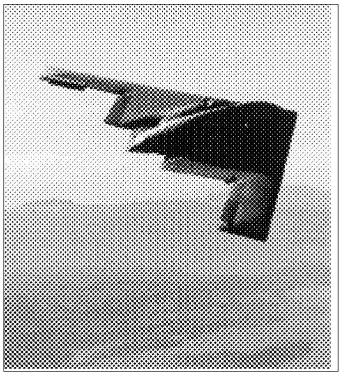
Case Study 2: CMI in the Polymeric Composites Industry

Composite materials are quite common today and are used in nearly every segment of civilian and military industry. Composite materials consist of two or more identifiable constituents that together exhibit properties that are generally superior to the properties of the individual constituents. These materials are certainly not new; the early inhabitants of Egypt, for example, used composite bricks of mud and straw to construct many dwellings. Reinforced concrete, the carbon-epoxy used in some fishing rods and tennis rackets, the lightweight composite used in some armor, and the fiberglass-epoxy used in fishing and racing boats are all examples of various types of composite materials. A 1993 study by the Strategic Analysis Division of the Department of Commerce found that the value of the U.S. market for polymeric-matrix, metal matrix and carbon/carbon composites in 1991 was $2.6 billion, and the worldwide total value was $4.7 billion.[1] (See box 3.)

A wide variety of fiber-resin combinations is in use today, and the market for polymeric-matrix composites—especially for aerospace and military-related products—is large. Until recently, the military applications of polymeric composites were driven mostly by performance advantages. However, over the past few years, cost has become an increasingly important factor in mili-



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[1] U.S. Department of Commerce, *Critical Technology Assessment of the U.S. Advanced Composites Industry* (Washington, DC: U.S. Government Printing Office), December 1993.

BOX 3: Composite Materials

Ceramic-Matrix Composites

Ceramic-matrix composites are composed of reinforcing ceramics embedded in a ceramic-matrix. For example, the reinforcements can be long, continuous fibers; short fibers; small, discontinuous whiskers; particulate; or platelets, Typical reinforcements include alumina, cordierite, mullite, silicon carbide, silicon nitride, zirconia, titanium diboride, fused silica, and graphite, Common matrix materials include alumina, cordierite, mullite, silicon carbide, silicon nitride, zirconia, and titanium diboride,

Ceramic-matrix composites have excellent corrosion resistance, excellent high-temperature resistance, high levels of hardness, relatively high elastic moduli, and low relative weight, They can be classified into three general categories: monolithic or single-phase ceramics (those with no discrete reinforcements); discontinuous fiber-, whisker-, or platelet-reinforced ceramics; and long, continuous-fiber-reinforced ceramics, Unlike polymeric-matrix composites, which need reinforcements primarily to enhance structural properties, ceramic-matrix composites use the reinforcements to improve fracture toughness, reliability, and durability, as well as to enhance structural properties,

Metal-Matrix Composites

Metal-matrix composites (MMC) consist of matrix materials, such as lightweight alloys of aluminum, magnesium, or titanium, reinforced with ceramic particulate, whiskers, or fibers. As is the case with ceramic-matrix composites, reinforcements can be continuous or discontinuous, Carbon fibers and ceramic fibers are used as continuous reinforcements in metal-matrix composites, Typical ceramic fibers used as continuous reinforcements are alumina, silica, boron, alumina-silica, zirconia, magnesia, mullite, boron nitride, silicon nitride, and titanium diboride. Typical discontinuous reinforcements include particulate and whiskers, The most common types of particulate are alumina, titanium carbide, silicon carbide, boron carbide, and tungsten carbide, The most common types of whiskers are silicon carbide, silicon nitride, and alumina,

Carbon-Carbon Composites

Carbon-carbon composites consist of carbon fibers as the reinforcing fiber and a carbonaceous material as a matrix material, Carbon-carbon composites are usually classified into two types: structural and nonstructural, The reinforcing fibers can have many forms: chopped, continuous, two-dimensional woven, and three-dimensional woven, The choice of reinforcement depends on the application,

The process of depositing carbon into a carbon-fiber preform to act as a matrix material is called *densification.* The carbonaceous matrix material is deposited in the carbon fiber preform in two general ways, The most common method is chemical-vapor deposition (CVD), also known as chemical-vapor infiltration (CVI). In this method, the pyrolitic carbon is deposited by the chemical cracking of natural gas at very high temperatures and very low pressures. The second method is referred to as liquid impregnation, In this method, a relatively high-char-yield liquid resin is impregnated into the carbon preform and then carbonized at high temperatures to form the carbon matrix. Both processes must be repeated many times to achieve usual levels of densification, making carbon-carbon composites rather expensive.

The microstructure of the carbonaceous matrix material has an important effect on the properties of the final composite. Microstructure range from small, randomly oriented crystallite known as isotropic crystals to larger, highly oriented lamellar crystallite structures, A significant amount of research work is under way to develop quantitative correlations between microstructure and mechanical and thermal properties of carbon-carbon composites.

SOURCE: U.S. Congress, Office of Technology Assessment, 1995,

TABLE 4: Comparative Properties of Fiber Reinforcements

Material	Density (lbs./in.^{3})	Tensile strength (KSI)	Tensile modulus (MSI)	Specific tensile strength x10^5[lbs/in^2/lbs/in^3]
S-Glass	0.09	665	12,4	73.8
Carbon (T-300)	0.06	450	34	75
Carbon (T650-42)	0.06	730	42	121
Aramid (K-49)	0.052	550	18	105
Boron	0.09	510	58	56.7
Silicon carbide	0.086	400	28	46.5
Aluminum (7075-T6)	0.101	81	10,4	8.1

SOURCE: M.Y.C. Niu, "Composite Airframe Structures" (Hong Kong Conmilit Press, 1992)

tary acquisition. In some instances, cost is now more important than incremental improvements in performance. As competitive pressures increase, cost will play a greater role in the civilian and military markets.

In the commercial sector, cost, coupled with unique function, has long been the major force behind the use of polymeric-matrix composites. For example, fiberglass boats are not only superior to wooden boats in many measures of performance, they are also less expensive to purchase and maintain than wooden boats. Enclosures for electronic devices manufactured from injection-molded composites can also be significantly less expensive than their machined metal counterparts.

The focus of this study is polymeric-matrix-composite materials made by combining short or long fibers or particulate and an organically based matrix material, which binds the fibers or particulate together. Normally, the reinforcements (i.e., the fibers or particulate) are used to carry structural loads, and the matrix material, or resin, is used to hold the fibers together, to protect the fibers, and to transmit structural loads between the reinforcing fibers. This study briefly examines the potential for civil-military integration in the polymeric composites industry. It considers the technology and discusses the current structure and trends of the industry. Finally, it considers factors that enhance or detract from the potential for integration.

TECHNOLOGY AND USE OF POLYMERIC-MATRIX COMPOSITES

▮ Fiber Technology

The typical fibers used in today's polymeric-matrix composites are carbon, aramid fibers, and glass. Fibers come in many forms, such as particulates and short and long fibers. They are primarily responsible for the structural properties of the composite, such as strength and stiffness. The fiber form is usually selected to meet the particular structural requirements of the item being manufactured.

The specific tensile strength (defined as tensile strength divided by density) of composites compared to aluminum is shown in table 4. The higher the specific tensile strength, the lighter the material and the better the structural application for a particular load carrying capability.

▮ Resin Technology

The organic matrices, or resins, most often used in composites can be divided into two major classes: *thermoses* and *thermoplastics*. The choice of resin is largely based on ultimate-use temperature, toughness, environmental resistance, and ease of manufacture. (See table 5.)

TABLE 5: Properties of Thermosets and Thermopla

Resin type	Process temperature	Process time	Service temperature	Solvent resistance	Toughness
Thermoset	Low	High	High	High	Low
Thermoplastic	High	Low	Low	Low	High

SOURCE U S Congress, Office of Technology Assessment, *New Structural Materials Technologies, OTA-TM-E-32* (Washington, DC U S Government Printing Office), September 1986.

TABLE 6: Properties of Thermoset Resins

Material type	Mechanical properties	Upper use temperature	Processibility	cost
Epoxy	Excellent	200-250 “F	Good	Low-medium
Polyester	Fair	180 OF	Good	Low-medium
Phenolic	Fair	350 OF	Fair	Low-medium
Polyimide	Good	500-600 ‘F	Fair-difficult	High
Bismaleimide	Good	350 OF	Good	Low-medium

SOURCE: M.Y.C. Niu, ''Composite Airframe Structures” (Hong Kong: Conmilit Press), 1992.

Thermoset resins change their chemical composition when they are heated (called curing) to form high-strength, high-stiffness, rather brittle cross-linked networks. This process is irreversible. Thermoset resins have been used for many structural applications. The most commonly used thermoset resins are epoxies, polyesters, phenolics, and polyamides, which includes bismaleimides. (See table 6.) Polyamides can also exhibit some thermoplastic behavior at high temperatures. (See box 4.)

Thermoplastic resins differ significantly from thermoset resins and are gaining in popularity. They are expected to be used in the Air Force's Advanced Tactical Fighter. Thermoplastic resins are usually rather high-molecular-weight materials that, rather than being cured to shape, are heated and then formed into shape. No (or very little) chemical reaction takes place in the manufacturing process. The manufacturing process is reversible to some extent, and thermoplastics can be reused and reformed into other shapes. Thermoplastics fall into four general subclasses: amorphous, crystalline, liquid crystal, and pseudothermoplastic.

■ Polymeric Composites as Structural Material

The enormous number of available fibers, fiber forms, and matrix resins allows nearly unlimited freedom and creativity in engineering an optimum material for any given application. While this variety provides a tremendous opportunity for creative problem solving, it challenges traditional thinking about structural design and certification.

Once the fiber is combined with the resin matrix to form a structure, the *interphase* is created. The interactions of the fiber and the resin, which result in the interphase, range from very weak, in the case of electrostatic forces, to very strong, in the case of actual chemical bonding. The nature of the interphase profoundly affects the resultant properties of the composite, and plays a key role in properties such as compressive strength, resistance to fatigue, solvents, heat, and moisture.

The advantages of composites as structural material can be better understood by examining some typical properties of these materials and comparing them with those of conventional materials. (See table 7.) For example, a comparison of spe-

BOX 4: Commonly Used Resins

Thermoset Resins

Epoxy resins are widely used in composite applications. Epoxies in general use are reactive polymers that begin as low-molecular-weight materials and progress to highly cross-linked dimensionally stable materials as they are cured. They generally provide very good resistance to chemicals and solvents, but the mechanical properties are adversely affected by moisture. Epoxies adhere well to most commonly used fibers and exhibit low shrinkage, but they are brittle and subject to impact damage that is not always observable to the naked eye.

Polyesters are formed from the polymerization of a diacid and a diol, which react together to form many ester linkages. Curing agents are then added to the basic formula to provide a rigid cross-linked polymer. Polyesters are relatively inexpensive compared with standard epoxies. They can be cured at low temperatures to provide good mechanical and electrical properties. Like the epoxies, however, they tend to absorb water, which can adversely affect mechanical performance, especially at elevated temperatures. Polyesters possess exceptionally good resistance to acids. They are used in the manufacture of radomes, bowdomes, and other submarine structures, as well as in hulls and masts.

Phenolics are one of the oldest commercially used resins. These very complex materials are formed from the reaction of phenol and formaldehyde. If the reaction is run with excess formaldehyde under basic conditions, the product is called a resole. If the reaction is run with excess phenol under acidic conditions, the product is called a novolac. A resole can be converted to a phenolic with heat only, whereas converting a novolac to a phenolic requires the addition of an amine hardener (or catalyst) and heat. Phenolics are used for aircraft-interior applications and rocket-motor exit nozzles

Polyamides tolerate higher use temperatures than do standard epoxies and polyesters. These materials are used for applications in the 400 to 500 ‘F range and are quite difficult to process. However, they exhibit fair damage tolerance, good temperature resistance, and good mechanical properties. Polyamides are used in the manufacture of missile fins, the Global Positioning Satellite, and printed circuit boards.

Bismaleimides are a subclass of polyamides. They are more easily processed than are the conventional polyamides because they can be processed at lower temperatures. However, to develop their mechanical properties to the fullest extent, they must be subjected to an additional heating cycle (a postcure) of approximately 475 F. Bismaleimides are used for aircraft body skins on the AV8-B Harrier and the Advanced Cruise Missile and for the structure of the Advanced Tactical Fighter.

Damage tolerance has become more important with the ever-increasing use of composites. Producers have made significant improvements in damage tolerance. “Toughened” systems have been developed, and some of the newer systems approach the damage-tolerance capability of thermoplastics.

(continued on next page)

cific tensile strengths and specific shear moduli helps explain the structural advantages of composites.[2]

Differences in specific properties provide designers with a range of choices. For instance, if tensile strength is critical to a particular application—for example, for cables to support a bridge deck structure—the most efficient material for that application would have the highest specific tensile strength, which results in the lightest-weight product. In table 7, that material is the unidirectional carbon-epoxy composite. If shear

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[2] Specific properties, such as specific tensile strength, are calculated by dividing the property, by the material’s density. For example, aluminum’s specific tensile strength is calculated by dividing its tensile strength by its density.

BOX 4: Commonly Used Resins (Cont'd.)

Thermoplastic Resins

Amorphous thermoplastics have no regular order in their molecular structure, have no definite melting point, and are not normally affected by moisture pickup, but they can be affected by solvents, Although they do not possess rigid three-dimensional chemical links, as do thermoses, they typically have long, loosely intertwined molecular chains that serve to enhance their mechanical properties, They exhibit good damage-tolerance properties,

Crystalline thermoplastics have crystalline regions that exhibit some amount of definite order, as well as an amorphous structure overall. These materials possess a definite melting-point range and can have better mechanical properties than do purely amorphous thermoplastics. They exhibit good resistance to solvents, low moisture pickup, and excellent damage tolerance, The materials, however, often show some variability in terms of mechanical properties because the amount of crystallinity present in the end product (which affects mechanical characteristics) is a function of processing and can be difficult to control, They are used in the rudder assemblies of the F117-A (Stealth) fighter.

Liquid-crystalline thermoplastics possess a molecular structure that is often highly anisotropic and aligned in one particular direction. This alignment has profound effects on the mechanical properties of these materials, Typically, the mechanical properties are quite outstanding along the axis of alignment and not as good along the off-axis, Liquid-crystalline thermoplastics are in the early stages of development but hold great promise for tailoring the properties of a composite at the molecular level, They will probably be used in injection molding to create such products as electronic enclosures.

Pseudothermoplastics exhibit some characteristics of both thermoses and amorphous thermoplastics, These materials are often condensation polymers formed by a chemical reaction during the curing or forming process, However, the degree of cross-linking is very low, enabling these materials to be reformed and reused, Many psuedothermoplastics are in the very early stages of development.

SOURCE: U.S. Congress, Office of Technology Assessment, 1995,

strength is critical—for example, the rib webs in an aircraft wing structure-the most efficient material would be the quasi-isotropic carbon-epoxy composite. Real-world structures are usually subjected to rather complex loading schemes, and the best choice of a material for a given application is often determined by a combination of properties.

▮ The Polymeric Composites Market

According to the Composites Institute, a division of the Society of Plastics Industry, Inc., the composites market in the United States produced 2.68 billion lbs. in 1993, an increase of 5.2 percent from 1992. The data are compiled from over 410 firms, including raw materials and equipment suppliers and producers of composite products, and are segregated into nine market segments: aircraft, aerospace, and military; appliance and business equipment; construction; consumer products; corrosion-resistant equipment; electrical and electronic; marine; transportation; and other. (See figure 5.) In the aircraft, aerospace, and military segment, by far the most important single market, shipments in 1993 were 19.5 percent less than those in 1992. (See figure 6.)

The use of composites is driven by requirements falling into three broad categories: performance and function, quality and reliability, and cost. Some examples of unique performance and function requirements in defense systems include reduced weight, transparency to electromagnetic radiation (stealth), dimensional stability, and resistance to ballistic penetration.

Weight reduction in aircraft systems, for example, can result in increased maneuverability, increased range, increased payload, increased speed

TABLE 7: Comparison of Common Composites with Metals

Material	Tensile strength (KSI)	Shear modulus (MSI)	Density (lbs./in^3)	Specific tensile strength x10^3[lbs/in^2/lbs/in^3]	Specific shear modulus x10^6[lbs/in^2/lbs/in^3]
Aluminum (6061)	42	3.8	0.098	428.57	38.78
Steel (4340)	260	11	0.284	915.49	38.73
Cast iron	44	7	0.26	169.23	26.92
Unidirectional EGlass epoxy	150	0.8	0.075	2000	10.67
Unidirectional boron-epoxy	180	0.7	0.073	2465.75	9.59
Unidirectional aramid-epoxy	180	0.3	0.05	3600	6.0
Unidirectional carbon-epoxy	200	0.7	0.055	3636.36	12.73
Quasi-isotropic carbon/epoxy	80	2.8	0.055	1454.66	5091

SOURCE "Design Guide for Advanced Composites Application," *Advanced Composites Magazine, 1993*

(for a given thrust capability), and decreased fuel consumption, and it has led to the use of polymeric composites that are stiffer and stronger than metals at equivalent weights. The increased fatigue resistance of composites also leads to longer service life.

Many polymeric composite structures have been more expensive than their metal counterparts, especially in terms of acquisition costs. However, recent advances in design practices and composites manufacturing technologies have reduced this cost differential. In some cases, especially where several smaller-parts can be combined into one larger composite part because of a particular property advantage or better manufacturing technology, the composite part is now less expensive than the metal part.

Commercial uses of polymeric-matrix composites are very diverse. Some specific examples include weight in the transportation industry; x-ray transparency and biocompatability in the medical industry; corrosion resistance in the automotive, chemical, and oil industries; tailorable mechanical properties in the sporting goods industry; and electrical resistance and electromagnetic shielding in the electronics industry. In many cases, the materials used for defense applications are identical to those used for commercial applications. The quality specifications for commercial applications are, however, often less strict than those for military applications.

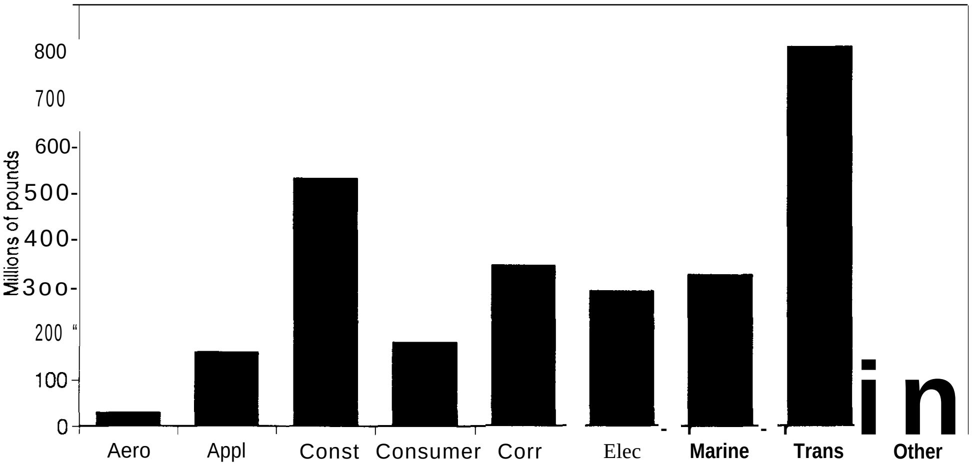
Defense Applications

Polymeric composites are used in a wide variety of defense applications and are found in almost every major weapon system produced. In many cases, weapons systems could not perform their missions without polymeric composite materials. (See table 8.)

The Army uses composites in its helicopters, land vehicles, missiles, munitions, and support equipment. The excellent fatigue and damping characteristics of composites make them ideal for helicopters. Carbon-epoxy materials, for example, are used in the construction of helicopter airframes, refueling booms, skin panels of various types, lightweight bridging, antenna masts, and munitions. Aramid (Kevlar) epoxy is used in helicopter rotor blades, span liners (to protect personnel from shrapnel), launch tubes, helmets, and tactical shelters. Glass-epoxy (both S-Glass and E-Glass) is used in items such as fuel tanks, span liners, rotor blades, launch tubes, motor cases, and bore evacuators. Composites have extended the service life of helicopter rotor blades by a factor of 2 to 3 and have enabled designers to improve the design of the blade. Finally, the airframes of the new generation of helicopters will be largely made of polymeric composites.

The Navy uses polymeric composites in its fixed-wing aircraft, rotary aircraft, ships and submarines, missiles, and satellites. Carbon-epoxy is

FIGURE 5: 1993 Polymeric Composite Shipments



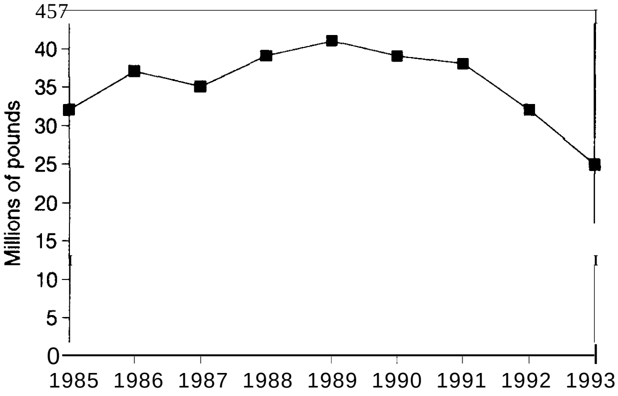
SOURCE: Society of Plastics Industry, Inc. , *Composites Institute Semi-Annual Report, New* York, NY, August 1993

used for wing skins and doors, stabilizer skins, leading and trailing edges, basic airframe structures, refueling booms, and skin panels. The upper wing skin of the Marine Corps AV-8B, for example, is one of the largest one-piece carbon-epoxy aircraft structures made. Over twenty-six percent of the AV-8B's structural weight is polymeric composite material. The Navy also used polymeric-matrix composites to rewing A-6 aircraft. Carbon-epoxy is used in the fabrication of the aircraft ribs, spars, and skins. Aramid (Kevlar) epoxy is used for fairing, spoilers, rotor blades, and launch tubes. Glass-epoxy is used in fairings, spoilers, radomes, rotor blades, fuel tanks, sonar domes, ship hulls, launch tubes, and electromagnetic windows. The V-22 Osprey tilt-rotor craft will use a significant amount of carbon-epoxy composite as primary structural material: approximately 50 percent (by weight) of the fuselage structure, the wing leading and trailing edges, the wing itself, and the empennage. Composites are used in many marine applications because of their acoustical properties.

The Navy has the largest and heaviest (65,000 lbs.) single-piece composite structure of any of the U.S. armed Services: the glass-toughened epoxy bowdome used in the SSN-21 Seawolf submarine. The MHC-51 coastal mine hunter has an all-composite hull.

The Air Force uses composites in a wide variety of aircraft, missiles, launch vehicles, and satellites. Carbon-epoxy structures include wing skins, access doors, stabilizer skins, leading and trailing edges, motor cases, storage spheres,

FIGURE 6: Trends in Aircraft, Aerospace, and Military Composite Shipments



SOURCE: Society of Plastics Industry, Inc., *Composites Institute Semi-Annual Report, New* York, NY, August 1993,

TABLE 8: Defense Aviation and Space Use of Composite Materials

Rotary-wing aircraft	OH-58, OH-6A, UH-60A, CH-46, CH-47D, AH-IS, MH-60, RAH-66, AH-64A
Fixed-wing aircraft	B-2, B-52, B-1 , AC-130U, C-135, C-26A, C-135, C-26, A-10, TR-1 , F-15, F-1 17A, F-16, F-22, F-111, C-17, C-58, KC-10, V-22, AV-8B, F/A-18, F-14, A-6
Missiles	LGM-118A, AGM-129A, AGM-131, MGM-134A, Hellfire, AMRAAM, Patriot, AGM-65, MLRS, HARM, AT-4, TOW-2, AAWS-M, Stinger, D-5, Tomahawk
Satellites	MILSTAR, Defense System Communication Satellite II, Defense Support Program, Global Positioning System

SOURCE: Office of Technology Assessment, 1995, based on information from H. Reinert and P Hauwiller, *Horizontal Assessment of the Organic Composites Industrial Base,* WL TR 928044 (Beavercreek, OH: Universal Technology Corp. , July 19, 1992), and other sources

adapter skirts, longerons, struts, and trusses. Aramid (Kevlar) epoxy is used in fairings, spoilers, ducting, leading and trailing edges, motor cases, rings, insulation, face sheets, and antennas. Glass-epoxy is used in fairings, spoilers, wing tips, radomes, electromagnetic windows, antennas, and struts. About 40 percent, by basic structural weight, of the airframe of the F-22 tactical fighter will be composite materials.

Commercial Applications

Polymeric-matrix composites have both aerospace and nonaerospace commercial applications. As in the military, strength and light weight enhance aerospace applications.

Aerospace use

Polymeric composite structures have a wide variety of applications on large civilian-transport aircraft. For example, the Boeing 747 uses a 6-ft.-high winglet, carbon-epoxy front- and rear-wing spars, and spar covers made from a carbon-epoxy honeycomb-sandwich structure. The inboard and outboard spoilers, aileron, rudder, elevator, and inboard trailing-edge flap of the B757 are all made from carbon-epoxy composites. The B767 uses carbon-epoxy in the inboard and outboard ailerons, the rudder, the vertical fin tip, and the inboard and outboard spoilers. Carbon and Kevlar-epoxy are used in the trailing-edge-flap track-support fairings, the fixed trailing-edge panels, the vertical-fin fixed trailing-edge panel, the horizontal stabilizer tip, the outboard-flap trailing-edge wedge, the main landing-gear doors, and wing-to-body fairing. Glass and carbon-epoxy are used in the nose-landing-gear doors.

The choice of which composite to use for a particular structure depends on the complex interaction of many factors, including critical loading strength and stiffness criteria, damage tolerance, repairability, ease of manufacture, and cost. Cost and “acceptance and understanding by structural designers” are cited as two reasons why U.S. manufacturers do not make more use of composites on large commercial transport aircraft.

Smaller civilian aircraft use polymeric-matrix composites much more extensively than large aircraft. The Beech Starship, a twin-pusher canard aircraft, is an outstanding example of the full utilization of polymeric composite materials. The airframe is made of carbon-epoxy facesheets bonded to a low-density Nomex honeycomb core. This sandwich structure is very lightweight and extremely efficient. The structural weight of the aircraft is about 15 percent less than a conventional aluminum airplane, and the cost of producing the composite structure is approaching the cost of fabricating an aluminum structure.

Non-aerospace use

Polymeric composites have a wide variety of non-aerospace applications. The sporting goods industry, for example, represents a significant commercial market: tennis rackets, golf clubs, high-performance racing bicycles, canoes, kayaks, canoe and kayak paddles, bobsleds, and snow skis are a few of the applications. Sporting goods companies have taken composite design and manufacturing technologies to very high levels. Indeed, most tennis rackets are currently designed and manufactured using sophisticated hybrid composite technologies to create very specific properties. Carbon fibers and aramid fibers, for example, are combined to tailor the stiffness (primarily from the carbon) with the energy-damping characteristics of aramid to produce rackets with certain *power and feel* or control characteristics. Some manufacturers use a combination of ceramic and carbon fibers in their rackets to achieve a particular balance of properties. No professional tennis player could be competitive today with the wood, steel, or aluminum rackets of the past.

Many cars and trucks now have polymeric composites body panels, hoods, bumpers, cabs, fairings, air deflectors, and truck sleeping compartments. These applications represent *secondary* structure, that is, structure that does not carry primary loads in the vehicle. Several companies are involved in producing specialty vehicles, such as mass-transit vehicles and extremely lightweight commuter and delivery vans, that incorporate composite materials, primarily glass-polyesters, in their primary structural components. The design philosophy is to produce one-piece structures that greatly reduce assembly costs. However, these vehicles are being manufactured in small numbers by fabrication techniques that require hand custom work, rather than in the large volumes associated with the mainstream light-car, light-truck market.

Successful prototypes of cargo-carrying rail cars have been produced by using filament-winding manufacturing techniques appropriate for small production volumes at a cost comparable to that of metal cars. However, no major market for these cars materialized, the company that developed the techniques was sold, and the new owners elected not to market the product.

The medical uses of polymeric-matrix composites include x-ray tables, prostheses, and implants. The potential liability associated with the latter applications has hindered their use, however.

The commercial marine industry represents a large potential market for the application of polymeric matrix composites. Major uses are glass-polyester powerboats, pleasure yachts, and recreational watercraft such as jet skis. The very sophisticated America's Cup yachts use carbon, aramid, and glass composites extensively in their construction.

The infrastructure market is increasingly important and potentially very large. Polymeric composite materials, for example, can solve some of the problems resulting from the deficiencies of conventional steel-reinforced-concrete materials. Applications include vehicular and pedestrian bridge decks (DOD's Technology Reinvestment Project has funded a demonstration project), associated structural components such as pins and hangers, light poles, in-ground gasoline storage tanks, and over-wrappings to prolong the structural life of existing bridges and to increase their resistance to failure from earthquakes. Gasoline retailers now use composite gasoline tanks to replace older, corroded, leaking steel tanks.

Applications of polymeric composites in the construction industry include composite tub and shower units, panels for interior partitions, prefabricated equipment shelters, ladders, and glazing for institutional buildings.

THE STRUCTURE OF THE POLYMERIC COMPOSITES INDUSTRY

U.S. Structure

The polymeric composites industry is composed of resin-matrix suppliers, fiber suppliers, prepreggers,[3] textile weavers, equipment suppliers, parts

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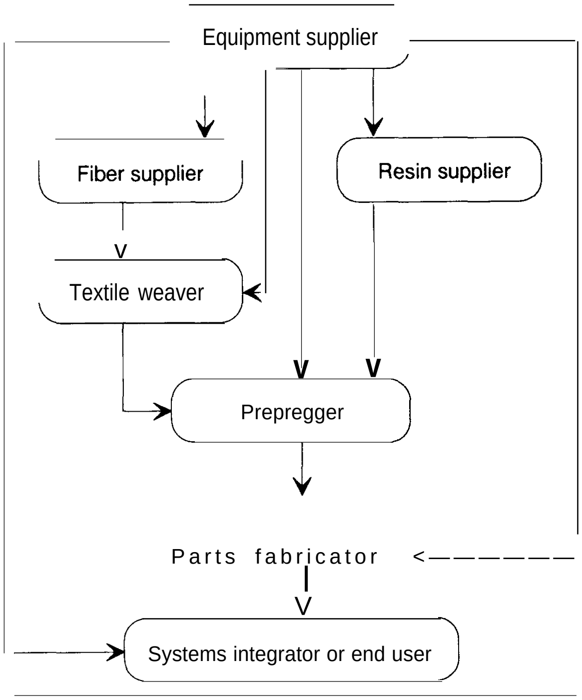
[3] Prepreggers take their name from their process: the impregnation of reinforcing fibers with the resins under controlled conditions.

FIGURE 7: Structure of the Polymeric Composites Industry



SOURCE: Office of Technology Assessment, 1995, based on information from Off Ice of Technology Assessment, "The Advanced Composites Industry, " *Holding the Edge. Maintaining the Defense Technology Base,* Vol *2.* Appendixes.

manufacturers, systems integrators, independent consultants, and end users. (See figure 7.) The industry has a fair amount of vertical integration. (See table 9.)

Resin-matrix suppliers tend to be large chemical companies that supply the basic resins and additives to prepreggers. Fiber suppliers also tend to be large chemical companies that provide various fiber forms to prepreggers and independent textile weavers, who weave the fibers into fabrics for various applications. Equipment suppliers provide such things as fabrication equipment and consumable items used in the manufacture of end-item parts. Prepreggers combine the fibers with the resins to form prepreg, which is generally used as the "raw material" for the fabricators. Parts manufacturers actually manufacture component or end-item parts. Systems integrators integrate the subassembly parts into a final product.

▮ Global Structure

European polymeric composite firms, like U.S. firms, have forward integrated into the prepreg and structures manufacturing business to gain the value added in the business process. In the early 1990s, British Petroleum, for example, worked in fibers, resins, fabrics, prepreg and structures. Ciba-Geigy worked in everything except fibers, as did Shell and Imperial Chemical Industries. (See box 5.)

As in the United States and Europe, many different companies in Japan produce composite products. These companies include Toray Industries, Sumitomo, Toho Rayon, Mitsubishi Rayou, Asahi Hasei Carbon Fiber, and Nippon Polyimide. Japanese companies that typically started as material suppliers continue to forward-integrate to expand their business both domestically and in the United States. In Japan, sporting goods and leisure products constitute the largest market for polymeric composite materials.

▮ Industry Trends

There are both negative and positive trends in the industry. The drops in defense spending and commercial aerospace have had a major negative impact on the industry. The 1993 study by the Strategic Analysis Division of the Commerce Department found that nearly 40 percent of the firms in this business reported operating losses in 1991.[4] Overall employment in the industry dropped nearly 20 percent between 1990 and 1993. Research and development (R&D) employment in 1993 was down nearly 40 percent from its peak in 1990, indicating a dramatic decrease in R&D investments in the private sector. Consolidation, divestment, and layoffs of skilled production workers and technologists have become quite common.

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[4] *Critical Technology Assessment of the U.S. Advanced Composites Industry,* op. cit., footnote **51.**

TABLE 9: Firms Involved in the Polymeric Composites Industry in Early 1994

Item	Company
Resin	American Cyanamid, Amoco, BASF, B.P. Chemicals, Ciba-Geigy, Dow, Epolin, Fiber-Resin Corp., Hercules, Hexel, ICI/Fiberite, Masterbond, McCann, Minnesota Mining and Manufacturing, Poly-Freeze, Polyrene Development, PTM&W, Shell, S.P. Systems, Textron
Fiber	
Suppliers	Allied Signal, Amoco, AKZO, Ashland, DuPont, Great Lakes Carbon, Hercules, Mitsubishi Rayon, Owens Corning, PPG, Textron Specialty Materials, Toho Rayon, Toray, Zoltek
Weavers	Advanced Textiles, Atlantic Richfield, BGF, Burnham Products, Clark Schwebel, Dexter, Fabric Development, Fiber Materials, Highland Industries, J.B. Martin, J.P. Stevens, Ketema, Miliken, Mutual Industries, North American Textiles, Precision Fabrics Group, Techniweave, Textile Composites, Textile Technologies, Textron, Woven Structures, Zoltek
Composite equipment	Airtech International, AVS, Bondline Products, Cincinnati Milicron, Dow Corning, Grim, Icon Industries, Ingersoll, Liquid Controls, North American Textiles, Precision Fabrics Group, Richmond Aircraft Products, RIM Systems, Schnee-Morehead, Thermal Equipment, United McGill, Wacker Silicone
Prepreggers	American Cyanamid, BASF, B.P. Chemicals, Ciba-Geigy, Fiber Cote, Fiber Materials, Fiber Resin, Hexel, ICI/Fiberite, McCann, Minnesota Mining and Manufacturing, Newport Adhesives, Quantum, S.P. Systems, YLA
Major parts manufactures/end users/systems integrators	
Defense	ABB, Aerojet, Alcoa-CSD, Bell Helicopter, Boeing, B.P. Chemicals, Brunswick, General Dynamics, Grumman, Hercules, Kaman, Lockheed, LTV, Martin Marietta, McDonnell Douglas, Morton Thiokol, Northrop, Rockwell, Rohr, Sikorsky, Teledyne
Commercial	Boeing, Chrysler, Composite Horizons, Dunlop, DuPont, Ford, General Motors, Hercules, Hexel, Prince, Wilson Sporting Goods

SOURCE: Office of Technology Assessment 1994, based on information from H. Reinert and P. Hauwiller, *Horizontal Assessment of the Organic Composites Industrial Base,* WLTR928044 (Beavercreek, OH; Universal Technology Corp., July 19, 1992), Office of Technology Assessment, "The Advanced Composites Industry, " *Holding the Edge: Maintaining the Defense Technology Base, vol. 2:*appendixes, 1990, and other sources.

On the other hand, according to the Composites Institute, the weight of U.S. shipments of composites in 1993 was 5.2 percent higher than it was in 1992.[5] In addition, four markets that represent 72 percent of the composites industry by market share (transportation, construction, electrical-electronic, and marine) were all forecasting faster growth rates than the general economy.

The major concern of those worried about the health of the industry is the aerospace-aircraft-military sector, where shipments decreased 19.5 percent in 1993. This downward trend is cause for alarm because this segment of the market generally represents the leading edge in technology development in polymeric composites. In the past, developments in aerospace/military have tended to filter down to commercial uses in other segments of the economy, and have provided technological and economic stimulation in those segments. As a result, this sector is viewed as a "leading indicator" of the polymeric composites industry overall.

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[5] Society of plastics Industry, Inc., *Composites Institute Semi-Annual Statistical Report* (New York, NY: Society of plastics Industry, Inc.), August 1992.

BOX 5: Efforts by Consortia To Support Composites Technology

Consortia are emerging as a powerful force in the composites industry as a result of government policy initiatives, such as cooperative R&D agreements, that encourage pre-competitive development activities and that tend to enhance civilian-military integration. The typical consortium consists of groups of companies, including suppliers, fabricators, and end users, that band together to develop pre-competitive technology that can be used by all members. Funding is either a combination of federal funding and member funding or strictly member funding. Several consortia have been formed to address pre-competitive issues related to composites technology. Most of the industry representatives interviewed by OTA consider consortia essential if the U.S. industry is to survive and compete in the global marketplace. Because of the rapidly changing pace of the technology, no one company can afford the R&D investments required to address all the related multidisciplinary issues. Also, consortia are a cost-effective means for companies to address pre-competitive technology issues of interest to the entire community. The fact that many in industry have come to the conclusion that pre-competitive technology cooperation is possible reflects a major shift in attitude toward R&D investment strategy; for many years, companies believed that all related technology information was competitive in nature.

A wide spectrum of technology issues ranging from basic research to materials database development to manufacturing technology development are addressed in consortia.

Composite Materials Characterization, Inc., for example, is composed of Dow Chemical, Lockheed, General Electric, Grumman, LTV, Rohr, and Sikorsky. These members are primarily resin suppliers, fabricators, and end users of composite products. The purpose of this consortium is to establish standards for test methods, processes, evaluation criteria, and materials selection. The consortium also tests new composite materials to establish a consistent independent database of mechanical properties for promising materials. The database is not intended to be a detailed design database for design allowable; rather, it is intended for screening and general comparison of emerging materials. The participating companies fund this effort with no federal help, and the annual investment is about $500,000 to $700,000. However, the data are available only to consortium members.

The Automotive Composites Consortium consists of the “big three” automotive manufacturers — Ford, General Motors, and Chrysler. The purpose of this consortium is to establish joint research programs to demonstrate the advantages of structural polymeric composites for automotive applications and to develop pre-competitive technology necessary for implementation. The consortium is currently working on a demonstration program on rapid resin-transfer molding of structural parts, such as the front end of the Ford Escort. Very ambitious goals have been set for the program, including manufacturing the parts in 5 minutes or less using structural reaction injection molding (SRI M). These manufacturing times are necessary for an economically viable production process for the volumes common in automotive production.

The Center for Composite Materials at the University of Delaware operates a U.S. Army Research Office/University Research Program that concentrates on the manufacturing science of composites from a research perspective. The Center also offers several educational products, including a Design Encyclopedia, an interactive videodisk course on the Experimental Mechanics of Composite Materials, and a video series entitled “Introduction to Composites. ” Each year, it sponsors a workshop about composites for members and a symposium for the public.

The National Center for Manufacturing Science (NCMS) in Ann Arbor, Michigan, is a broad-based manufacturing consortium that addresses many types of manufacturing technologies and issues relating to manufacturing. Only a very small portion of its work is devoted to composites.

(continued on next page)

BOX 5: Efforts by Consortia To Support Composites Technology (Cont'd.)

The Composites Automation Consortium of Burbank, California, consists of Dow Chemical, Charles Stark Draper Laboratories, Foster Miller, Hexcel Corp., Ingersoll Milling Machine, Lockheed Corp., and several others. This consortium is developing automated manufacturing assembly and joining systems to produce composite structures. Its focus is not to develop machines for one assembly or joining technique but to develop machines that are inherently flexible enough to handle a variety of joining and fiber-placement processes. Automated fiber placement and joining had been identified as a critical technology for manufacturing polymeric composite structures in a cost-effective way.

The Great Lakes Composites Consortium, Inc., of Kenosha, Wisconsin, is probably the most broad-based consortium in the United States that concentrates solely on composites manufacturing. This consortium operates the U.S. Navy's Center of Excellence for Composites Manufacturing Technology and consists of over 60 members from all regions of the United States. The principal members are Bell Helicopter-Textron, Inc., Grumman Corp., Lockheed Corp., McDonnell-Douglas Corp., Northrop Corp., and Rockwell International Corp. Other members represent automotive suppliers, machine-tool builders, electrical-control manufacturers, shipbuilders, hand-tool manufacturers, and research institutes and universities. The consortium sponsors applied technology development and technology transfer programs at member facilities. One unique feature of this consortium is the Composites Technology Center in Kenosha, which is a modern composites manufacturing and teaching facility that allows members to transfer technology using the concept of "shared manufacturing. " The consortium's major initiatives include materials and process development, affordable tooling development, net-shape fabrication, fit-up and assembly technology, large structural repair, and environmental-compliance activities.

SOURCE: Office of Technology Assessment, 1995.

Although the number of commercial users of composite materials is growing, demand for defense products is declining and mirrors the decline in the defense budget.

An examination of public and private R&D investments in the advanced-composites industry between 1989 and 1993 reveals another interesting trend. In 1989, when the general perception was that demand for these materials would increase, private investment was a much greater part of the total investment in the industry than was public investment. Confronted with more difficult business conditions in the early 1990s, however, the private sector reduced its R&D spending and the government's share of the investment risk increased.

Designers and manufacturers are reportedly becoming more sophisticated in their technical capabilities, but there are relatively few technical experts in composite design and analysis. Most of these experts have obtained their education through years of on-the-job experience and/or graduate school courses. In general, undergraduate schools do not emphasize composites in formal degree programs. One reason often given for this is that composites technology is truly a multidisciplinary field, and many universities find it difficult to develop effective undergraduate interdisciplinary programs. To design and use composites effectively, technical experts need to understand the basics of chemistry, physics, materials science, mechanical engineering, manufacturing engineering, and must be computer literate. Many in the industry believe that the lack of a formal curriculum in composite materials technology at the undergraduate level has inhibited the widespread use of composites in industrial applications. Industry is also concerned about the lack of basic math and science skills for its composites labor force.

Manufacturers interviewed for this study generally reported a need to improve the manufacturing technology of polymeric composites. For many sophisticated aerospace applications, manufacturing output is low and costs are high. Traditional processes are cumbersome and uneven in quality. The federal government has provided a significant amount of funding for manufacturing-technology development under a variety of programs, which according to some industry observers, have yielded good results for defense applications.[6] Examples of manufacturing-technology programs with both defense and commercial applications include developing resin-transfer molding, injection molding, automated fiber placement, and tooling. (See box 5.)

Material suppliers and small fabricators have been severely hurt by the downturn in business. Some have filed for protection under the bankruptcy laws, others have been put up for sale by their parent organizations. S.P. Systems has been put up for sale by its Italian parent, Montecatini, as have the composites operations of B.P. Chemicals. Alcoa attempted to divest itself of its composites operations but took them off the market when no suitable buyer could be found. The same thing happened to Fiberite, whose parent company is British-based Imperial Chemical Industries (ICI). Industry insiders say that the parent organizations often paid too much for the companies and were subsequently unable to recoup their investments. Continued consolidation and downsizing is expected.

CIVIL-MILITARY INTEGRATION

OTA interviewed several representative firms to assess the current level of integration and factors that favor or constrain integration. The firms chosen, all of which have had significant experience with the government and civilian sectors of the market, were a large, diversified chemical company that started as a material supplier and forward-integrated into parts manufacturing; a small, very capable fabricator that recently diversified out of the military sector entirely into the commercial aerospace sector; a small company that provides the commercial and military marine industries with composite structures and R&D; and a large, diversified commercial and military aerospace company whose development efforts are considered pioneering in the composites field. OTA conducted standardized, indepth interviews with key executives of these firms. In addition to these interviews, less formal interviews were conducted with other material suppliers, designers, manufacturers, and users of polymeric composite materials to expand the database and gather as wide a variety of opinions as possible. Because of competition among firms and the reluctance of some individuals to be quoted directly, some descriptions of specific applications, customers, market share, and specific strategies are not given. Rather, information is presented as general observation.

The firms represent diverse business activities. Their product mix varies from a high of 30/70 civilian/military, to a 50/50 civilian/military, to nearly all civilian (aerospace and nonaerospace), and finally to 100 percent civilian. Their products range from basic polymeric composite raw materials to large fabricated structures, and almost everything in between, including medical x-ray tables, bicycle wheels, aircraft structural parts, recreational boat parts, corrosion-resistant electrical housings, and infrastructure parts, such as small bridges, piers, and poles.

▮ Factors Favoring Integration

Several technical, market, and policy factors favor integration.

Technical Factors

Technical factors favoring civil-military integration in the polymeric composites industry include common design and software, similar manufacturing processes, common inspection technology, and common materials.

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[6] Interviews conducted for this assessment.

Common design and software

The increasingly sophisticated products of both the civilian and military markets require firms to update and enhance their design, analysis, and materials-selection processes. Firms now have at their disposal a wide range of design, modeling, and analysis software.[7] This software allows the designer to conceptualize products, often with three-dimensional details, and translates material properties into quantitative material requirements and spatial arrangements to meet product specifications. Much of the impetus for developing modeling capabilities stemmed from military requirements that demanded detailed design and analysis of products, and from the need to substantiate the mechanical and environmental performance of products before anyone would buy them.

The federal government is sponsoring several design technology R&D efforts. An example is the concurrent engineering and manufacturing systems development at the Design and Manufacturing Institute of the Stevens Institute of Technology in Hoboken, New Jersey. This effort, which has been funded by the Army Research Office and the U.S. Navy's MANTECH program, seeks to develop sophisticated software that incorporates artificial intelligence in the form of expert-system rules in the design, analysis, and manufacturing process and attempts to integrate them into one package. The goal is to reduce significantly the time it takes to go from conceptualizing the product to delivering it to the customer. Indeed, now that the know-how to manufacture high-quality, low-defect products is widespread, time to market is the key issue in global competitiveness.

Similar manufacturing processes

End-use-product structural and environmental requirements greatly influence, and in many instances dictate, the choice of the manufacturing process. Many common manufacturing-process technologies, however, can be used to make products for both the defense and commercial markets. For example, injection molding of short-fiber composites is used to produce electronic enclosures for commercial computers or military electronics, and autoclave curing technology, coupled with continuous fiber-reinforced raw materials, is used to produce wing skins for commercial jetliners and military fighter aircraft.

Not all manufacturing-process technologies, however, can be adapted to produce civilian and military products in cost-effective ways. For instance, manufacturing technologies required to produce low-observable structures for military applications have been rather expensive because of the unique nature of the product's requirements. Several firms in conjunction with DOD are pursuing the development of lower-cost manufacturing processes for *stealth* structures.

Common inspection technology

Nondestructive testing techniques developed primarily to assess military applications product quality are applicable in both markets. Information derived from *inspection* investigations helps to provide a database and the knowledge needed to improve and optimize existing manufacturing processes. However, commercial products, especially nonaerospace commercial products, rarely have the same high level of formal inspection re-

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[7] One reasonably priced software package called Auto-Cad (manufactured by Auto-Desk, Inc.) runs on personal computers, features three-dimensional modeling, and sells for a few thousand dollars. Another design package named Pro-Engineer (manufactured by Parametric Technology Corporation) features three-dimensional modeling and parametric dimensioning, which uses mathematical equations to describe and automatically recalculate the relationship among part attributes, such as length, width, and height, when changes are made. This type of software package costs about $10,000. SDRC, Inc., manufactures IDEAS, a parametric-based three-dimensional modeling system that includes finite element modeling capabilities for stress and thermal modeling and fluid dynamics. This system is in the $10,000 to $20,000 price range. A much more sophisticated system, ICAD, is being marketed by ICAD, Inc. ICAD incorporates artificial intelligence in the form of knowledge-based rules to assist the designer in creating sophisticated parts. This type of system is in the $100,000 price range.

quirements as do military or commercial aerospace products.

Common materials

Another technical factor favoring civilian-military integration in the polymeric composites industry is the ability to use common materials, especially in the aerospace sector. Both commercial and defense aerospace demands that structures be made from materials deemed to be *qualified* in various mechanical-property evaluations and manufactured in a *precisely controlled* process. In the case of some commercial applications outside the aerospace market, however, the *aerospace way*, as it has been termed, may actually inhibit integration because of the cost of precisely controlling the process.

Market Factors

The major market factors that favor civil-military integration in the polymeric composites industry are the reduced defense market and the current approaches to quality assurance and customer satisfaction.

Reduced defense market

The reduced demand for military aerospace products has already been noted. Commercial aircraft producers are also experiencing a downturn in demand for new aircraft. Many airlines have either not exercised production options or have canceled existing production options. The reduction is forcing material suppliers and manufacturers, as well as end users, to look to new markets if they are to survive and grow. The civilian nonaerospace market (composed of bridges, railcars, light poles, prostheses, highway dividers, structural enhancements to existing structures, and sporting goods and other recreational products) is the logical place to look for new product applications. Many firms are doing so, but with mixed results.

Bridge components such as pins, hangers, and cables are thought to be huge potential markets for the industry. Some have suggested that the federal government, through the Federal Highway Administration, could increase the funding for demonstration projects already under way, sponsor additional projects, and accelerate the rate at which technology is demonstrated and applied. The Technology Reinvestment Project awarded a multimillion-dollar contract to the Advanced Technology Transfer Consortium to develop and deploy many of the technologies needed to exploit the use of composites in the infrastructure, especially in vehicular and pedestrian bridge-building and bridge-repair technologies.

The development of new, nondefense composites markets could allow firms to stabilize their business base, thus facilitating military-civilian integration. As was noted earlier, the transportation, marine, construction, and electrical-electronics markets were expected to grow faster than the general economy in 1993, making them attractive possibilities. There is, however, a question about how cost-effective the transition from military and civilian aerospace applications to nonaerospace commercial applications will be. Such transitions often require significant changes in a firm's culture and its business practices. (See *Factors Inhibiting Integration*, below.)

Approaches to quality and customer satisfaction

The trend toward *lean production* will also enhance civilian-military integration in the composites industry. This strategy is not the same as traditional divestment and consolidation; rather, it refers to redesigning the business to provide existing customers and markets with high-quality products in a timely fashion. This concept has been extended to new-product development, forcing firms to integrate their development activities and to transfer technology between previously separate customer bases.

In the past, the predominant view in both the military and commercial composites sectors was that quality was *inspected in* the product. Each item was inspected separately. This practice led to a very large and cumbersome quality-control system that added significant cost to products. Over the past decade, the military and commercial companies have moved to implement a different philosophy of quality, reducing reliance on detailed examinations and increasing the reliance on detection and elimination of process problems. Changes in federal regulations and paperwork requirements are needed to promote this approach at DOD. The DOD changes in the application of military specifications and standards address some of these issues.

The adoption of a modern philosophy of quality strongly affects a firm's approach to operations in general and to manufacturing operations specifically. The development of high-quality, flexible manufacturing processes is an outgrowth of these improvements and should help firms serve both the civilian and military markets.

Policy Factors

Finally, several recent policies appear to favor civilian-military integration efforts in the composites industry. The DOD attempt to adopt the total quality management (TQM) philosophy is one step. Adopting a TQM approach promotes integration efforts because it encourages defense firms to move toward "lean production" and develop closer cooperation among suppliers and customers. Further, if the government truly adopts this philosophy, defense-procurement activities should be conducted more like those in the private sector and firms seeking to serve both markets would not have to support two different operational systems (e.g., defense and commercial accounting and quality control). However, the fact that one company interviewed for this study recently spun off a sister company as a means to separate its government and commercial composite business activities is evidence that the objectives of this policy have not yet been achieved.

ARPA's Technology Reinvestment Project (TRP) includes several composite projects. Industry representatives interviewed generally believed that the TRP can have a significant positive impact on integration in this industry. Some argued that the TRP is emphasizing dual-use technologies that apply equally well to military and civilian uses. The development of product applications for both markets could lead to an overall expansion in the use of composite products. This expansion would tend not only to lower overall costs for existing and new products but would also create spinoff applications. Further, firms stated that TRP funding, which is cost-shared by the private sector, represents investments in the technology that could not otherwise be made by the industry. (See box 6.)

Factors Inhibiting Integration

Technical Factors

Several technical differences between markets inhibit civil-military integration, including the length of the design process, product requirements, and the material-properties database and testing methods.

Length of the design process

In the military market and in the civilian aerospace market, customer requirements tend to be developed by large, complex organizations over relatively long periods. In contrast, firms providing commercial, nonaerospace applications of composites are required to respond to relatively rapid market changes and the design phase is compressed. Complexity is also a factor in the length of the design process. Aerospace products perform functions that are often more complex and potentially more dangerous than are those of other commercial products. Problems can arise when one organization attempts to serve both markets simultaneously because organizations often have difficulty "shifting gears" to meet customer needs.

Product requirements

Civilian and military applications usually have very different product requirements, especially for nonaerospace applications. To serve a market with diverse product requirements, an organization needs diverse design and manufacturing skills. However, because of the nature of military products, specialists tend to concentrate in rather narrow technical areas. This specialization can become a barrier to addressing the wide range of technical issues arising in the commercial nonaerospace market.

As a result of differing product requirements, the manufacturing technologies and procedures needed to satisfy many commercial applications are quite different from the ones that are suitable for military applications. Even when these skills can be developed within an organization, the cost of doing so can be very high. In addition, diverse manufacturing methods often require the use of different types of equipment, which can require large amounts of capital investment.

Material-properties database and testing methods

The development of acceptable material properties and testing standards represents a significant investment. Often, the data needed to serve one market are vastly different from those needed for another market. Testing standards required to certify or produce "believable" results can cost millions of dollars. Many firms simply cannot afford this investment.

Industry members and federal users of composite materials are attempting to develop standards for testing and a common database for the mechanical and environmental performance of composite materials. Much of this work is funded by DOD and defense firms, which contribute the time and travel expenses of their technical experts in the field. The development and acceptance of standard testing methods and a commonly accepted design database would help lower the cost of using composites.

Market Factors

Certain product or market characteristics inhibit civilian-military integration, including production volume and size and procurement practices.

Production volume and size

Typical military and commercial aerospace products are usually large and are produced in relatively low volumes. Because aerospace manufacturing equipment and processes are geared to large, low-volume products, these firms find it difficult to address civilian markets that are composed of small, very high-volume products. One potential exception is the use of composite structures in infrastructure applications, such as bridges, which are large structures produced in relatively low volumes.

Procurement practices

Almost every industry participant interviewed by OTA cited government procurement practice as one of the leading factors inhibiting civilian-military integration. Government procurement regulations are viewed as too complex, often contradictory, and difficult to interpret. Because of the nature and complexity of the regulations, significant costs are incurred.

Some observers have argued that large organizations sometimes have difficulty quantifying the effects of the regulations on product costs because these organizations employ so many people who are working both on the government procurement process and on civilian markets. Although most of these organizations segregate costs very precisely according to government accounting regulations, there is still inefficiency and some level of error in the process.

One small company that serves the military and civilian markets reported that if a commercial product has a cost of 1.0, the nearly identical government product would cost between 1.6 and 2.0. Three factors generally account for this differential: quality-assurance and documentation costs, security costs, and contract administration costs. Quality assurance and documentation is estimated to be responsible for approximately 50 percent of the increase; security, 30 percent; and contract administration, 20 percent.

Policy Factors

Government policies were identified as perhaps the most complicated factors inhibiting civil-military integration in the polymeric composites industry. They encompass a wide range of often competing social, economic, and business policies, including policies to limit profits, subsidize foreign competitors, require domestic investment, set taxes, protect intellectual property, establish export controls, and defer cost-sharing requirements.

BOX 6: Recent Federal Efforts To Support Composites Technology

The Federal government has sponsored a considerable amount of composites R&D and has made significant attempts to coordinate these activities across the various federal agencies. The Federal Coordinating Council for Science, Engineering, and Technology (FCCSET), established in 1976 to address science and technology policy issues affecting multiple federal agencies, included the Committee on Industry and Technology (CIT). The CIT has promulgated the Advance Materials and Processing Plan (AMPP) designed to improve the manufacture and performance of advanced materials, to increase productivity, and to bolster economic growth. A CIT Working Group on Materials (COMAT) was established to coordinate CIT's activities.

Federal funding for R&D in advanced materials was $2.1 billion in FY 1993 with a planned $2.1 billion in FY 1994. Federal investment for composites, including ceramic and metal matrix composites, in FY 1993 was $225,3 million with a projected $199,7 million in FY 1994, The decrease in FY 1994 reflected DOD budget cuts. Such figures exclude classified R&D activities funded under specific DOD systems-related programs. The funding for such activities is said to be considerable.

All the military services and ARPA invest in composites technologies. DOD programs range from basic R&D through exploratory and advanced development to manufacturing technology development. The Services tend to support programs that directly affect their missions: the Army supports programs involving the use of composites in helicopters and ground fighting vehicles; the Air Force supports activities related to aircraft structures, missiles, and satellites; and the Navy supports activities related to submarines, surface ships, and aircraft. ARPA tends to concentrate its efforts in higher-risk, higher-payoff areas than do the Services.

NASA has invested most of its efforts in two composites-related activities: the Advanced Composites Technology (ACT) program and the High Speed Civil Transport (HSCT) program. ACT concentrates primarily on applications for transport aircraft. It is aimed at improving structural performance, particularly damage tolerance, while reducing processing and fabrication costs. Stated goals include

Many people believe that reform of the procurement process and related regulations is the single most important task to be accomplished in enhancing civilian-military integration. Many of those interviewed pointed out that current procurement regulations are poorly thought out and are often inconsistent. They observed that current practices stem from an attempt to control a small minority of firms that have taken advantage of the system in the past and that the majority of honest firms are being penalized. The procurement process is said to actually inhibit the adoption of modem quality and manufacturing practices because current regulations are too complex, stipulate the exact process to be followed by contractors, discourage close product-supplier partnerships that might be very efficient and cost-effective, and tend to perpetuate inefficient manufacturing and engineering practices. Moreover, the paperwork associated with government contracts is thought to be excessive. Many businesses make the case that they simply could not compete in the global commercial economy if they were required to generate the paperwork associated with government contracts.

Limiting "profit," or earnings as a fixed percentage above costs, reportedly inhibits integration. Industry (especially the carbon-fiber manufacturers) believes that the capital-intensive nature of the polymeric composites business was not adequately addressed when the allowable profits were determined. Typically, $2 to $4 of invested capital is required to generate $1 of sales revenue in this technology. Given the guidelines now in effect, coupled with the downturn in DOD business volumes, the industry as a whole generates poor returns on invested capital.

BOX 6: Recent Federal Efforts To Support Composites Technology (Cont'd.)

cutting acquisition costs by 20 to 25 percent and reducing structural weights by 30 to 50 percent for resized aircraft, Automated manufacturing techniques, such as filament winding, pultrusion, resin transfer molding, and automated tape-to-fiber placements, are being explored as ways to improve quality and cut manufacturing costs. Emphasis is being placed on automated textile processes needed to fabricate near net-shaped structural elements, which have significantly improved damage tolerance with respect to conventional structures, Over $100 million was invested before 1994. About $25 million has been committed until 1997, when investments are projected to be in the $45 million to $65 million range until the program is completed in 2002.

Investments in HSCT are directed primarily toward development of composite materials. Projected requirements for these materials include a 60,000-hour service life at about 300 to 350 OF The long service-life requirement represents the major challenge for polymeric matrix composites in this application,

The Department of Energy (DOE) has supported composites technology primarily in or through its classification of "materials characterization, synthesis and processing. " A recent initiative is aimed at developing lightweight composite materials that can be used in passenger automobiles and later recycled. Candidate components include chassis, frames, body parts, and panels.

The Department of Commerce's National Institute of Standards and Technology (NIST) has sponsored significant efforts in polymeric matrix composites. The two main areas of interest are improving the speed, reliability, and cost-effectiveness of fabrication and developing a better understanding and predictive capability for long-term performance. Specific technical initiatives include the development of mold-filling models useful for resin-transfer molding and cooperation with the Automotive Composites Consortium to demonstrate front-end structures and cross members. Another technical effort Involves implementing in situ process monitoring and control for the resin transfer-molding process.

SOURCE" Office of Technology Assessment, 1995.

Firms also complained about foreign-government subsidies. American firms report difficulty competing in the bidding process with companies that are heavily subsidized by their own governments. Moreover, firms argued that foreign companies are able to form joint ventures with little concern for antitrust laws. Many of those interviewed think that regulations related to vertically integrated industrial consortia could be simplified and in some cases relaxed to allow U.S. firms additional competitive advantages. In the Department of Commerce study cited earlier, individual respondents generally expressed a fear of U.S. antitrust regulations, even though a majority admitted that they had not adequately examined the technical details of the regulations and could not say whether they were really a barrier to working together.

One legislative mandate (Public Law 100-202, Statute 1329-77, Section 8088, and the related DFARS 225.7013-2 and DFARS 252.225.7022) requires domestic investment in facilities as a prerequisite for participation in future government programs. This requirement created an unprofitable situation in the carbon-fiber industry by increasing capacity much faster than demand. Several companies have reported that after they made the investments, the market for carbon fibers in these DOD applications did not materialize, and they were unable to recoup their investments.

Some of those interviewed argued that current tax policies inhibit investments in the advanced-composites business. The specific concern was the limit on a firm's abilities to depreciate obsolescent equipment (thus decreasing income taxes) in a technology that changes very rapidly. Historically, accelerated depreciation has allowed firms to reduce taxes and increase cash flow. These increased cash flows can be used to finance further investments. In terms of available investment capital, it can be argued that firms that attempt to serve the civilian and military markets require more capital because the equipment and manufacturing-process requirements needed to serve both markets might be quite diverse.

The protection of intellectual property is a concern for firms conducting military business. Many of the firms believe U.S. intellectual property is subject to unauthorized transfer to foreign entities as a result of participation in offset programs. Although protection against unauthorized transfer is in place, some of those interviewed said they were nervous that such transfers may happen inadvertently.

On the other hand, others interviewed raised concerns about export controls. Some argued that export controls imposed by the United States have arbitrarily limited the participation of many U.S. companies in foreign markets where the application of polymeric composites in civilian markets is widespread. Some argue that many European countries are more advanced in their use of polymeric matrix composites and that restrictions on U.S. firms and U.S. technology place arbitrary limits on their ability to compete in these markets. Industry insiders also point out that technology transfer from Europe to the United States would be a plus.

Finally, some industry observers expressed their belief that the TRP cost-sharing requirements are detrimental to integration. The idea of deferring cost-sharing requirements until a particular project generates enough profit may have merit, especially in an industry such as polymeric composites, where nearly half the companies reported operating losses as a result of their dependence on defense business. Deferring cost-sharing may be especially advantageous for small firms that have very few resources to commit to ideas and whose access to investment capital, especially R&D capital, is quite limited.

▮ Implications of Enhanced Integration

For the Defense Sector

The reduction in defense spending has had a major impact on those firms who have done defense work. Some companies have left the business entirely, and one major company is in bankruptcy. Thousands of high-skilled jobs have already been lost, and thousands more will be lost if firms do not find additional markets. Enhanced civil-military integration might help stabilize this situation and ensure that essential skills and capabilities are available to serve the national interest.

Integration might also reduce costs of raw materials and manufactured goods, especially if policies and procedures are adopted that allow commercially accepted products to be used for military applications. This argument is essentially the common volume-price argument—that is, as demand for a product increases, manufacturers can use economies of scale to reduce costs, thereby reducing prices for the end user. Some in government argue that using commercial products for military applications will often not work because many military applications have unique requirements. Arguably, there is merit to the notion of "peculiar and extreme use" for certain specific applications; however, other observers have argued that military requirements are sometimes generated from a list of "nice-to-have" attributes rather than mission-essential characteristics.

Civilian products are often engineered and developed more rapidly than typical military products. A more integrated base might include closer cooperation between defense-oriented firms and other firms skilled in rapid design and product prototyping.

For the Civilian Sector

Those interviewed also thought that enhanced integration might benefit the civilian sector. It was pointed out that a significant amount of specialized engineering and manufacturing technology that has been developed for defense applications can be used in commercial applications. Examples include specialized information on electromagnetic shielding and on structures that require electrical continuity. This technology transfer could result in new products and markets in the civilian sector, perhaps in the computer industry, thereby stabilizing and creating additional employment. Care would still have to be taken with respect to any security implications of this technology transfer.

Another area of potential interest is the considerable amount of specialized performance data generated for defense applications that could be used as a basis for new-product development in the civilian sector. For example, the specialized electrical, vibrational-damping, and acoustical data generated for composites could be used in unique electronic or sonic-electronic applications for the information superhighway. In addition, several firms have said that the defense emphasis on a rigorous approach to quality has helped them to improve their own quality, but they have found that the paperwork associated with the defense approach is unnecessary.