EMBODIED ENERGY

4.3.1 Fiber-Reinforced Plastics

The FRP embodied energy requirements were given in Sec. 3. The total energy needed to manufacture SMC with 30% fiberglass reinforcement was 24.15×10^3 Btu/lb, with feedstock requirements representing 31% of the total. Transportation energy requirements of 220 Btu/lb increase the total to 24.4×10^3 Btu/lb.[27] On a volume basis, the energy requirements are 1.63×10^3 Btu/in^3. A 10% scrap rate (without recycle) is included in these figures.

4.3.2 Steel

The material conventionally employed for automobile body panels is CRLC steel sheet. The process sequence for production of CRLC sheet is depicted schematically in Fig. 4.3, and the process steps are enumerated in Table 4.5. Because of its tremendous economic importance, the energy and materials flows associated with this process sequence have been extensively examined.[28-30] Recently, the levels of process participation characteristic of automobile-related CRLC steel sheet have been identified.[27] Since 1975 the steel industry has achieved a reduction in energy consumption of somewhat more than 10%.

As shown in Fig. 4.3, the process alternatives for CRLC sheet manufacture primarily concern how the molten steel is generated and how it is converted into slabs. Molten steel can be produced from iron ore in two steps via a blast furnace and either a basic oxygen furnace (BOF) or an open-hearth furnace (OHF). A third and quite different method of molten steel production is via an electric-arc furnace (EAF), using scrap as feed. This method is much less energy intensive than the other two. However, it cannot accommodate iron ore and is not used for automobile-related CRLC sheet. Reference 27 estimates that the 1976 process splits for automobile-related molten steel were 77.3% BOF and 22.7% OHF, and that the average charge mix was 73.6% blast furnace hot metal and 26.4% scrap.

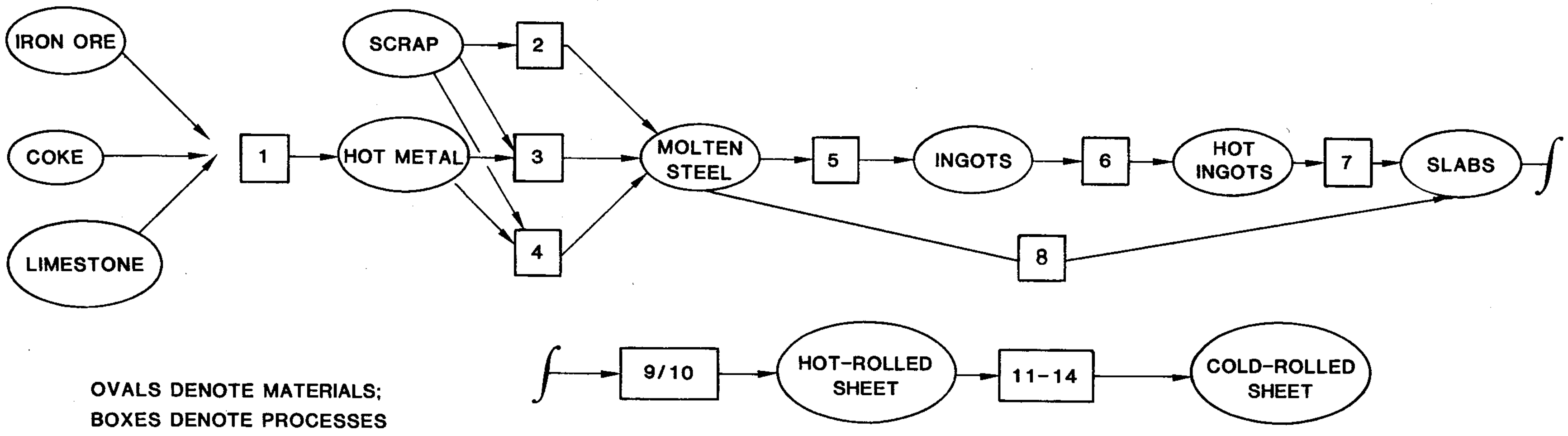

Fig. 4.3 Process Sequence for Cold-Rolled/Low-Carbon Steel Sheet

The second process sequence variable is production of slabs from molten metal. Recent years have seen increasing use of continuous casting, which is 15% less energy intensive than production of conventional ingots. Reference 27 estimates that 17% of slab production was via continuous casting by late 1978.

Energy consumption in 1975 during CRLC sheet production via the six alternative process sequences is given in Table 4.6. Aggregate energy from all the participating processes in 1975 was 20.1 x 10^3 Btu/lb, while present-day energy consumption is estimated to be 18.1 x 10^3 Btu/lb. Assuming an average distance of 300 mi from the steel mill to Detroit, the transportation energy required is approximately 400 Btu/lb. The fabrication energy (stamping) is estimated to be 130 Btu/lb and the offal rate to be 25%.[27] The total embodied energy for the fabricated steel component is (18.5/0.75) + 0.13 = 24.8 x 10^3 Btu/lb. The energy requirements for HSS are thought to be approximately the same as for CRLC steel.

Table 4.5 Cold-Rolled/Low-Carbon Steel Sheet Production Processes

1	Blast furnace
2	Electric arc furnace
3	Basic oxygen furnace
4	Open hearth furnace
5	Ingot casting
6	Soaking pits
7	Slabbing mill
8	Continuous slab casting
9	Slab reheat furnace
10	Hot strip mill
11	Pickle line
12	Cold rolling mill
13	Annealing
14	Temper mill

4.3.3 Aluminum

The approach taken to assess the embodied energy of an aluminum automobile body panel is similar to that for steel. The process sequence for aluminum sheet production is shown in Fig. 4.4, and the participating processes are identified in Table 4.7. Figure 4.4 has been simplified by grouping processes 5-16 together, because most of the important process considerations are at the beginning of the sequence. For example, 75% of the energy needed for producing aluminum sheet from bauxite occurs during the Hall-Heroult electrolysis of alumina (process 2). In addition, use of scrap to produce aluminum ingots via the reverbatory furnace (process 4) requires only 10% of the energy needed to proceed from bauxite ore via processes 1, 2, and 3.

Its extremely energy intensive nature has caused the aluminum process sequence, like that of steel, to be widely studied.[27,31] Reference 27 has performed a literature review and has identified the levels of process participation associated with producing aluminum sheet for automobiles. The energy estimates in Refs. 27 and 31 are quite similar.

Because of the large differences in their processing energies, the relative participation of virgin ore and recycled scrap has a major impact

Table 4.6 Energy Consumption in Cold-Rolled/Low-Carbon Steel Sheet Manufacture, 1975

Process Route	Sequence Energy (10^3 Btu/lb)	Participation	Aggregate Energy (10^3 Btu/lb)
Conventional ingots			
Basic-oxygen furnace	20.8	0.773 x 0.83	13.3
Open-hearth furnace	20.2	0.227 x 0.83	3.8
Electric-arc furnace	11.9	-	-
Continuous casting			
Basic-oxygen furnace	17.7	0.773 x 0.17	2.3
Open-hearth furnace	17.2	0.227 x 0.17	0.7
Electric-arc furnace	9.9	-	-
Total			20.1

Source: Ref. 27.

on the aggregate energy required for aluminum sheet. From an energy standpoint, one would prefer to use as much scrap as possible. The major constraint to this is the effectiveness of the collection and recycling system for post-consumer scrap. Automobiles and aluminum cans are two of the best candidates for recycle. For automobiles, a recycle system for aluminum and other vehicle materials, primarily steel, is well established. In the case of cans, the can is composed solely of aluminum so that recycle processing is minimized. Studies have established that 53% of the aluminum in cars is being recovered,[21] and 26% of aluminum cans are being recycled.[32] Other aluminum products are not recycled to the same degree, so that only 10% of annual aluminum output is derived from post-consumer scrap.[33]

The reverbatory furnace plays an important role, in that it processes the large quantities of mill scrap generated during aluminum sheet fabrication. Thirty-five percent of the initial aluminum ingot is turned into mill scrap during processes 5-16. The overall materials flow for aluminum sheet is shown in Fig. 4.5. Although purchased scrap represents only 10% of the output, the reverbatory furnace, which has a 90% efficiency, processes 40.5% of the material.

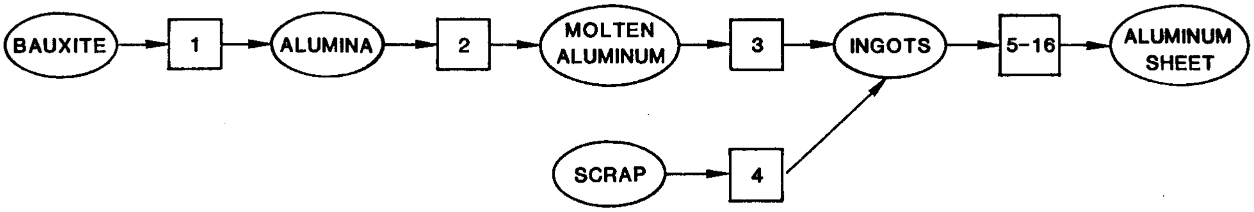

Fig. 4.4 Aluminum Sheet Process Sequence

The process energy to produce aluminum sheet is given in Table 4.8. Assuming an additional 400 Btu/lb for 300-mi transport to Detroit, the embodied energy of the sheet entering automobile part manufacture is 121.3 x 10^3 Btu/lb. The fabrication energy is estimated to be the same as for steel (130 Btu/lb) and the same 25% offal rate is assumed. The embodied energy of aluminum sheet for automobile manufacture is (121.3/0.75) + 0.13 = 161.9 x 10^3 Btu/lb. This is more than six times as great as the 24.8 x 10^3 Btu/lb for steel and the 24.4 x 10^3 Btu/lb for SMC (see Table 4.9).

Table 4.7 Aluminum Sheet Production Processes

1	Bayer process
2	Hall-Heroult process (electrolysis)
3	Holding furnace, casting
4	Reverbatory furnace
5	Scalper
6	Heating furnace
7	Hot reversing mill
8	End shear
9	Continuous mill
10	Annealing furnace
11	Cold rolling mill
12	Shear
13	Heat treating furnace
14	Stretcher
15	Finish shear
16	Aging furnace

4.4 DEPENDENCE OF FUEL SAVINGS ON VEHICLE WEIGHT

Automobile weight reduction achieved through use of FRP and aluminum components, or other means, translates directly into vehicle fuel savings. An estimate of the potential magnitude of these transportation energy savings can be derived from a U.S. Department of Transportation (DOT) correlation of fuel economy and vehicle weight.[35,36] The correlation for a given year is based on test data collected for a large number of vehicle models in that year. The empirical relation is:

$$FE = A(W)^{-a}(HP/W)^{-b} \qquad (17)$$

where:

FE = EPA composite fuel economy over a designated driving cycle (mpg),

W = vehicle inertia weight (dry weight plus passengers and fluids),

HP = rated engine horsepower, and

A,a,b = scaling coefficients that depend on engine characteristics.

The scaling coefficients differ for vehicles having gasoline and diesel engines. They also change from year to year as vehicle performance characteristics (other than weight) are improved. The values for 1979 vehicles with gasoline engines are: A = 8680, a = 0.863, b = 0.284.

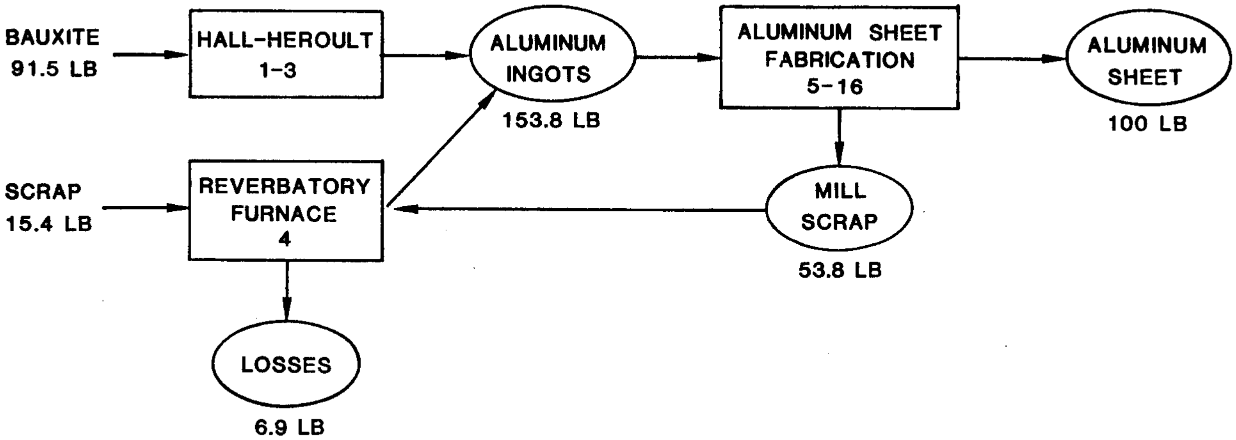

Fig. 4.5 Material Flows in Aluminum Sheet Manufacture

Table 4.8 Energy Consumption in Aluminum Sheet Manufacture, 1980[a]

Process Route	Sequence Energy (10^3 Btu/lb)	Participation (%)	Aggregate Energy (10^3 Btu/lb)
Bayer/Hall-Heroult	189.9	59.5	113.0
Reverbatory furnace	19.4	40.5	7.9
Total		100.0	120.9

[a] This table assumes: (1) the materials flow sequence shown in Fig. 4.4, (2) an industry average of 115.8 x 10^3 Btu/lb in 1980 for aluminum ingot production via the Hall-Heroult process,[34] (3) 4.9 x 10^3 Btu/lb for scrap-to-ingot via the reverbatory furnace, (4) 11.9 x 10^3 Btu/lb for aluminum ingot to sheet, and (5) 34.12% thermal efficiency in electricity generation.

Equation 17 can be easily rearranged in terms of fuel consumption, FC, which is the reciprocal of fuel economy. Differentiating the equation then yields the change in fuel consumption with change in vehicle weight:

$$\lambda \equiv \frac{d(FC)}{dW} \tag{18}$$

$$\equiv \frac{a}{A} W^{a-1}\left(\frac{HP}{W}\right)^b$$

where the performance parameter (HP/W) is held constant. For a 3000-lb gasoline engine vehicle with a performance parameter of 0.03 hp/lb:

$$\lambda = 1.23 \times 10^{-5} \text{ gal/mi/lb} \tag{19}$$

If the effect of weight reduction alone is to be evaluated, an adjustment must be made. The DOT data employed in developing Eq. 17 include the effect of

Table 4.9 Embodied Energies of Steel, Fiber-Reinforced Plastics, and Aluminum Sheet (10^3 Btu/lb)

Material	Sheet Assembly	Transportation (to Detroit)	Fabrication and Losses	Total Energy
Steel (CRLC)	18.1	0.4	6.3[a]	24.8
Fiber-reinforced plastics (SMC-30)	17.9	0.2	6.4[b]	24.4
Resin (30%)	(10.4)			
Fiberglass (30%)	(6.6)			
Filler (40%)	(0.1)			
SMC fabrication[c]	(0.8)			
Aluminum	120.9	0.4	40.6	161.9

[a] Includes product fabrication energy and 25% offal rate.

[b] Includes product fabrication energy and 10% scrap rate.

[c] Includes 4% material losses; energy included with product fabrication.

changes in aerodynamic drag as well as weight reduction. The share attributable to aerodynamic drag has been estimated at 20-40%. A value of 24% is identified as the aerodynamic drag share of brake horsepower in Ref. 37. This value is assumed for the present computations and yields the following fuel consumption dependence on weight:

$$\lambda_W = 0.93 \times 10^{-5} \text{ gal/mi/lb} \tag{20}$$

This value is consistent with values estimated by auto manufacturers.[3,23,38]

The significance of λ_W can be demonstrated by determining the reduction in fuel consumption to be attained by the vehicle weight reduction identified for 1977-1985 (see Table 4.1). Vehicle weight is projected to diminish by 1200 lb over this period. Assuming a vehicle life of 100,000 mi, each 1985 vehicle will consume an average of 1116 gal less than the corresponding 1977 vehicle operating over the same distance.* If 9 x 10^6 domestic cars are sold each year and they each have a 10-yr average life, aggregate reduction in fuel consumption will reach 10.0 x 10^9 gal of gasoline per year when the entire vehicle fleet has achieved that weight reduction. This represents an 11% reduction in automotive fuel consumption relative to that consumed in 1979.[39]

4.5 ENERGY IMPLICATIONS OF MATERIALS SUBSTITUTION

Previous sections have provided the basis for assessing the energy implications of replacing a steel automobile body panel by one composed of FRP

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*More exactly, Eq. 18 can be integrated with respect to weight between 3000-4200 lb, then corrected for aerodynamic drag. The result, 1120 lb, is nearly the same as that obtained by multiplying the weight change by λ_W.

or of aluminum. The results of this assessment are presented in Table 4.10. As discussed in Sec. 4.2, a 1.0-lb steel component can be replaced by a structurally equivalent 0.6-lb FRP component or a 0.5-lb aluminum component. The 0.4-lb primary weight reduction achieved using the FRP component can be further translated into a 0.2-lb secondary weight reduction. In other words, 1.5 lb of primary and secondary steel can be replaced by 0.6 lb of FRP and 0.3 lb of secondary steel.* Likewise, the 0.5-lb aluminum-related primary weight reduction permits an accompanying 0.25-lb secondary weight reduction. Thus,

Table 4.10 Energy Reduction Potential of Fiber-Reinforced Plastics and Aluminum Components (relative to a one-pound steel component)

Variable	FRP[a]	Aluminum
Reduction in weight (lb)		
Primary	0.4	0.50
Secondary	0.2	0.25
Total	0.6	0.75
Reduction in embodied energy (10^3 Btu)		
Component	10.2	-56.2
Secondary[b]	5.0	6.2
Total	15.2	-50.0
Reduction in transportation energy over 100,000-mi lifetime (10^3 Btu)[c]	69.8	87.2
Total energy reduction (10^3 Btu)	85.0	37.2

[a] Sheet molding compound containing 30% (by weight) fiberglass.

[b] Secondary components are assumed to be composed of steel.

[c] Transportation energy requirements are calculated using the weight reduction factor 0.93×10^{-5} gal/mi/lb. The embodied energy of gasoline is estimated to be 125×10^3 Btu/gal.

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*The basis for this calculation is 1.0 lb of steel as primary weight, and 0.5 lb of steel as associated secondary weight. The secondary material is assumed to be steel for simplicity in estimating its energy intensity. In addition, cast aluminum, zinc, copper, lead, glass, rubber, plastics, and miscellaneous materials contribute to the secondary materials mix. Since these other materials have greater energy intensities than steel, use of steel as a proxy underestimates the energy gains to be achieved in materials substitution.

1.5 lb of primary and secondary steel can be replaced by 0.5 lb of aluminum and 0.25 lb of secondary steel.

The embodied energies of the 1.0-lb steel component, the 0.6-lb FRP component, and the 0.5-lb aluminum component are calculated using the unit embodied energies of each material identified in Sec. 4.3. As noted, reductions in embodied energy achieved via the secondary weight reduction are computed assuming that steel is the secondary material. The FRP component is able to achieve a 15.2 x 10^3 Btu reduction in embodied energy. The sixfold higher unit embodied energy of the aluminum component leads to a 50.0 x 10^3 Btu increase in embodied energy in spite of the 50% lighter component weight.

Reductions in fuel consumption are the dominant effect stemming from the materials substitution. These are calculated for a vehicle life of 100,000 mi using the fuel/weight factor of 0.93 x 10^{-5} gal/lb/mi (Eq. 20). The embodied energy of gasoline is estimated to be 125 x 10^3 Btu/gal. The FRP component achieves a 69.8 x 10^3 Btu improvement in fuel consumption relative to the steel component. When this is added to the improvement in embodied energy, a total energy difference of 85.0 x 10^3 Btu results. Aluminum achieves an even larger transportation energy savings of 87.2 x 10^3 Btu. This offsets the embodied energy penalty of aluminum so that total energy is reduced 37.2 x 10^3 Btu relative to steel.

Both FRP and aluminum provide significant opportunities for energy conservation in automobile manufacture and use. As HSS gain acceptance, however, the 10-20% weight reduction they offer will offset aluminum's energy advantage and will substantially reduce that of FRP. (The total energy reduction achieved using HSS to reduce primary weight by 20% is 42.5 x 10^3 Btu.) The materials usage decision will then hinge on the considerations discussed in Sec. 4.1. The high cost of aluminum sheet is expected to critically restrict its use. Fiber-reinforced plastics usage will depend on the industry's ability to surmount the manufacturing difficulties discussed in Sec. 4.1.2. The market competition aspects of the potential energy savings appear to be sufficiently great for FRP to gain a significant market share.

4.6 ENERGY RESOURCE CONSUMPTION

An important aspect of steel, FRP, and aluminum competition in automotive applications is the type of energy resource consumed in their manufacture. Two aspects are of particular interest: (1) how much petroleum is used, because that energy resource is currently of great concern; and (2) how much electricity is used, because electricity can be generated by a variety of fuels or by hydropower and total fuel demand depends on the electricity source. The first issue is raised most frequently with regard to plastics, because hydrocarbons compose the body of these materials. The second issue is most relevant to aluminum because of its high energy requirements for electrolysis.

The embodied energies of manufacture were identified in Sec. 4.3 for each of the three materials: steel, 24.8 x 10^3 Btu/lb; FRP, 24.4 x 10^3 Btu/lb; and aluminum, 161.9 x 10^3 Btu/lb. In the case of steel and aluminum, the energy requirements arise from mining, metal sheet manufacture, sheet transport to Detroit, and product fabrication. In the case of FRP, they arise from feedstocks used in resin production; fuels required to manufacture resin, fiberglass, and filler, and to fabricate and mold SMC; and materials transport to Detroit. In order to translate the total embodied energy values into fuel requirements, the types of fuels employed in each industry must be identified. This has been done by DOE as part of their Industrial Energy Efficiency Program.* The most recent results for the industries of interest are given in Table 4.11. The iron and steel industry depends mainly on coal and coke (64%), the aluminum industry on electricity (68%), and fiberglass manufacture on natural gas (75%).

The fuel participations given in Table 4.11 for steel and aluminum can be directly employed to estimate fuel use in sheet processing, transportation, and product fabrication (see Table 4.12). For steel, the direct energy requirements are 21.44×10^3 Btu/lb fuels and 1.14×10^3 Btu/lb electricity, for a total of 22.58×10^3 Btu/lb. In comparison, 22.84×10^3 Btu/lb fuels and 47.44×10^3 Btu/lb electricity are employed in aluminum manufacture, for a total of 70.28×10^3 Btu/lb. The electricity component of the energy requirement is allocated among fuels using the values given for electricity generation in Table 4.11 and assumes a thermal efficiency of 34.12%. This thermal efficiency was applied to all electrical power, because nearly all U.S. hydroelectric sites have been developed and significant near-term expansion of nuclear capacity is unlikely. Hence, future electricity generating

Table 4.11 Fuel Participation by Industry, 1978 (%)

Fuel	Industry				Electricity Generation
	Iron and Steel	Aluminum	Chemicals[a]	Fiberglass	
Petroleum	11	5	34	6	17
Natural gas	21	20	29	75	14
Coal/coke	63	7	-	-	44
Electricity[b]	5	68	37	19	-
Hydropower, nuclear power, and others	-	-	-	-	25
Total	100	100	100	100	100

[a] Steam usage in the chemical industry (4%) has been allocated to petroleum (2%), natural gas (1%), and coal/coke (1%).[40]

[b] Electricity is valued at 3412 Btu/kWh for all but the chemical industry, for which it is valued at 10,000 Btu/kWh.

Sources: Ref. 40 (industrial fuel allocations) and 41 (fuel use in electricity generation).

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*Fuel use by industrial sector is also surveyed periodically as part of the Census of Manufactures.

Table 4.12 Fuel Participation in Embodied Energy of Steel, Fiber-Reinforced Plastics, and Aluminum Components (10^3 Btu/lb of component)

Material	Petroleum	Natural Gas	Coal/ Coke	Electricity	Hydro, Nuclear, and Other	Total
Steel						
Sheet processing	2.42	4.62	13.87	1.10	-	22.01
Transportation	0.53	-	-	-	-	0.53
Fabrication	-	-	-	0.04	-	0.04
Direct energy[a]	2.95	4.62	13.87	1.14	-	22.58
Electricity generation[b]	0.57	0.47	1.48	(1.14)	0.84	2.22
Total fuels[c]	3.52	5.09	15.35	-	0.84	24.80
SMC-30 (FRP)						
Resin	7.69	1.85	-	0.85	-	10.30
Fiberglass	0.04	5.20	-	0.83	-	6.07
Filler (calcium carbonate)	0.11	-	-	0.02	-	0.13
Transportation	0.24	-	-	-	-	0.24
Fabrication	-	0.08	-	1.43	-	1.51
Direct energy	8.08	7.13	-	3.13	-	18.34
Electricity generation	1.51	1.27	4.06	(3.13)	2.33	6.04
Total fuels	9.59	8.40	4.06	-	2.33	24.38
Aluminum						
Sheet processing	3.49	13.94	4.88	47.40	-	69.71
Transportation	0.53	-	-	-	-	0.53
Fabrication	-	-	-	0.04	-	0.04
Direct energy	4.02	13.94	4.88	47.44	-	70.28
Electricity generation	23.64	19.47	61.18	(47.44)	34.76	91.61
Total fuels	27.66	33.41	66.06	-	34.76	161.89

[a] Direct energy includes fuel energy and electrical energy valued at its thermal equivalent.

[b] Fuel energy loss during electricity generation is calculated assuming 34.12% thermal efficiency and using the fuels participation given in Table 4.10.

[c] Total fuels includes fuel energy and electrical energy valued at its fuel equivalent (see footnote b). These are the values developed in Secs. 3 and 4 of this report.

capacity will mainly be thermally based. The total fuels requirement of aluminum manufacture is 6.5 times that of steel, but the corresponding ratio for direct energy requirements is significantly less at 3.1.

Using the average electricity generating facility mix, petroleum consumption by aluminum is nearly eight times that by steel. On the other hand, the large base-load demand of aluminum permits construction of dedicated coal-fired facilities. If all new aluminum capacity were based on coal-fired electricity, petroleum demand by aluminum in new facilities would be only 4.02 x 10^3 Btu/lb, while coal demand would increase to 143.9 x 10^3 Btu/lb. If a large share of the electricity consumed in aluminum production were hydro-based, as has historically been the case, and the hydro is valued at its thermal equivalent, the total fuels requirement for aluminum decreases substantially. For example, 40% hydro would lead to a total fuels requirement of 125.2 x 10^3 Btu/lb, which is 23% less than the value shown in Table 4.12.

Identification of fuels consumption in FRP manufacture requires considering the participating constituents. Resin accounts for 30% of the FRP product being evaluated, which is SMC containing 30% fiberglass (SMC-30) (see Sec. 3.4). Resin energy requirements are 22.16 x 10^3 Btu/lb for feedstock and 12.47 x 10^3 Btu/lb for process energy. Referring to Fig. 3.4, all hydrocarbon feedstocks except ethane are based on petroleum. Altogether, the petroleum-based feedstocks -- gas oil, naphtha, and reformate -- account for 18.93 x 10^3 Btu/lb. Ethane, a by-product of natural gas production, accounts for the other 3.23 x 10^3 Btu/lb of feedstock energy. Process energy requirements for the resin can be allocated among fuels using the chemical industry values given in Table 4.10. Fiberglass, which accounts for 30% of the FRP, requires 0.3 x 10^3 Btu/lb for raw materials mining and 21.80 x 10^3 Btu/lb for manufacture. The mining energy is thought to be composed of 33% petroleum (for diesel engines) and 67% electricity, and the manufacturing fuels participation is 15 x 10^3 Btu/lb natural gas and 6.8 x 10^3 Btu/lb electricity.[15] Filler energy requirements of 0.35 x 10^3 Btu/lb for mining, beneficiation, and drying have been estimated as 67% petroleum and 33% electricity. Table 4.12 shows the fuel requirements for each FRP constituent and the overall total. The 24.4 x 10^3 Btu/lb total fuel requirements are slightly less than those for steel and only one-sixth those for aluminum. Petroleum consumption in FRP manufacture is 9.59 x 10^3 Btu/lb, nearly three times that for steel.

The fuel requirements of the competing materials can be placed in an automotive context by extending the previous analysis, which is summarized in Table 4.9. As discussed previously, on the average 1.0 lb of steel in an automobile body panel can be replaced with equivalent structural effectiveness by 0.6 lb of FRP or 0.5 lb of aluminum. In addition, the primary weight reduction achieved can be further translated into a secondary weight reduction in engine, support structure, and drive train components. Potential secondary weight reduction was estimated to be 50% of the primary weight reduction. The comparative material weights are shown in the first column of Table 4.13. The first three rows for each material in this table then identify the embodied energy requirements for each product (as given in Table 4.12) for the material weights given in the first column. Steel is assumed to be the secondary material in each instance. The lifetime transportation energy requirements for one pound of vehicle weight were identified earlier as 116 x 10^3 Btu/lb. Thus, the weight reductions achieved by FRP and aluminum represent significant petroleum savings over the vehicle lifetime.

Table 4.13 Life Cycle Fuels Participation in Structurally Equivalent Steel, Fiber-Reinforced Plastics, and Aluminum Automobile Components

Material	Weight (lb)	Petroleum (10^3 Btu)	Natural Gas (10^3 Btu)	Coal/ Coke (10^3 Btu)	Hydro, Nuclear, and Other (10^3 Btu)	Total (10^3 Btu)
Steel						
Primary	1.0	3.52	5.09	15.35	0.84	24.80
Secondary	0.5	1.76	2.55	7.67	0.42	12.40
Embodied	-	5.28	7.64	23.02	1.26	37.20
Transportation	-	174.38	-	-	-	174.38
Total	1.5	179.66	7.64	23.02	1.26	211.58
SMC-30 (FRP)						
Primary	0.6	5.75	5.04	2.44	1.40	14.63
Secondary	0.3	1.06	1.53	4.60	0.25	7.44
Embodied	-	6.81	6.57	7.04	1.65	22.07
Transportation	-	104.63	-	-	-	104.63
Total	0.9	111.44	6.57	7.04	1.65	126.70
Aluminum						
Primary	0.5	13.83	16.71	33.03	17.38	80.95
Secondary	0.25	0.88	1.27	3.84	0.21	6.20
Embodied	-	14.71	17.98	36.87	17.59	87.15
Transportation	-	87.19	-	-	-	87.19
Total	0.75	101.90	17.98	36.87	17.59	174.34

The lighter weight of the FRP component and its accompanying secondary weight reduction enables FRP to achieve lower embodied energy requirements and lower petroleum requirements than steel. In comparison, aluminum is less than either steel or FRP in petroleum consumption, and less than steel but greater than FRP in total energy requirements. In relative terms, the FRP component requires only 62% as much petroleum as the steel component, and 60% as much total fuel. Likewise, the aluminum component requires only 57% as much petroleum as the steel component, and the total fuel requirements of aluminum are 18% less than those for steel.

In summary, FRP can provide energy benefits from both points of view -- total energy and petroleum consumption. Aluminum provides a slightly greater reduction in petroleum consumption at a 38% increase in total energy relative to FRP. As noted previously, industry data indicate that nearly 40% of the electricity requirements of the aluminum industry are now based on hydroelectric power generation. If the thermal losses of this portion of electricity generation were excluded, the total fuel requirements of aluminum would be reduced to 118.6 x 10^3 Btu/lb, which makes them 6% less than those for FRP.

5 CONCLUSION

5.1 GENERAL FINDINGS

Fiber-reinforced plastics can perform many of the structural functions of steel in automotive applications, but at a lighter weight. For this reason, FRP are a promising alternative in the ongoing effort in the United States to improve vehicle fuel economy by reducing vehicle weight. It is projected that average vehicle dry weight will be reduced 30% between 1977 and 1985 to meet 1985 CAFE requirements of 27.5 mph. Only about 18% of this weight reduction from 3750 lb to 2600 lb is expected to result from materials substitutions, because vehicle downsizing offers a more productive first alternative. After 1985, however, further decreases in vehicle weight are anticipated to result primarily from materials substitutions. Aluminum and FRP are the two materials expected to provide the stiffest competition to steel. Steel manufacturers are responding by developing lightweight HSS that offer weight reductions that are slightly less than half those achievable with FRP or aluminum, but which maintain present production technology.

Fuel economy has been correlated with vehicle weight and aerodynamic drag for all U.S. automobile models over a period of years by DOT. For a gasoline vehicle weighing 3000 lb and having a performance parameter of 0.03 hp/lb, the effect of weight reduction (corrected for aerodynamic drag) is 9.3×10^{-6} gal/mi/lb. Thus, assuming a vehicle lifetime of 100×10^3 mi, each pound of weight reduction saves 0.93 gal of gasoline. In energy terms, this is equivalent to a savings of 116×10^3 Btu/lb of weight reduction.

The embodied energy, structural weight, and fuel economy (transportation energy) characteristics of steel, FRP, and aluminum were assessed to determine the overall energy savings achievable by materials substitution. In body panels, a 1.0-lb steel component with an associated 0.5 lb in secondary weight is equivalent to a 0.6-lb FRP component with an associated 0.3-lb secondary weight or a 0.5-lb aluminum component with an associated 0.25-lb secondary weight. (Because of its predominant usage, steel is assumed to be the secondary material in each case.) Table 5.1 summarizes the energy requirements of structurally equivalent automotive body panels. Fiber-reinforced plastics offer the greatest improvements in both embodied and total

Table 5.1 Energy Requirements of Structurally Equivalent Automotive Body Panels, Including Associated Secondary Weights (10^3 Btu)

Energy Requirements	Steel	FRP[a]	Aluminum
Life cycle transportation energy	174.4	104.6	87.2
Embodied energy	37.2	22.1	87.2
Total	211.6	126.7	174.4

[a] Sheet molding compound containing 30% (by weight) fiberglass.

energy requirements. Aluminum, on the other hand, achieves the greatest savings in transportation energy, but this does not fully compensate for its large embodied energy requirements.

Table 5.2 summarizes the direct and total energy requirements for the three competing materials and identifies the petroleum requirements of each. This table is based on the average U.S. fuel usage of each industry and on current fuel requirements of electricity generation. If the electricity requirements of all new U.S. aluminum capacity were supplied by dedicated, base-load, coal-fired power plants, aluminum's petroleum consumption would be reduced to 4.0 x 10^3 Btu/lb, while its coal consumption would increase to 143.9 x 10^3 Btu/lb.

5.2 RESEARCH AND DEVELOPMENT NEEDS

Industry representatives indicated that the most significant constraints to greater use of FRP were (1) inadequate processing techniques (poor surface quality, low production rates, and undeveloped assembly techniques), (2) lack of a product characterization data base (uncertain energy absorption characteristics and inadequate knowledge of material properties), and (3) lack of recyclability (little progress is anticipated for the foreseeable future). Appropriate objectives of FRP research and development activity in these and other areas are summarized in Table 5.3.

Although some research and development effort is underway in each of these areas, it is of limited scope. For the most part, the automotive industry is focused on attaining the 1985 CAFE standards via vehicle downsizing.* Extensive materials substitution will probably be delayed until the

Table 5.2 Summary of Fuel Requirements of Steel, Fiber-Reinforced Plastics, and Aluminum Components (10^3 Btu/lb of component)

Energy Requirements	Steel	FRP[a]	Aluminum
Direct energy	22.58	18.34	70.28
Electricity generation[b]	2.22	6.04	91.61
Total	24.80	24.38	161.89
Petroleum only	3.52	9.59	27.66

[a] Sheet molding compound containing 30% (by weight) fiberglass.

[b] Fuel energy loss during electricity generation, assuming 34.12% thermal efficiency.

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*Market competition, rather than the CAFE standards, has now become the driving force for achieving improved fuel economy.

Table 5.3 Objectives for Fiber-Reinforced Plastics Research and Development

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Materials

Resins. Faster curing resins with greater mechanical strength are needed. Although UPE resins cure in 2 min, they are somewhat weak mechanically. Epoxy resins are mechanically strong but take 30-60 min to cure, even when curing agents and accelerators are used. Vinyl esters represent a compromise, having the curing behavior of polyesters with mechanical properties intermediate between polyester and epoxy resins.

Reinforcements. Replacements for fiberglass that are cost effective and stronger would enable greater weight reductions through the use of FRP. While carbon/graphite fibers are promising, it is unlikely that their costs can be reduced below $6-10/lb in the foreseeable future. Achievement of even these costs will require switching to a material like pitch for the precursor material. Because of cost considerations, hybrid systems composed of both fiberglass and carbon/graphite fibers are likely to be adopted. Metal whiskers offer greater weight reductions, but at a cost far too great for automotive applications.

Fillers. Lighter weight fillers would be desirable. Although microspheres are lightweight, they tend to degrade surface quality.

Processing Techniques

Surface Finish. External automobile body panels require Class A surface quality. Difficulties with FRP as regards porosity and thermal shrinkage, especially near reinforcing ribs, must be overcome. In-mold urethane coatings help to offset porosity effects, and thermoplastic additives counteract thermal shrinkage. Mixed glass lengths can be used to achieve good surface quality (short fibers) and mechanical strength (long fibers). The shorter fibers also flow into the reinforcing ribs.

Production Rate. A further need is to achieve rapid wetting, with a swift increase in viscosity after wetting. Alternatives include cooling after wetting, evaporating a low-viscosity solvent, and inducing a chemical reaction. Silane coatings on the fibers can enhance wetting quality; charge preheating can reduce in-mold time; and rotating molds can reduce press utilization time.

Reproducibility. More than 150 variables must be adjusted during the process sequence from resin formulation to product molding. Microprocessor control is a promising way of controlling SMC formulation variables, such as resin thickness, glass fiber dispersal, and carrier film tension.

Scrappage Reduction. Scrappage should be kept at 5% or less for economic competitiveness. This must be done for complex parts

Table 5.3 (Cont'd)

over the entire production run, including initial process adjustments.

Bonding and Joining Methods. Significant advances are needed in rapid-curing bonding agents; methods of bond clamping during cure so that the manufacturing process can continue; and quick, nondestructive testing methods.

Reinforced Thermoplastics. Reinforced thermoplastics offer shorter cycle times, easier automation, and less post-mold finishing. Data must be developed on the rheological behavior of this fiber/resin system and on the mobility of fibers during the molding process.

Product Characterization

Analytical Techniques. Finite element analysis, computer-aided design, computer graphics, and other techniques are needed to take advantage of the strongly anisotropic characteristics of FRP.

Testing Procedures. High-speed, nondestructive testing methods are necessary for all phases of FRP utilization. Tests are needed for bond integrity, mechanical strength as a function of orientation, performance in adverse environments, and reinforcement dispersion.

Design Engineering Data. Performance characteristics must be established for all types of service and failure conditions.

Fundamental Properties. The interfacial bond between resin and reinforcement needs to be fully characterized.

more cost effective downsizing opportunities are exploited. This lack of emphasis on materials substitution plus cash shortages resulting from Detroit's recent market difficulties have severely restricted research and development funds in the materials area. A number of industry representatives stated that support from a governmental agency like the U.S. Department of Energy (DOE) could be extremely helpful and that savings in total energy through use of FRP components in automotive applications might justify such governmental activity. The objective would be to develop the necessary engineering data and production expertise over the next few years so that FRP could participate fully in the materials tradeoff decisions to be made in the mid-1980s. The government could play two complementary roles: (1) financial support, possibly including tax incentives, for FRP-related research and development within the industrial and academic communities and (2) in-house development of basic engineering data.

Most funding for FRP development not related to the automotive industry is provided by the National Aeronautics and Space Administration (NASA). Research and development programs are conducted at NASA laboratories, and NASA supports contract research at universities, nonprofit research centers, and within industry. Because this effort is devoted to low-volume aerospace applications, the results usually do not apply to high-volume, cost-competitive automotive applications. One could foresee, therefore, an agency like DOE performing a funding role similar to that of NASA, but for automotive applications. While all areas of research could reasonably be supported, development of improved processing techniques should be emphasized.

Because no large-scale research center now exists for FRP materials, the second governmental role, that of establishing a significant in-house FRP engineering data base, could have significant benefits. Without such an effort, it is unlikely that sufficient data will be gathered, even over 5 yr, to support widespread use of FRP. For example, the necessary mechanical testing would require months to conduct, possibly involving up to 100×10^6 cycles. Such a coordinated testing program of anisotropic FRP materials involving more than 150 variables cannot be significantly compressed. This type of research is long term and of a fundamental nature -- not the type of problem best handled by the automotive industry, which of necessity emphasizes optimal solutions to short-term problems using existing resources. Also, the limited research funds of the automotive firms will likely be directed to a myriad of other problems, such as development of new engines. In summary, potential benefit in terms of national energy resources seems to support direct governmental activity in the conduct of FRP-related exploratory engineering design.

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