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## 43.1 INTRODUCTION

This chapter describes the use of composites for industrial and commercial applications, which perhaps is best described as 'Miscellaneous' or 'All Other Applications'. It is an overview of the myriad number of applications that cannot always be neatly grouped into major sectors as with transportation, marine, aerospace/defense, sports, and the like. Briefly described are representative applications, the benefits offered by composites, highlights of the primary materials and processes, and some conclusions about the approximate market size for this extremely diverse market sector. No attempt is made to define the technology of the materials and processes, as these are well covered in other chapters.

## 43.2 HISTORICAL PERSPECTIVE

Advanced composites (typically produced using high-performance fibers and/or resins) historically have been dominant in the aerospace and defense sectors and in many sporting goods products. Hand lay-up with autoclave molding have been the major processes used for part fabrication. Engineered composites applications for several decades have been fabricated predominantly from

materials such as E-glass fiber reinforcements, and polyester, some of the low-temperature performing epoxies, or a variety of engineering thermoplastic resins, usually referred to as fiberglass-reinforced plastics or FRP (or in Europe, GRP). Processes used have been mainly the hand lay-up, compression, injection, filament winding and pultrusion methods. Most unit volumes for advanced composites range from the hundreds of units per year to a few thousand, unlike the tens of thousands of units typical with automotive parts. Some of the most mature FRP applications (yet still with solid growth rates) include electrical insulating sheet and sheet molding compound (SMC), bulk molding compound insulators, glass fabric reinforced electronic printed circuit boards, pultruded items such as ladders, filament wound electrical tubing, thermoset SMC and injection molded thermoplastic business equipment and appliance housings, hand lay-up antennas, and others. This base of FRP applications has been used as a launching platform for a huge diversity of new applications. Many now utilize the more advanced fibers and resin systems or hybrids of these material systems.

## 43.3 PROGRESS

With the slowdown in worldwide defense spending during the early 1990s, numerous producers have looked to new market opportunities for growth, especially for advanced

fiber and resin products, and increasingly to hybrids of several materials. As a result, advanced and hybrid fiber reinforced products are now moving into the application sectors formerly dominated by metals and even glass fiber products. Also, the focus on 'defense conversion' has resulted in retargeting of some governmental budgets to support defense contractor conversion to civil applications. Many of these applications reside in the commercial and industrial market sectors, the focus of this chapter.

A vast diversification of composites has occurred in this sector. From the 1960s and 1970s with many electrical, electronic, appliance and business equipment applications, the business has grown into pressure vessels, laptop computers, centrifuges, flywheels, fuel cells, railroad car components, drive shafts, fuel pumps, loom components, musical instruments, oil and gas riser pipe, power lighting and distribution poles, industrial process rolls, advanced wind turbines and much more. The processes used here have remained fairly constant: pultrusion, filament winding, compression molding, injection molding and hand lay-up, but the use of resin transfer molding has increased dramatically for many of these applications. Materials applications that were almost exclusively fiberglass and polyester, thermoplastics, or low-temperature curing epoxies have evolved into much more vinyl ester usage and migrated to the use of more high-performance fibers such as Kevlar® and Twaron® aramids, Spectra® high-molecular weight polyethylene (HMWPE), and many types and forms of the carbon fibers. Ceramic matrix composites (CMCs) and metal matrix composites (MMCs) are of increasing interest and are sometimes competing with polymer-based fiber composites (PMCs), for example in automotive drive shafts. Even carbon fiber reinforced carbon matrix materials (C-C) are moving from the aerospace sector into commercial use. The use of 'advanced' materials has now matured enough that it is considered by many in the

industry to be counter productive to even use the term 'advanced composites' anymore.

#### 43.4 APPLICATIONS REVIEW

Following is an alphabetical review of application segments of this market or of unique and emerging material systems used broadly in related industrial applications. Representative organizations are cited as examples of the types of companies and institutions active in these market sectors so that the reader can research further into the applications of interest. Applications believed at this time to offer the opportunity for significant growth are presented in the most depth. Some applications covered also fit into other market sectors, but their technology is unique or they are industrial components sold into the other markets, so they are described here. Throughout the chapter, tables highlight many applications by major market sector, some long established and many in the emerging growth stage, to stimulate the reader's thinking on other potential applications that might benefit from applying composites. Those applications in the tables that tend toward more usage of the highest performance materials are listed with an asterisk (\*).

##### 43.4.1 ANTENNAS

Telescoping composite tubes are used to form a lightweight antenna support intended for military use and the ultimate in portability. The tubes must be exceptionally light, so the producer used woven Spectra UHMWPE fiber in epoxy resin. They are fabricated using a conventional roll-wrap process similar to that used to produce composite fishing rods. The total weight is only 1.8–2.2 kg (4–5 lb) including 11 nested tubes that collapse to only 711 mm (28 in) for portability but can easily be extended and locked to form a support pole 6.7 mm (22 ft) long.

Resin transfer molding is increasingly displacing hand lay-up for fiberglass/polyester

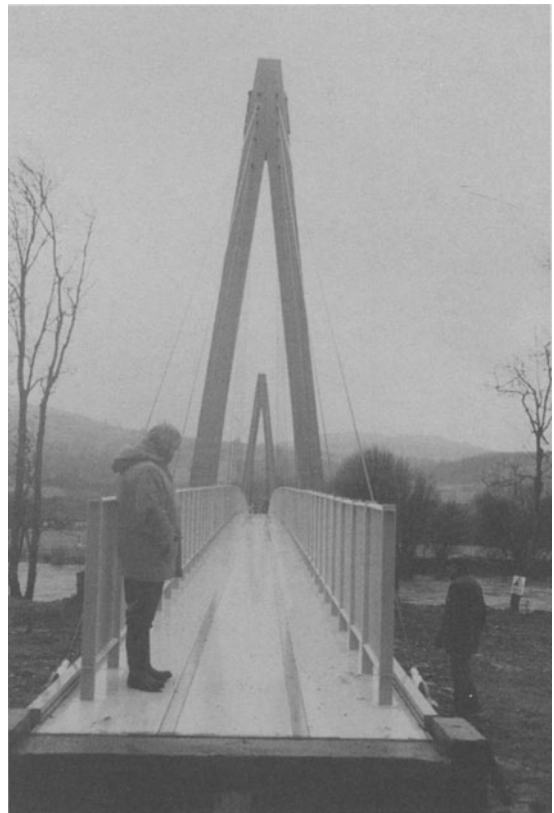
communications antenna dishes. When the new technologies for direct-broadcast satellites become more commercial, small composite dish antennas, probably produced using compression molded SMC, could become a booming market.

#### 43.4.2 BRIDGES

Mostly small foot bridges or the railings, ladders and decking of structures in highly corrosive environments typically have used FRP components over the last few decades. However, in the last several years there has been a great increase in interest in the use of fiber composites for civil engineering and infrastructure applications. One segment of particularly high interest is composite bridges that offer great corrosion resistance and weight savings. Composite tendons or reinforcing bars reinforced with fiberglass, carbon fiber or aramid fiber are being studied aggressively for use as rebar or for prestressing of concrete bridge decks. Defense Advanced Research Projects Agency (DARPA, Arlington, VA) has funded a Technology Reinvestment Project (TRP) at the University of California at San Diego (UCSD) and with the Advanced Composites Technology Transfer/Bridge Renewal Consortium for three technology demonstration areas. First is the development of low-cost fiberglass or carbon fiber reinforced plastic (CFRP) filament wound jackets for the repair and upgrading of freeway bridge or parking structure columns to make them more earthquake resistant. Second is a composite or hybrid composite/concrete bridge deck technology that would allow rapid replacement of bridges on highways and interstates. Last is a plan for a 130 m (450 ft) cable-stayed all-composite vehicular bridge to be built at UCSD over the Interstate freeway at La Jolla, CA, in the late 1990s. All of the advanced fibers, along with E-glass fiber, are of high interest for these projects. Also, high-speed, low-cost fabrication processes will help to achieve competitive

economics and performance versus conventional technologies of steel and concrete.

Other organizations are working on a variety of bridge programs where composites are the central enabling technology for improved civil engineering structures. For example, FRP and CFRP laminated plates are adhesively/mechanically bonded to the underside of steel or concrete bridge beams to extend their structural in-service life. In Scotland, in 1992, an all-composites cable-stayed footbridge was installed between two portions of the Linksleader Golf Club and across the Tay River (Fig. 43.1). Installation was accomplished using mostly on-site hand labor. Much of the structure was constructed



**Fig. 43.1** All-composite cable-stayed bridge, assembled from isopolyester composites. The bridge's A-frame towers are 17.5 m (57 ft) high. (Courtesy of Amoco Chemical Co.)

**Table 43.1** Construction/civil engineering/ infrastructure

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Bridge girder upgrade plates*
Foot bridges*
Cable-stayed bridges*
Replacement bridge decks*
Earthquake repair and upgrades/column wrap*
Bridge decking, panels, enclosures*
Pipeline rehabilitation liners*
Manhole covers
Trench covers
Cables, tendons, rebar, dowel bars*
Acoustic wall panels*
Marine piling
Piers*
Computer room flooring*
Curtain walls*
Glulam wood beams*
Mine roof bolts
Earth anchor rods
Residential ballistic wall panels
Coalescent grid/water treatment*
Toxic waste disposal tanks*
Chemical grating
Platforms
Walkways

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from pultruded shapes. In mid-1994, in the UK, a 2720 kg (6000 lb) replacement lift bridge deck for a road across a canal was constructed from pultruded FRP and mounted on steel beams attached to the lift mechanism. Bridge counterweights were reduced, offering cost savings. The infrastructure business sector, particularly roads and bridges, could become one of the largest growth areas for composites to displace steel and concrete over the next decade or more. Development of appropriate codes and standards along with strong cost/performance demonstration projects are keys to success.

#### 43.4.3 BUSINESS EQUIPMENT

This sector is one of the more mature and has been heavily dominated for many years by compression molded or injection molded reinforced thermoplastics for housings, bases,

and internal components. For example, Harbec Plastics (Ontario, NY) is a custom injection molder for a compensating arm for a business machine printer housing using 30 v/o fiberglass/polycarbonate compound. They also mold a print head carriage using carbon fiber/PC with Teflon added for wear resistance. Such parts are common to most typewriters and printers. Carbon fiber provides electrostatic dissipation. Equally important is the dimensional stability they obtain to meet a specification for precision-molded inserts with a 0.025 mm (0.001 in) concentricity on two critical shaft bearings. Growth in this segment comes mainly from further displacement of other materials as composites gain market share. The benefit of high value here is increased design freedom offered by the light and strong FRP materials. This sector is dominated by the molding compounders and the custom molders such as Premix (No. Kingsville, OH) and Rostone (Lafayette, IN).

**Table 43.2** Appliances/business equipment

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Sanitaryware
Dishwashers
Oven door handles
Frying pan components
Phone/fax EMI covers*
Copier housings and components*
Computer cassette robotic system*
Refrigerator liners
Business machine bases
Laptop computer cases*
Microphone booms*
Dishwashers
Air conditioners
Office furniture*
Toasters

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#### 43.4.4 CABLE CARS

Composite cabins were retrofitted to replace steel and aluminum at Chamonix, France to reduce the weight of the cable cars at a ski resort. Ingenex, a French engineering firm,

built new lightweight car bodies using sandwich construction with Kevlar/epoxy face sheets and a Nomex® honeycomb core. The supporting arm that holds each cable car is fabricated from carbon fiber/epoxy over a Nomex core. These replacement structures allow for many more passengers to be carried on the existing system. This avoided having to scrap the existing system that was becoming overloaded, thus avoiding rebuilding the whole system reportedly at a cost 10 times as much.

#### 43.4.5 CARBON-CARBON COMPOSITES FOR NON-AEROSPACE MARKETS

The vast majority of uses for C-C composites are in aerospace and defense. However, many potential industrial applications are emerging for this unique high-temperature resistant material system. DOE has studied C-C composites for fusion energy systems. One project involved brazing C-C composites. Another program studied development of pitch-based carbon fiber (PBCF) reinforced C-C composite tiles to line the inside walls of future fusion devices such as the Compact Ignition Tokamak (CIT). Perhaps such tiles later will find application in commercial heat exchangers. Kureha Chemical Industry Co., Ltd, and Osaka Gas Co., Ltd of Japan are active in the USA market. Applications targeted include C-C structures for high-temperature furnaces and fuel cells, wet and dry friction materials, plus brake disks and self-lubricating bearings for automotive and truck applications. C-C brakes and clutches are used worldwide in some racing car classes such as Formula 1 and for the Indianapolis 500 race but are banned from other classes due to the premium cost.

#### 43.4.6 CERAMIC-MATRIX COMPOSITES (CMCs)

These materials have received a significant boost in funding because of continuing interest by the USA Department of Energy Office of

Industrial Technologies. Their Continuous Fiber Ceramic Composites (CFCC) Program Plan (10-year plan) was an expansion of the continuing support activity directed toward 'enabling technology' efforts since 1987. DOE defines a CFCC as a long fiber (ceramic, glass or carbon) embedded in a ceramic matrix. Concerns about CMCs raised by potential industrial users include material and processing costs, long-term component fracture toughness, general durability in a variety of environments, the ability to join components with different compositions and the availability of near-net-shape fabrication methods with 3-D fiber architectures (preforms). A relatively new type of ceramics, CFCCs offer the potential to meet the demands for a variety of industrial applications. Some primary applications envisioned for these materials include: burners/combustors, chemical reactors and process equipment, heat recovery systems, refractories and related products, separation/filtration systems, stationary engines, waste incineration systems, tooling, structural components, biomedical parts, wear parts in machinery, and other specialty high-temperature products.

Hexcel Corp. (Pleasanton, CA) offers high-performance ceramic materials for various military components such as missile fins, radomes, jet engine parts, and high-temperature tooling, but much larger potential markets might develop in the commercial sector, especially for less-expensive CFCCs using E-glass fiber or other low-cost reinforcements. Examples cited by Hexcel include honeycomb heat exchangers used in high-pressure coal-fired gas turbine generators and feed tubes (used to overcome corrosion and thermal shock problems) for a toxic waste incinerator operating at 870°C (1600°F).

Successful conversion of the applications noted above could generate savings of 1.1 quads (a quadrillion BTUs) of thermal energy per year, and reduce NO<sub>x</sub> emissions by 0.6 million tons/year, according to the DOE.

#### 43.4.7 CONDUCTIVE FIBER FOR SHIELDING BUSINESS EQUIPMENT

Cytec Industries sells a conductive fiber concentrate or intermediate containing carbon fiber for electrical conductivity. In most of these products, Cytec starts with continuous, standard 33 msi, 12K carbon fiber that is electroplated with nickel before being chopped into 6.35 mm (0.25 in) lengths. The fiber loading is typically 60–75%, even to 90% if sold to a compounder who adds resin to make a specified injection molding compound.

#### 43.4.8 CORROSION-RESISTANT SECONDARY STRUCTURES – GRATING, LADDERS, PIPING

Composite products are offered by many companies including Amalga, Brunswick, Fibergrate, International Grating, Creative Pultrusions and others. Strongwell takes pultruded structural fiberglass shapes (tradename: Extren), fabricates them into useful structures, and distributes to various industrial customers. The material is available in over 100 standard sizes and shapes, and is produced in three series: general-purpose, fire-retardant and a premium grade that is both fire retardant and highly corrosion resistant. This grade, called Extren 625, uses a vinyl ester resin; the other two are made with polyester formulations. Applications include handrails, stairways, ladders, cable and channel trays, platforms and walkways, troughs, weir and baffle plates, racks, bridges, identification signs, sump tanks, battery boxes, drain pipes, etc. Besides the offshore drilling and production industry, Strongwell serves a variety of industries, including aquaculture, chemical processing, food/beverage, marine, metal processing, waste treatment, petrochemical, power plants, pulp and paper mills, radar installations, transportation and many specialized applications such as raised computer floors. For static dissipation, carbon fibers can be located at the surface of grating (Fig. 43.2).

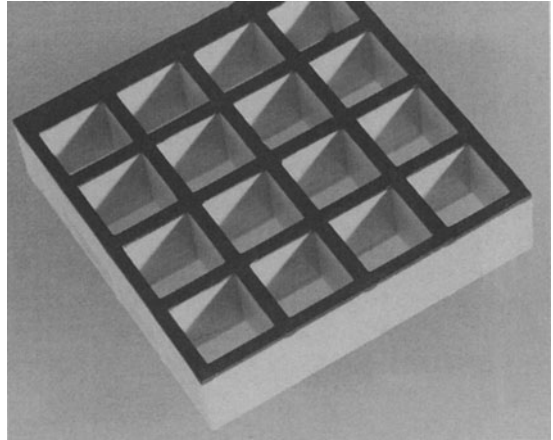


Fig. 43.2 Conductive FRP grating for static electricity dissipation. (Courtesy of CI/SPI.)

#### 43.4.9 DRIVE SHAFTS – PICKUP TRUCKS AND COOLING TOWERS

Strongwell continues to use substantial amounts of carbon fiber for the hybrid drive shafts they sell to Dana for shipment to General Motors. At close to 226 800 kg (500 000 lb) per year of carbon fiber usage and estimated to climb soon to one million lb, this is said to be the largest industrial application for carbon fiber reinforcements. The carbon fibers, mainly from Hexcel, are pultruded with resin along an aluminum tube and overwrapped with fiberglass for damage tolerance.

Carbon fiber/epoxy is used for cooling tower drive shafts as well. SpyroTech (Lincoln, NE) is a major supplier of these shafts along with Amalga Composites (W. Allis, WI), Addax, Inc. (Lincoln, NE) and ACPT (Huntington Beach, CA). A circumferential wrap of E-glass/epoxy is added for debulking and impact protection. These shafts exhibit up to five times the durability at one-fifth the weight of steel shafts and are far more corrosion resistant. Cooling tower shafts (as with vehicular shafts) produced with carbon fibers are stiffer and can be produced in lengths twice as long as with steel without suffering vibration damage in use, eliminating the need for intermediate bearings and supports.

## 43.4.10 ELECTRICAL AND ELECTRONICS

This sector of the market is composed of many applications that are maturing or have high penetration compared with other materials. Applications include motor and generator components, switch gear, insulating sheet, molded insulators, subway third rail insulating cover board, FR-4 and G-10/11 glass fabric reinforced epoxy printed circuit boards (PCBs), utility transmission and distribution

**Table 43.3** Electrical/electronics/energy systems/communications

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Electric motors
Fuse tubes
Lighting poles
Distribution poles
Cable tray
Power tool cases
Motor control centers
Printed circuit boards
Circuit breakers
Guy wire insulators
Utility transmission towers
Electrical bus bars
Distribution transformer cores, cases
Shielding – RFI, ESD, EMI*
Battery boxes, casings
Electron beam accelerators*
Electrical insulators
Electrified third rail cover board
Electrical switchgear
Power hot-line tools
Electronic connectors
Outlet boxes
Aerial lift truck booms
Electronics chassis*
Computer chip carriers*
Electronic equipment racks*
Fuel cells*
Flywheel mechanical batteries*
Superconducting magnetic energy storage (SMES)
Wind turbine blades*
Telescoping portable antennas*
Communications antenna dishes
Radio masts*
Satellite TV dish antennas
Microwave guides
Fiber optic cable tension members

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insulating hardware, ladders and hotline tools for line installers, lighting poles, connectors, microchip encapsulation and many more. Fiberglass reinforcement predominates due to its insulating characteristics and low cost. Sales are cyclical due to the high market share held by FRP, but there is still strong growth seen from penetration gains versus phenolic, porcelain, and other materials.

## 43.4.11 FIREFIGHTER BREATHING APPARATUS

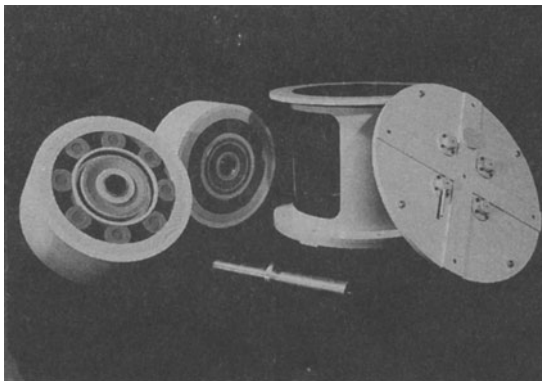
The key component of firefighter breathing apparatus is the air storage bottle that comes in different sizes, materials, and pressure ratings. Structural Composites Industries (Pomona, CA) continues to be well ahead of all competitors making small filament-wound composite pressure vessels. SCI supplies air bottles (all of their firefighter's bottles use S-2 Glass) to Mine Safety Appliances. They reportedly have never had a field failure. Many air breathing systems distributed by MSA are used to escape smoke or other noxious materials in mines, chemical plants, refineries, hotels, aircraft, etc. SCI also is a major supplier for the escape-slide air bottles in use on transport aircraft built by Boeing and Airbus. Many composite oxygen storage bottles are produced for hospital and home care and for use in highflying commercial and general-aviation aircraft (for example, for escape slide inflation but using Kevlar 49/epoxy overwraps for decreased weight).

Other composite bottles are used to inflate rafts, balloons and other flotation systems. EFI Corp. (San Jose, CA), a subsidiary of Racal Electronics in the UK, and Luxfer USA Ltd (Riverside, CA) continue to be SCI's main competitors as suppliers of firefighter air bottles. They sell air bottles to Scott, Survivair, North Safety and others in the USA and overseas. About 250 fire departments in American cities have bought hundreds of thousands of composite bottles to replace the much heavier steel bottles. Lighter bottles with longer lasting air supplies give firefighters more time on

station in the heat of a fire fight. The bottles must store air for long periods at 31 MPa (4500 psig).

#### 43.4.12 FLYWHEEL MECHANICAL BATTERY SYSTEMS

US Flywheel Systems, Inc. (Camarillo, CA), Calstart (Burbank, CA), American Flywheel Systems (Seattle, WA) and others all hope to supply kinetic energy storage flywheel systems (now often called mechanical storage batteries) for future electrical vehicles in California and elsewhere (Fig. 43.3). Flywheel batteries have an estimated 5–10 times the watt hours per pound storage capacity of conventional lead acid batteries. They are impervious to temperature variations, may be drained repeatedly of stored energy without cyclic degradation, can be recharged in as little as a few minutes, should last 30–40 years without requiring replacement or maintenance, and create no toxic waste problems. Mileage range in an electric car (such as GM's Impact) could reach a projected 482–640 km (300–400 miles) or more according to some developers, as opposed to a practical range of only 95–128 km (60–80 miles) for today's electric cars using conventional battery systems.



**Fig. 43.3** Flywheel battery components. (Courtesy of American Flywheel Systems.)

Larger flywheels also show promise for stationary energy storage and peak power shaving applications, and the business opportunity for such systems could be enormous. Federal technology centers, such as the Lawrence Livermore and Oak Ridge National Laboratories, now are part of teaming arrangements to enhance flywheel technology transfer from defense and other government programs to the private sector.

The rims of the rotating wheels in these systems are filament wound using advanced fiber composites, including E glass, S-2 glass, Kevlar and carbon fibers. At speeds attainable by composite wheels, metal flywheels disintegrate. Use of this system is a good example of technology transfer from aerospace to the civilian sector.

An electric car with a flywheel storage system on board (and perhaps with regenerative braking through the flywheels) could approach zero emissions and is expected to meet the much tighter California air quality standards set for early next century. California, New York and Massachusetts, have mandated that 2% of cars sold in those states in 1998 must be zero emission vehicles; the percentages increase to 5% in 2001 and 10% in 2003. The challenge is how to offer an affordable car with desirable range and performance that can meet those goals.

Lawrence Livermore National Laboratory reported during a SAMPE seminar that the use of composite flywheels in an electromechanical battery 'would be ideal for use in electric powered vehicles'. They found that a high-strength carbon fiber (such as Toray's T700 or T1000) yielded the highest energy storage capacity. Since then, Lawrence Livermore National Laboratory and General Motors Corp. have teamed on a three-year, \$3 million project to develop a new generation of more efficient automobile flywheel batteries. The GM vehicle project is part of the 'Partnership for New Generation Vehicles program' launched by President Clinton in September 1993.



#### 43.4.13 FUEL TANKS FOR NATURAL GAS VEHICLES (NGV)

Lincoln Composites (Lincoln, NE) and EDO Corp. (Canada) introduced certified 'all-composite' compressed natural gas (CNG) pressure vessels under the 1993 US ANSI/AGA standard called NGV2 for ultra-light, nonmetallic natural gas vehicle fuel tanks. The availability of these certified plastic-lined, composite-overwrapped fuel tanks is expected to accelerate the usage of advanced composites into this potentially large alternate-fuel marketplace for composites. Besides weight savings of up to 70% (compared with steel, aluminum, or metal-lined NGV tanks) and greater durability, the new tanks offer increased fuel capacity, extending driving range.

The weight savings are achieved through use of a hybrid composite, for example using a 30 msi modulus T650/35 carbon fiber from Amoco Performance Products (Alpharetta, GA) or a Toray T700S/12K carbon fiber. Hybridized with the carbon fiber might be an E-glass fiber roving from Owens-Corning, PPG, or Vetrotex Certaineed to reinforce an epoxy resin formulation. The composite is filament wound over a thermoplastic liner of high-density polyethylene (HDPE). In the hybrid, carbon fiber provides an extremely high strength-to-weight ratio, with the ability to withstand many pressure cycles along with superior fatigue characteristics, while the fiberglass enhances toughness. HDPE liners are lighter weight than steel or aluminum and more resistant than both to the highly corrosive elements sometimes found in natural gas supplies around the USA. A minimum 15-year life expectancy is set for the NGV2 tanks; after that they are to be discarded.

Other pressure vessel programs are underway at Comdyne I, Compositex (Kaiser), Fiber Dynamics, Amalga and Structural Composites. Large customers for the older fiberglass/epoxy overwrapped aluminum NGV fuel tanks include General Motors and

Chrysler and many city transit bus operators such as Tacoma, Sacramento, Salt Lake City, Reading, Binghamton and other Northeast and Canadian cities. Recent failures of CNG tanks during refueling (reportedly caused by exposure to unexpected acid solutions) appear to have been solved with an installation redesign and protective coatings. Additional interest comes from utilities such as Southern California Gas & Electric and Columbia Gas companies.

Carbon fiber priced today at about \$5–6/kg (\$11–13/lb) for high-strength 12K fiber is about twice as expensive as S-2 glass fiber and much higher than E glass but appears economically competitive for this market. One of the above supplier companies did a cost and weight analysis to decide how much of a premium would have to be paid if higher-strength fibers were used rather than E glass. Using E-glass/epoxy overwrap, the weight would be about 45 kg (100 lb). S-2 glass reduces the weight to 36–38 kg (80–85 lb), and a 12K carbon fiber/epoxy overwrap reduces the weight to 18–20 kg (40–43 lb). Using fiber costs of \$2.20, 11–13.00 and 26.50/kg (\$1, \$5–6 and \$12/lb) respectively, the estimated fiber cost per NGV pressure vessel is \$64 for E glass, \$300–315 for S-2 glass, and \$285–310 for carbon fiber. Combining the various cost components brings the heaviest (E glass) tank cost to \$380–400, S-2 tank to \$700–720, and the carbon fiber tank to \$600–620. Thus, to save about 27.2 kg (60 lb) by switching from E glass to carbon fiber reinforcement, the cost premium is about \$220, or \$3.6–3.7 per pound saved. Auto designers in the past have suggested that a \$2 premium per pound saved was acceptable, but they might be willing to pay more now in view of the environmental benefits gained by burning cleaner fuel.

The combined production of mid-size pickup trucks in the USA by Chrysler, Ford and General Motors is reported to be more than 600 000 per year. If only 10% are built with natural gas as the fuel and there are two or three fuel tanks on each truck, there is a

very large potential market in the millions of pounds of materials required. Transit buses may be an even larger market.

**Table 43.4** Transportation system equipment

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Seats/frames
Monorail cars
Mobile storage modules – CNG*
CNG/NGV fuel tanks*
Rail freight car doors
Rail car knuckles
Hydrogen storage tanks*
Intermodal containers
Maglev train guideways*
High-speed train brakes*
Concept/show car chassis*
Electric vehicle frames/chassis*
Racing car brakes and clutches*
Solar-powered racing vehicles*
Highway reflecting markers
Airport approach light towers
Airport ticket counter tops
Drive shafts – pickup trucks*
Aircraft escape slide inflation bottles*
Ship propulsion shafts*
Cablecar cabins and support arms*
Shipboard crane components

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#### 43.4.14 GLULAM BEAMS

Composites are leading to revolutionary wood beams for bridges; laminated beams benefit dramatically from use of carbon and aramid fibers and cost less. Wood structural building materials have required only the highest quality wood to achieve necessary performance levels. Wood ('the original composite') has a high strength-to-weight ratio; however, highly engineered components such as beams have had to allow for the inherent variability of wood and wood types. The best woods have come from 'old growth' forests that today are in decline or are in designated wilderness areas. Logging practices and environmental considerations (remember the spotted owl?) have removed 'old growth' as a source and have driven producers to consider new technologies.

American Laminators (Drain, OR) and the Wood Science & Technology Institute (Corvallis, OR) have developed a superior line of glued-laminated (glulam) wood beam products based on Douglas fir and composites. Because these beams are a hybrid material system, they marry the light weight and high strength of aramid/carbon fiber composites with the already light weight, high strength nature of wood to make a product that can compete favorably with steel, concrete, and other wood beams. Of special note is that these new composite/wood beams for buildings or bridges outperform conventional wood beam products and usually can be offered at a purchase price or first cost of about 25–45% less than conventional glulam beams!

Dead weight design load is reduced by 40–60% for large structures and long spans. For structures where deflection is a major consideration in design, the patented technology takes advantage of the high modulus of Akzo Nobel Fortafil carbon fiber with 33 msi modulus and 550 ksi tensile to more than double the design capacity in compression versus typical unreinforced glulam products. Where increased tensile performance is required, Akzo Nobel Fibers' Twaron or DuPont's Kevlar 49 aramid yarn is used. Some of these beams can be massive; e.g. typically 24 m long × 1200 mm deep × 254 mm wide (80 ft × 4 ft × 10 in) to much larger. The fibers reinforce pultruded plates that are adhesively laminated during the standard beam forming and bonding.

Many structures (100 as of this writing) are already in place using the new composite glulams, in California, Oregon, Wisconsin and Hokkaido, Japan. More structures now are in the design stages (ca. 100) including large domed structures with over 164 m (500 ft) clear spans, for Japan, USA and European clients. Estimates by various participants suggest that the global opportunity for this composite/wood beam technology is in the billions of dollars. In the USA, the conventional

glulam market is over \$1.2 billion/year and is supplied by 147 beam manufacturers. Potential requirements in the 45 million kg (100 million lb) range for just the high strength carbon and aramid fibers are seen about the year 2000. One observer close to the project said that 'this has to make a big splash in composites and could be the biggest new composites application in 20 years!'

#### 43.4.15 HIGH-PRESSURE TUBING AND BATTERY CASINGS

Amalga Composites filament winds carbon fiber/epoxy over battery casings for Johnson Controls. The Inconel liner has a carbon fiber/epoxy overwrap which is under 0.34 MPa (50 psi) stress when discharged and 5.86 MPa (850 psi) when fully charged. These batteries are designed to be buried in the desert to power instruments during the night and they are recharged during the day. Amalga also makes vessels for high-pressure applications, including a filament wound carbon fiber/epoxy-overwrapped steel tank to withstand 3.41 MPa (500 psi) for use as an emergency backup pressure cell for the F-22 fighter. Other interesting high-pressure products are carbon fiber/epoxy-reinforced metallic cylinders that achieve 41–83 MPa (6000–12 000 psi) of pressure capability. Lower pressure pneumatic tubes are being made by Amalga for service at 1.7 MPa (250 psi), and these usually are reinforced with a fiber-glass/epoxy overwrap.

#### 43.4.16 HIGH-SPEED TRAIN BRAKES – CARBON–CARBON

Carbone Industrie in France has been testing carbon-carbon brakes on the French TGV Atlantique line. Two similar but slightly different applications are being tested; for the drive wheels and for the bogey. The C–C brakes must qualify on cars being stopped from 300–350 km/h (to 215 mph) before they can be considered for regular service. Alsthom, the

TGV car designer and builder, must decide whether the weight savings, lack of fade and projected longer life (as with similar C–C aircraft brakes systems) justify a change in the steel brakes now in service. With plans to build similar high-speed rail systems in Texas and other parts of the USA, there is growing interest in the results of the tests. Several companies in Japan have similar interest in using C–C brakes on proposed advanced bullet trains, which also might reach speeds of 350 km/h. Later magnetic levitation (maglev) trains which will approach 500 km/h may be assessed for use of these ultra-high-performance brakes.

#### 43.4.17 HYDROGEN FUEL STORAGE

Hydrogen storage tanks may offer potential for filament-wound pressure vessels, but it will be several years before this can possibly occur. Syracuse University received a grant from the Department of Energy to prove a novel approach to hydrogen storage. The hydrogen would be stored in a filament-wound tank in which activated carbon granules are closely packed. After being cooled in a liquid nitrogen heat exchanger to the desired storage temperature, the hydrogen is passed through the activated carbon where some is adsorbed. It is then stored at low temperature (150K) and relatively low pressure 5.51 MPa (800 psig) before being released via slight heating of the granular carbon while opening a valve for controlled release into the nearby hydrogen-oxygen fuel cell. A design engineer predicts that a car powered by an electric motor energized with a hydrogen-oxygen fuel cell will be able to outperform a similar vehicle powered by a gasoline engine. Since hydrogen as a fuel requires a massive change to the fueling infrastructure, the timing for this market sector is hard to predict. If such an infrastructure is installed, there will likely emerge many more composites applications such as large tanks and pipelines.

**Table 43.5** Miscellaneous

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"Jurassic Park" dinosaurs
High-altitude balloon gondolas*
Aquaculture cages for fish farming
Telescope tubes*
Helmets*
Superconducting supercollider*
Firefighter air bottles*
Oxygen storage bottles*
Life raft inflation bottles*
Flag poles
Deep-submergence capsules*
Riot control body armor/shields*

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43.4.18 LAPTOP COMPUTERS

Lightweight laptop computers with carbon fiber reinforced plastic cases were first introduced in the USA in the early 1990s at the giant Comdex computer show in Las Vegas. Toshiba America Information Systems (Irvine, CA) introduced three models, reporting that their light weight 2.5–3.6 kg (5.5–7.9 lb) and portability were partially due to the use of a carbon fiber molded case (Fig. 43.4). The new cases



**Fig. 43.4** Lightweight computer case with nonwoven fiber reinforcement. (Courtesy of Toshiba America Information Systems, Inc.)

molded with nonwoven-fabric are 20–50% lighter than older, thicker plastic cases and have a wall thickness of only 3.04 mm (0.12 in) without sacrificing ruggedness. The carbon fiber/thermoplastic is supplied by Kobe Steel Ltd. and Mitsubishi Rayon Co., Ltd of Japan.

In a related competitive development, Advanced Logic Research, Inc. (ALR - Irvine, CA), introduced the world's first modular notebook PCs offering processor chip upgrades. The ALR notebooks are ergonomically designed with a thin carbon fiber reinforced, lightweight case that fits into a standard-size briefcase. Other notebook computer producers have composite development programs underway.

Based on market share estimates provided by Stanford Resources, Inc. in *PC Magazine* (August 1994), Compaq has the largest market share today at 14.1% of shipments in 1993, Apple is second at 13.6%, Toshiba is third at 11.1%, IBM is fourth at 7.1%, followed by dozens of other producers.

43.4.19 LOOM COMPONENTS

DFI Pultruded Composites, Inc. (Erlanger, KY) was one of the first to successfully pultrude carbon fiber/epoxy, once quick-curing epoxies of the proper viscosity became available. One of their better customers is in Europe for DFI's pultruded lightweight, low inertia, carbon fiber shuttle arms that rapidly reciprocate in the older style but updated rapier looms still being used by many industrial fabric weavers. The shuttle arms are delivered in six lengths ranging from approximately 1.3 to 2.1 m. DFI used 34 msi modulus carbon fibers as the reinforcement. [Incidentally, one of their unique products is a pultruded rod using carbon fiber/epoxy with a diameter as small as 0.25 mm (0.010 in).] Polygon Company Div. of Plas/Steel Industries (Walkerton, IN) pultrudes a carbon fiber/epoxy, high-speed loom frame component for a USA equipment producer, using Akzo Nobel Fortafil's 50K filament fiber.

## 43.4.20 MAGLEV TRAIN GUIDEWAYS

Magnetic levitation or maglev train system concept definition contracts are funded by the DOT-Federal Railway Administration under the \$151 billion Intermodal Surface Transportation Act which was passed in 1991 and included \$750 million to be used specifically to complete the design and construction of a USA demonstration maglev line about 32 km (20 mile) long. The German Transrapid maglev system design is planned for the 20 km (13 mile) demonstration system to be built in Orlando, FL. USA and Canadian companies competing for future maglev system contracts include Northrop Grumman, Foster-Miller, Magneplane, Boeing, Bombardier and Morrison-Knudsen (the latter three are proposing the most extensive use of composites on the 'rolling' stock, perhaps including the outer skins of the maglev cars plus the interiors).

On the maglev vehicles, General Electric is developing shielded superconducting magnets and their coil design, shielding, motors, levitation and carbon fiber/epoxy cryostats. To employ the latest methods of producing low-cost composite train vehicle structures and to keep costs down, carbon fiber will be used selectively, with high-performance fiberglass the main reinforcement for sandwich panels, possible low-FST (fire, smoke toxicity) materials for the vehicle interiors.

Regarding the guideway, they favor a U-shaped configuration and either reinforced concrete throughout or with a composite grille at the center of each guideway beam. To reinforce the concrete, they recommend using post-tensioned FRP tendons in the magnetic field and closest to the path of the cars and more conventional steel rebar prestressing in the lower regions of the supporting columns, well away from the high magnetic field to avoid raising the maglev drag coefficient significantly. Magneplane International predicts that the guideway will be the dominant cost component, so it has first design priority. Their target is not to exceed \$6.2 million per

km (\$10 million per mile) for a dual track guideway. Their design includes a concrete box beam for the guideway with the bottom of the vehicle 'wrapped' around the beam for safety. The guideway might use a hybrid of fiberglass and carbon fiber rebar rather than steel rebar reinforcement. Foster-Miller is focused on high-performance, low-cost guideways. Most of their current emphasis is on using high-strength FRP post-tensioning members (both transverse and longitudinal) in the upper areas of the guideway. West Virginia University is working on a DOT-FRA contract titled: 'Assessment of Maglev Guideway Systems'. Imbedded fiber optic systems may be used to monitor entire guideway systems and to detect potential trouble spots such as joints. West Virginia University data show that if FRP rebar or tendons are used, the load-carrying capacity is about twice that achieved with steel. Although the initial cost might be five times greater, the weight reduction can be 80%, so on a performance-per-pound basis, FRP would be lower in installed cost than steel rebar reinforced concrete. WVU also is looking at more advanced composite materials, including carbon fiber and hybrids. Another option is to use an aramid fiber tendon, and candidates include Teijin's Technora, Akzo Nobel Fiber's Twaron and Du Pont's Kevlar.

## 43.4.21 MEDICAL, HEALTH AND SAFETY PRODUCTS (SEE CHAPTER 44)

BioMechanical Materials Corp. (Camarillo, CA) and Composiflex (Erie, PA) are among those selling carbon fiber/acrylic and carbon fiber/urethane sheet stock to orthotic equipment distributors. They in turn sell this material to hundreds of small local laboratories that fabricate components tailored by orthotists for each patient, including such items as arch supports, knee braces and custom sports braces. BioMechanical Materials among others also sells large quantities of composite sheet

and fabricated parts to sports shoe manufacturers, such as Brooks and L.A. Gear, for enhancing performance and the marketability of the top-end shoes. Hexcel supplies a unique hybrid E-glass and carbon fiber fabric reinforced epoxy 'chip' for arch supports in Reebok sports shoes. For electrical hazard protection, Composiflex produces a hybrid composite of fiberglass/carbon fiber/epoxy to fabricate lightweight toe plates for safety boots and puncture-resistant insoles, replacing the traditional steel inserts. This company gets its name from their product with multiple plies of oriented fiber composite which can control bending to certain directions.

**Table 43.6** Medical products

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MRI scanner cryogenic tubes*
X-ray tables*
Underwater therapy treadmill
Wheelchairs*
Orthotics - shoe arch, neck & knee braces*
Prostheses - artificial limbs*
External fixators - orthopaedics*
Rehabilitation baths
Medical centrifuges*
Hip implants*
Heart valves*
Dental/prosthetic cements
X-ray film cassettes*
Medical sensors*
Walking canes*
Artificial ligaments*

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#### 43.4.22 METAL-MATRIX COMPOSITES (MMCs)

Duralcan USA (Novi, MI) markets low-cost MMCs reinforced with alumina or silicon carbide particulate reinforcement. One of their most successful applications is the use of reinforced aluminum wire for tire studs. Finland and Sweden (and many USA states) banned the older steel-jacketed tungsten carbide studs from all-weather/snow tires due to road wear. Many people assumed that studs degrade highways prematurely because they wear away road surface. The real culprit is centrifugal force acting on the studs that causes the

older heavy tungsten studs to impact (rather than scrape) the road surface. A Duralcan MMC with 15 v/o alumina in 6061 aluminum is being substituted to limit road damage because of its lower weight. MMC wire is being shipped at the rate of 'several tons per month' for this application. Another interesting wire application is for flame spraying where the MMC adds to service life; alumina-reinforced aluminum wire is sprayed onto steel as an antiskid surface in marine environments such as ships, piers and oil platforms. Previously, pure aluminum was flame sprayed onto a steel surface before painting, serving as a corrosion barrier.

Among the many other applications in work or which have been tested to date are the following: extruded truck frame channels [C-channels of about 304 × 76 × 7620 mm (12 × 3 × 25 in)], motorcycle drive sprockets, a proportional valve for a truck lift gate, compressor piston-ring inserts, sporting goods such as golf clubs and brake components for standard and high-speed rail cars. Other promising applications are automobile brake rotors (initial orders are now being used for early production at this time) to reduce weight by replacing cast iron. Further component applications likely to emerge include pickup truck drive shafts, engine cylinder liners, automotive suspension arms, aircraft camera mounts, electrical housings, and pistons for automotive engines, piston inserts that reduce the energy required for high-speed reciprocating motion in large gas compressors, and tubing and forks for high-performance racing and mountain bicycles.

Recyclability is a major market issue for high-tonnage applications of many materials, especially now in Europe. Duralcan claims that their MMCs have a potential advantage over many other materials, including polymer-matrix composites, since MMCs can be recycled as a composite material or easily reclaimed into high-quality aluminum by melting and removing the reinforcing particles. Whether recycled or reclaimed, Duralcan

USA can achieve virgin material properties in new parts. For example, they have recycled pickup truck drive shaft extrusions up to four times, while retaining original property performance in subsequent parts. In the aluminum casting process, 30–40% of the process metal is not in the part but in the gates and risers, and all of this material is now being recycled.

Duralcan USA's parent company is Alcan Aluminium Ltd in Canada (Jonquiere, Quebec), and their plant has an ultimate capacity for these products of around 11–16 million kg (25–36 million lb) per year. In some applications (bikes and drive shafts, for example) these MMCs could readily displace some growth opportunities now seen for polymer composites.

MMCs from other producers also show great promise in the field of electronics. Multi-chip modules (MCMs) require high dimensional stability, thermal conductivity and thermal shock resistance. Mounting them on MMC provides these benefits, especially for high-density avionics applications on aircraft or for radar and other systems on board ships. For maximum thermal conductivity in electronic backplanes, Amoco Performance Products's K-1100 pitch-based carbon fiber might be used.

#### 43.4.23 MOBILE STORAGE MODULES FOR CNG

Aerojet and Pacific Gas & Electric have teamed to demonstrate a low-cost, lightweight composite Mobile Storage Module that is a large NGV fuel tank made of carbon fiber or fiberglass composite overwrapped aluminum used to transport CNG from the utility to the user. These tubes are currently 381 mm (15 in) diameter by 6096 mm (20 ft) long, and several of these would be mounted in a truck trailer that can be used to transport, store, and deliver natural gas fuel to fixed loading areas. These modules would be moved between fleet refueling stations, thereby avoiding the necessity of installing a costly pumping system.

Composite trailers could haul more fuel or would be allowed on roads with weight restrictions or service pads not capable of handling the heavier steel trailers. Manufacturers of the current steel tube trailers include Christi Park Industries in McKeesport (PA) and Trend Fuels in Austin (TX). Certification by the Department of Transportation (DOT) is required to allow use of large composite storage tanks on highways if loaded with compressed natural gas to 25 MPa (3600 psi) or higher. Projections for the composites potential in this one application range from 36–45 million kg (80–100 million lb).

#### 43.4.24 MOLDING COMPOUNDS FOR INJECTION MOLDING

A steadily growing segment of the advanced composites market is a variety of injection molded parts made with carbon fiber, or hybrids with fiberglass or aramid reinforcements. LNP Engineering Plastics, Inc. (a unit of Kawasaki Steel based in Exton, PA) participates in many current applications in the commercial and industrial sectors. (See Section 43.4.3.) There is a trend toward increased use of the higher-temperature thermoplastics, and at LNP these include polyethersulfone (PES), polyarylsulfone (PAS), polyetheretherketone (PEEK), polyphenylene sulfide (PPS) and polyetherimide (PEI, or Ultem). Their long fiber compounds called Verton offer performance at the high end of the mechanical performance spectrum for compounds.

RTP Company (Winona, MN), Comalloy International (Nashville, TN) and Compounding Technology, Inc. (Corona, CA) manufacture molding compounds made with the high-performance thermoplastic resins listed above plus large amounts of polycarbonates and nylons/polyamides, much of these for electrical and electronic insulating components. A smaller part of the business is nickel-coated carbon fiber for added conductivity, and they also use some stainless steel

fiber to make compounds suitable for EMI/RFI Shielding. DSM Engineering Plastics, Inc. (Evansville, IN) and others report a noticeable trend toward using higher-temperature glass-filled thermoplastics for components used in the electronics industry, mainly for connectors. Currently, the liquid crystal polymers (mainly Vectra from Hoechst Celanese and Xydar from Amoco) are widely used for electronics applications. Having been part of the Akzo organization for several years (and before that, Fiberfil), they have worked closely with Akzo Nobel Fortafil Fibers (Rockwood, TN) to develop special grades of chopped and milled carbon fibers with suitable finishes. Other suppliers include Toho Carbon Fibers and Hexel. Heavy-tow fiber (50K filament count and greater) made from commercial-grade PAN precursor is well suited to making lower-cost chopped fiber. Usage of carbon fiber has been going up every year and has reportedly passed annual consumption of 2.25 million kg (5 million lb) per year that would translate into compound volumes five to ten times that.

#### 43.4.25 MUSICAL INSTRUMENTS

Kaman Aerospace (Bloomfield, CT) offers the Ovation Instruments guitar. The top of the Ovation series is called the Adamas and its excellent tone is attributed to the use of a composite sandwich construction for the top. The outer and inner plies are single layers of 5-mil unidirectional carbon fiber/epoxy tape, while the core is 0.762 mm (0.030 in) thick birch veneer. Fiberglass composites are also used for other Adamas components, including the bowl. These are mostly handmade guitars so annual production is small. A producer of classical guitars is Kuau Technology (Maui, Hawaii) with carbon fiber/epoxy and the RTM process is their preference. The Luthier's Mercantile (Healdsburg, CA) catalog for stringed musical instrument producers generates 99% of their business via mail order. They offer carbon fiber/epoxy bar and sheet stock in

various sizes for reinforcing the necks of guitars or banjos, plus for making bridge blanks, fingerboard underlays, stiffening braces and other components requiring extra strength, stiffness and/or creep resistance. Other instruments now offered in carbon fiber and other composite materials, all claiming better tone and clarity, are violins and bows, bases, drums and sticks, sousaphones/tubas (an old application in FRP), harps, pianos and more.

**Table 43.7** Consumer products

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Camera tripods*
SCUBA tanks*
Banjos*
Sousaphones/tubas
Harps*
Pianos
Umbrellas*
Attache/brief cases*
Cassette tape/CD player cases*
Exercise equipment*
Art work bracing systems*
Guitars*
Violins and bows*
Bases*
Camera cases*
Eyeglass frames*
Caskets
Binocular/monocular bodies*
Running shoe arches*
Audio earphones*
Drums and sticks*

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#### 43.4.26 OIL AND GAS APPLICATIONS

Conoco, Inc. (Ponca City, OK), Shell (Houston, TX) and others are involved in oil and gas exploration to production depths typically to 619–928 m (2000–3000 ft) and to even more than 4 km (15 000 ft). Conoco is the first company with one of the new tension-leg platforms (TLP) in use. Shell is building such a platform and planning several more in partnership with Exxon and British Petroleum. The oil industry has a 'steel and concrete bias' which is the result



of many years of experience, relatively low initial cost, ample supply, current design codes, etc. However, new materials are the major technology thrust needed in offshore structures because the industry is forced to spend too much money fighting corrosion of steel.

Current offshore structural applications of composites include low-pressure pipe, gratings, handrails, equipment covers or enclosures and ladders. Future application development is likely to focus on FRP for high-pressure piping, pressure vessels, accommodation modules and blast walls. FRP products (mainly E-glass reinforced) provide installation savings ranging from 10–70%, improved life-cycle costs, enhanced safety, 30–70% weight savings and environmental advantages, according to studies by Conoco. It is expected that a variety of composite materials will be used for offshore structures, with carbon fiber, aramid and fiberglass reinforcements, thermosets and thermoplastic matrix resins and some hybrids.

The Institute Français du Pétrole supported development of advanced composite tubes developed by Aerospatiale for risers on offshore stationary drilling platforms and tension leg platforms. These tubes are hybrids of high-strength fiberglass and carbon fiber and are offered in diameters ranging from 76 to 300 mm (3 to 12 in) and in lengths up to 24 m (80 ft). Internal working pressures are in the 34–103 MPa (5000–15 000 psi) range, tensile loads to 90 000 kg (100 tons) will be accommodated by a special high-strength threaded steel alloy coupling, and the design life can be as high as 20 years. Typical drilling risers will be up to 10 times the height of the Eiffel Tower [up to 3000 m (9800 ft)] and weigh over  $2.2 \times 10^6$  kg (2500 tons). Syntactic foams control buoyancy and reduce the effects of sea loads from waves, currents and storms. The case for composites is clear, as weight savings could exceed 544 000 kg (600 tons). A 900 kg (one ton) reduction in the offshore superstructure or the risers results in a savings of 272 kg (3 tons) of displacement load on the platform. Working

closely with IFP and Aerospatiale Space & Strategic Systems are Lincoln Composites (Lincoln, NE and teamed with Aarding BV in The Netherlands) plus Coflexip & Services, Inc. (Paris). Coflexip is reportedly the leading producer of sub-sea pipelines and risers to transport oil and gas products at offshore production facilities. The initial product of the Lincoln–French joint venture was a composite TLP riser pipe that connects well-heads to tethered floating platforms. Risers provide a casing to protect the well bore and to carry the oil to the surface. Tethers will be 244.5 mm (9.60 in) diameter tubes, with a wall thickness of about 13.5 mm (0.53 in) and 12–17 m (40–55 ft) long.

**Table 43.8** Oil and gas exploration

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Tension leg platform tethers*
Fire shields – drilling rigs
Drilling tubes*
Sucker rods/slides
Oil well logging probes*
Tribological bushings, seals, 'O' rings*
Drilling motor shaft
Drill casing

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Longer-term commercial application growth in this sector for advanced composites should include moorings and tendons, drilling and production risers, drill pipe and tubing and some pressure vessels. With platform construction costs exceeding \$1.5 billion per unit, there could be a substantial dollar potential for the various composite applications. One producer estimates the current usage of steel to be as high as  $1.5\text{--}1.8 \times 10^9$  kg (1.7–2.0 million tons) used for oil- and gas-well downhole tubulars. Much of that could be displaced by composites (at one fifth the weight) because of their advantages in high specific strength, fatigue resistance, corrosion resistance, lighter weight, low coefficient of thermal expansion and reduced installation cost (due to lighter weight)

## 43.4.27 PIPELINE REHABILITATION

A high-volume application for Kevlar 49 and other aramid fiber reinforcement has been developed by Insituform of North America, Inc. (Memphis, TN) with the help of Du Pont. A patented product called Insituform has been used extensively for years in repairing and generally 'rehabilitating' old large-diameter, gravity-flow and pressure pipes. Insituform can repair or replace a damaged pipe very rapidly to minimize downtime. The process was developed in the UK many years ago but most of the recent progress has reportedly been made in the USA. A special needled polyester felt reconstruction tube (called Insitube) is coated on the outside (typically with a thin layer of polyurethane), and is custom engineered and manufactured to fit the damaged pipe exactly. It is impregnated with a liquid thermosetting resin (polyester, vinyl ester, or epoxy as appropriate for the chemical environment to be experienced) and lowered into a manhole through an inversion tube. One end of the Insitube is attached to the lower end of the inversion tube elbow. The resin-impregnated tube is turned inside out using cool water so that the smooth coated felt exterior then becomes the new interior surface of the pipe. Circulation of hot water through the tube then cures the resin-impregnated felt.

This repair process typically is performed on an old water or sewage pipe that has been buried for many years and which is starting to leak. The whole procedure can be done without digging up or otherwise disrupting the old pipe. Kevlar 49 is used to reinforce the polyester felt in the hoop direction. This reduces the felt thickness and the total weight, increasing the inside diameter of the repaired pipe, and generally adds both structural strength and rigidity. Also involved is Shell Chemical (Houston, TX) where a special quick-curing epoxy is being developed for this application. Dow Plastics (Midland, MI) supplies resins to another company in this business, In-Liner Corp., with their cured-in-place-pipe (CIPP) process, among many users.

## 43.4.28 POLES – POWER DISTRIBUTION AND LIGHTING

Shakespeare (Newberry, SC) developed filament wound distribution poles that were installed by Montana Power Co. These fiberglass/polyester poles weigh half as much as wood; material efficiency is improved through the use of stitched fabric reinforcements as well. Weight savings enhance the ease of installation in remote areas through use of smaller helicopters than required for wood poles (Fig. 43.5). The 355 mm (14 in) diameter poles are generally 12–14 m (40–45 ft) tall. Another major advantage of FRP poles is the elimination of chemical treatments required to preserve wood poles. An 80-year service life is



**Fig. 43.5** Installing lightweight composite utility poles by helicopter. (Courtesy of Amoco Chemical Co.)

targeted. In a related development, Composite Power Co. (Las Vegas, NV) fabricates FRP utility poles using pultrusion. Prospects for both companies are enhanced because of the environmental concerns when using treated wood poles and the cost escalation of older products that bring them closer to the current premium costs of composite poles.

The California DOT (Sacramento, CA) is potentially interested in the use of composites to build 53 m (175 ft) tall light standards for highway interchanges. Caltrans currently uses galvanized steel but these must be replaced periodically and are difficult to erect and maintain. Among the firms that have built tall steel light standards are Ameron, Union Steel, Valmont and Shakespeare. The hope is that current composite technology for lighting and power poles and for sailboat spars to 55 m (180 ft) height can be expanded into such highway infrastructure applications.

#### 43.4.29 PORTS AND HARBORS

A potentially significant new application with major potential for tonnage of FRP is that of dock and wharf pile fenders. Du Pont fabricated composite fenders for a systems company. Six developmental fenders were installed in mid-1994 in the Chesapeake Bay area. They replaced multiple sets of fender pilings in 10-pile clusters that had steel fender surfaces. The treated wood pilings only last about seven years on average, the steel plates are drastically deformed and rust relatively quickly.

The FRP fenders with UHMW polyethylene skinned impact surfaces to date have better withstood the impact of a 159 000 kg (350 000 lb) ferry boat (eight to ten times/day) than did the wood/steel system, with no damage reported in over two months as of this writing. The lightweight composite fenders were installed in only 3.5 h with a cherry picker while the steel and wood system require a barge crane at much greater expense.

Composite fenders are fabricated using

fiberglass knitted multiaxial fabrics from Brunswick Technologies, Inc. (Brunswick, ME) and vinyl ester resin from Dow Plastics (Midland, MI). The process is called Seemann Composite Resin Infusion Molding System or SCRIMP. Co-owners of the process technology that can infuse preforms of 6 m by 2 m (20 ft by 7 ft) in only 35 mm (1.4 in) are Hardcore, Seemann Fiberglass and TPI (also see rail item above). They license this process technology to others. The USA Navy has been assessing this technology for years in the development of major ship structures, including masts. Composites sheet pile from companies such as Creative Pultrusions and others are also likely to experience a major growth trend.

#### 43.4.30 RAILROAD ROLLING STOCK COMPONENTS

Burlington Northern Santa Fe Railroad (Ft. Worth, TX) is a very innovative company and plans use of composite overwrapped air bottles for use on locomotives. They favor the lightest version that would use a plastic liner and a carbon fiber/epoxy overwrap to replace heavy steel tanks for improved corrosion resistance and easier/safer installation by work crews. Weight saved on railroad rolling stock also increases the capacity for revenue generation from hauling increased cargo. Lincoln Composites and Compositek fabricate such air bottles while Dresser Industries' Nil-Cor Operations makes a variety of composite valves. Most use fiberglass/vinyl ester construction; others are made of carbon fiber/vinyl ester, fiberglass/polysulfone and fiberglass/polyphenylene sulfide composite.

BNSF also seeks to introduce composites on existing or new freight cars. A prototype composite knuckle is in the design stage for extended field tests. This is likely to be a hybrid featuring carbon fiber/epoxy with steel inserts to protect the high-wear areas. Another industry program is development of an FRP cargo door to be produced using a resin infusion process called SCRIMP offered

by Hardcore Composites (New Castle, DE), Seemann Fiberglass (Harrahan, LA), and TPI (Warren, RI).

Composite auto hauler composite cars with all-pultruded components of fiberglass/polyester have been developed by W. Brandt Goldsworthy & Assocs. (Torrance, CA) along with Alcoa Composites and Stoughton Composites (Brodhead, WI) for the Union Pacific. Many other freight car development programs are under way at Trinity Industries and elsewhere. Corrosion resistance and light weight are the two primary benefits of composites that are sparking this interest.

#### 43.4.31 RAILWAYS AND TUNNELS

Besides pultruded and filament wound composite cableways, ducts and piping, there is a vast array of associated molded parts for trackside, station equipment and furniture. Development of fiberglass reinforced phenolic-matrix composites, with their superior FST properties, has become an important contributor to the increasing acceptance of composites for interior components. European countries now virtually mandate using phenolic resin composites for underground railcar and station components. Some of ICI's Modar acrylic-modified polyester and also the less flammable phenolic-based composites were used in the Channel Tunnel, mainly for electrical cable tray. The market for composites in railways and tunnels could double during the next few years due mainly to the greater attention being paid to safety, including improved fire, smoke, and toxicity performance (reduced FST).

#### 43.4.32 ROLLS AND AIR SHAFTS

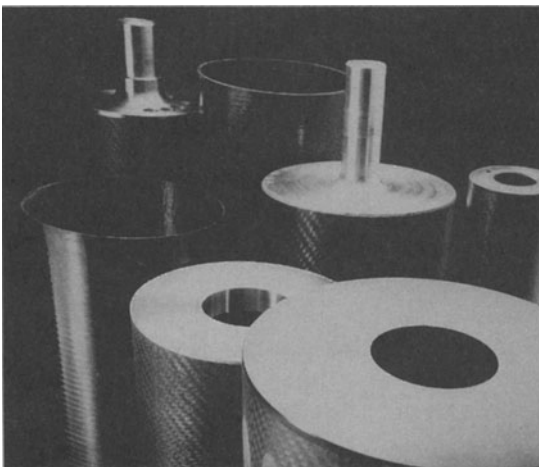
Industrial rolls and expanding air shafts used inside cardboard core tubes on winders to take up paper, films and foils will be major growth applications in the industrial composites sector. Tidland Corp. is said to be the world's leading supplier of core shafts of all types and

reportedly buy most of their carbon fiber/epoxy rolls from Lincoln Composites. Shafts from about 2–10 m (6–33 ft) long are fabricated using hybrid carbon fiber and fiberglass in epoxy which are about one-fifth the weight, operate at faster speeds and use less energy than the conventional steel rolls. Fiberite (Wilmington, DE), Epoch Industries (Garland, TX), Addax (Lincoln, NE), and Quality Composite, Inc. (Sandy, UT) are among others that fabricate such products. Amalga Composites, Inc. (Milwaukee, WI) is a more recent entry into the filament winding of carbon fiber/epoxy tubes for the industrial rolls used in paper and plastic film converting machinery and reportedly is a major supplier to American Roller (Bannockburn, IL). They use Grafil's 33 msi carbon fiber but leave the finishing and coating operations to American Roller. According to ARC, there are many potential applications for composite rolls. These include replacing the steel rolls commonly used in winder core, winder shaft, idler, layon and dancer/transducer positions to manufacture film, flexible packaging, foils, magnetic audio and video tape and photo- and pressure-sensitive papers on printing presses, laminators, coaters and blown film lines. However, selecting the right composite for each of these positions is not quite as simple as ordering an off-the-shelf product. ARC technical and marketing people make a special point of explaining why each composite roll should be customized to the end-user's specific application and operating parameters, especially because of the many types of composite materials and structural designs available on the market today.

Another filament wound tube fabricator for this application is SpyroTech Corp. (Lincoln, NE). Also, TPI (Warren, RI, and formerly called Tillotson Pearson) has been using filament winding to make fiberglass/epoxy and carbon fiber/epoxy tubes for paper mill rolls. It is noteworthy that Mitsubishi Rayon in Japan is one of the largest suppliers of such rolls in the world. These suppliers market the

major benefit of hybrid carbon fiber–fiberglass and 120°C (250°F) cure epoxy composite rolls and shafts compared to steel and aluminum shafts, namely a 50% weight reduction. Precision balancing allows higher operating speeds than with metal rolls. Advanced composite rolls exhibit 20% less deflection under loads. Also, composite rolls offer superior fatigue resistance for increased service life and improved damage tolerance versus steel or aluminum.

Polygon (Walkerton, IN) is a pultruder and braider active in fabrication of such industrial rolls. Composite Development Corp. (West Wareham, MA) also supplies to the converting industry that wants to use thinner gage paper/film/foils yet process at higher speeds, so the lightweight, low-inertia rolls produced using carbon fiber composites with the fabric roll-wrap process are rolls that offer improved handling characteristics (Fig. 43.6). Heavier rolls such as plate cylinder rolls (used to mount printing plates) offer excellent weight savings that are important in a process with constant and many job changeovers. Some producers of rolls use braided reinforcement preforms from companies such as A&P Technology (Covington, KY).



**Fig. 43.6** Composite industrial rolls. (Courtesy of Composite Development Corporation.)

**Table 43.9** Industrial equipment

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Coordinate measurement/3-D gaging*
Magnet support rings*
Torque tubes*
Paper folding plates*
Coating doctor blades*
Textile bobbins*
Instrument housings
Pump impellers*
Crane components
Backhoe components
Forklift components
Mixer drive shafts*
Containers
Chemical mixer paddles*
Liquid level measuring sticks
Surveying transit tripod
Industrial rolls – paper, film, foil, printing*
Water tanks
Chemical filters/frames
Radio-controlled vehicles
Mirrors*
Cryogenic vessels*
Core tube air shafts*
Generator housings
Welding robot arms*
Laser resonator spacer tubes*
Pump casings
Speaker housings*
Signage
Textile looms – rapiers, heddles, shuttle cocks, picker sticks*
Ball and butterfly valves
Conveyor belt support shafts
High-pressure hydraulic pipe*
Pneumatic piping*
Uranium enrichment centrifuges*
Cooling tower drive shafts*
Tote trays/Storage bins
Tooling*
Optical benches*
PCB conveyor components
Coil springs*
Underwater light housings
Light bulb sockets
Propellers
Fan blades
Ladders
Safety shoe toe guards
Industrial shaft couplings
Broom handles
Window cleaning squeegee handles
Cherry picker lifts

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The considerable weight reduction compared with steel rolls means less strain and fatigue and reduced injuries for the operators. For example, a steel roll that is slightly over 2489 mm (98 in) long, 152 mm (6 in) O.D., and 127 mm (5 in) I.D. would weigh approximately 188 kg (239 lb). A fiberglass-reinforced composites roll of the same dimensions would weigh 27 kg (61 lb), while a carbon fiber composites roll of this size weighs only 22 kg (49 lb).

#### 43.4.33 SMC – TOUGH, HIGH-PERFORMANCE

Premix, Inc. (No. Kingsville, OH) and their Quantum Composites division (Midland, MI), focus on 'ultra-high strength and toughness' Lytex SMC that is offered with carbon fiber or fiberglass reinforced epoxy or vinyl ester resins. Present nonaerospace uses for this unique SMC include a prosthetic foot, an automobile brake component, an electrical connector and more. Projected applications include automotive suspension and structural chassis components, recreational-vehicle high-impact parts and other applications demanding toughness and excellent dynamic fatigue resistance (including aerospace).

#### 43.4.34 SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEMS (SMES)

Composites play a key role in the insulation and structural systems of the SMES Program at General Dynamics Space Magnetics, now a unit of Martin Marietta. Years of development may now offer dramatic potential for carbon fiber and glass fiber composites in the future. The purpose of SMES is to economically store electrical energy from power production late at night and then to retrieve it during peak demand periods during the day.

Heading the team is Bechtel National, Inc. as system integrator. General Atomics is responsible for the coil supports and was the designer and fabricator of the first SMES unit to be operated successfully (1983) by an electric utility, Bonneville Power System. National

Institute of Standards and Technology (NIST) in Boulder, CO, and the Phillips Laboratory at Edwards AFB, CA, assist by conducting the low-temperature testing work. Competing technologies for SMES include pumped water storage, batteries, and potentially, flywheels.

Recent work has been focused on developing and testing the prototype of a full-size mockup of a SMES unit. E-glass fiber reinforced plastic curved, pultruded vinyl ester resin beams were developed to simultaneously provide essential electrical insulation (between conductor coils and between the conductor and the ground) and the conductor support structure.

Pultruded FRP was chosen because it provides reasonable structural performance and the required electrical insulation capabilities at cryogenic temperatures for an affordable cost. Test articles were fabricated and then the mechanical, thermal, and electrical properties were measured over the temperature range of 4–295K. FRP beams, pultruded by Compositex (of Brea, CA and now part of Kaiser Aerospace), met the goal of comparable performance to currently used and more expensive materials such as G-10 laminate produced with fiberglass fabric and epoxy resin. The tensile failure strains for the materials tested using liquid helium ranged from 1.2% at 295K to 1.9% at 4K. The pultrusion machine was built by Pultrex Ltd (Clacton-on-Sea, UK). Johnson Industries Composite Textile Reinforcements, Inc. (of Phenix City, AL) supplied the stitched fiberglass preform materials, which ranged from 9 to 18 plies in thickness.

SMES develops large radial loads when charging. This requires strong coil support straps, which are integrated by General Atomics (San Diego) and which were filament wound by Lincoln Composites (Lincoln, NE). The short straps look like a fan belt about 127 mm (5 in) wide and 762 mm (2.5 ft) long and are wound with S-2 glass fiber prepreg. Larger straps, about 89–1200 mm (3.5–4 ft) long and 100 mm (4 in) wide, are wound using carbon fiber prepreg.

The SMES Engineering Test Model (SMES-ETM) consists of a two layer, radial, helically wound, 96 m (315 ft) diameter solenoid coil that has been designed to store a minimum of 20 MWh of electrical energy in its magnetic field. The coil stack requires 66 layers of FRP curved beams for the support structure or 825 24 m (80 ft) sections weighing 907 kg (2000 lb) each. A full-sized, 20 MWh ETM demonstration unit will require about 725 000 kg (1.6 million lb) of FRP composite. A full-scale test model of SMES will consist of a large, cylindrical coil 91 m (300 ft) in diameter sunk into a 9 m (30 ft) deep trench in the ground. Stored energy can be retrieved slowly or almost instantaneously, and the technology is considered a promising method of storing electrical energy for peak load demands.

Bechtel estimates that the potential SMES market in the USA alone could be as high as \$3 billion/yr. The Electric Power Research Institute in Palo Alto (CA) and the SMES Utility Interest Group (SUIG, Dallas, TX) are promoting the commercial development of the SMES technology because it looks promising for electrical load leveling, increasing electrical system reliability, savings in fossil fuels, reduced air pollution, emergency backup power, virtually instantaneous response and the ability to store energy from intermittent sources such as solar and wind generation of electricity. EPRI estimates that by 2010, storage could usefully provide as much as 10% of the nation's generating capacity. Using storage to save power generated at night when power plants normally run at very low rates some day could potentially save the cost of building many new generating plants at far higher cost than adding SMES storage capacity.

#### 43.4.35 TRIBOLOGICAL APPLICATIONS - SEALS AND 'O'-RINGS

EGC Corporation (Houston, TX) is a custom fabricator of molded components for oil field and refinery applications. Their 'wear-resistant composite' is called XC-2 tribological material

and is produced using 68 w/o AS4 carbon fiber filament wound in PEEK thermoplastic matrix. They have reportedly produced well over 45 360 kg (100 000 lb) of parts with this material 'under production conditions, to aerospace requirements'. Also offered are parts molded from their injection-molding grade. Polygon offers a line of 'Poly Lube' composite bearing materials, hybrids of fiberglass and Teflon. Bal-Seal Engineering Company (Santa Ana, CA) markets carbon fiber and graphite-filled Teflon fluid seals and 'O'-rings. The primary benefits are dimensional stability and a low coefficient of friction under elevated temperature and pressure, with no 'extrusion' of the resin matrix. Carbon fiber adds to the tribological value of the rings through prevention of adhesion of the Teflon to the bearing surface. Tiodize (Huntington Beach, CA) sells self-lubricating composites based on carbon fiber in a high-temperature resin used for bushings, thrust bearings, rod-end bearings and ball-bearing retainer rings. They emphasize the advantage of using these materials compared to aluminum in retaining specific modulus at temperatures to 316°C (600°F).

#### 43.4.36 URANIUM ENRICHMENT CENTRIFUGES

Louisiana Energy Services is a joint effort of three USA electric utilities, Duke Power Co., Louisiana Power & Light Co. and Northern States Power Co. Along with the internationally known engineering firm of Fluor Daniel, Inc., Urenco will build and help operate a uranium fuel enrichment plant for these utilities. Urenco is a European organization with close to 15 years of experience operating commercial uranium enrichment plants in Germany, the UK and The Netherlands. Together, the three utilities own and operate 11 commercial nuclear power plants. In the enrichment plant, high-speed ultracentrifuges will be used to enrich the uranium and hopefully can supply nuclear plant fuel at a price lower than is being projected by DOE, according to the

program planners. Carbon fiber/epoxy filament wound composite tubes are to be used for the high-speed rotors but most of the technology details remain proprietary to Ureco. At this writing, Louisiana Energy Services continues with the approval process for the required environmental impact report in support of their license application. They hope to start construction soon, and have the new plant in full operation in the late 1990s. Similar composite centrifuge rotors are believed to be standard design for European and Japanese uranium enrichment work.

#### 43.4.37 VALVES

Dresser Valve & Controls Division, Nil-Cor Operations, (Alliance, Ohio), sells several types of composite valves to the chemical industry. Over 100 000 Nil-Cor advanced composite valves are currently in service at over 100 USA paper mills. Their current valve product line includes fiberglass and carbon fiber reinforced PPS, polysulfone and vinyl ester in several sizes and types. Fiberglass reinforcement and Dow Chemical's Derakane 470 vinyl ester resin (among others) are used in ball and butterfly valves for the chemical industry.

#### 43.4.38 WIND TURBINE BLADES

TPI, Inc. located their composite wind turbine blade production in Portsmouth, RI. TPI makes fiberglass/vinyl ester blades regularly for large operators of wind energy farms in the USA. The size of the individual generating units has gradually increased from the 50 and 100 kW sizes with 8 m (27 ft) composite blades that were most common several years ago to the larger 300-kW units that are now in demand. Each of the three new size blades is 17 m (56 ft) long and uses a sizable quantity of material. Production rates have reached as high as 5000–6000 blades per year. Among the critical aspects of making large windmill blades is the need for proper balance. This is one reason that the TPI product has succeeded

while other blade manufacturers had to fold when the market started to collapse several years ago.

Sandia National Laboratories (of Albuquerque, NM) developed advanced wind turbine technology using the vertical axis approach and signed a technology agreement with Flo-Wind Corp. (Pleasanton, CA). Flo-Wind has used extruded aluminum blades but plans use of composite blades. Flo-Wind currently operates 'over 500' such turbines with aluminum blades currently in operation on two California windfarms, likely candidates for retrofit with composite blades. Glasforms (San Jose, CA) is one of their prime suppliers for composite parts.

Competition continues to develop overseas. Japan's Tomen Corp. has joined with American and British firms to build several large wind power farms in Wales and Cornwall, UK, operated by a company called British Wind Farms, based in London. Included in their plans was the construction of 300 windmills with a total generating capacity of 77 000 kW. Many European countries are making sizable commitments to increased use of windpower, including Denmark, Germany, Holland and Spain.

The National Renewable Energy Laboratory, a unit of the Department of Energy (formerly called the Solar Energy Research Institute), is in Golden, CO. They are interested in all types of alternate energy systems, including battery-operated vehicles, engines that can use different types of fuels, including hybrids and biofuels. NREL sponsored an effort called the 'Advanced Wind Turbine Next Generation Preliminary Design Project', with the goal of bringing wind power generation costs down from the current 7–8¢ to below the 4–5¢ per kWh with coal generation. Wind generators must be made of materials likely to last at least 30 years, so the additional cost of using carbon or aramid fibers to reduce rotor blade weight and/or improve performance might be amortized over a long period.



Today there are over 15 000 windmills in California alone, with a total electrical generating capacity of 1300 megawatts. To date, they have generated a total of over two billion kWh, replacing 3.5 million barrels of oil. However, this is only 1.7% of the total power requirement of the state of California during the same period. There are more windmills overseas where about 70% of the total has been installed.

### 43.5 MARKET DATA

A frame of reference on market size is useful in assessing composites growth prospects. The Composites Institute of the Society of the Plastics Industry issued a news release February 8, 1994 stating that USA shipments of fiber reinforced plastics (FRP) reached an estimated  $1.23 \times 10^9$  kg (2.73 billion lb) in 1993. This was an increase of 6.9% over 1992 (this is almost entirely fiberglass-reinforced polyester, vinyl ester, and epoxy material but includes advanced fibers composites). Projected 1994 growth to  $1.32 \times 10^9$  kg (2.90 billion lb) of composites represents an increase of another 6.2%. Overall growth in sales of composites continues

at twice the growth rate of the Gross Domestic Product (GDP).

Sectors that fall mainly into the commercial and industrial applications arena, the focus of this chapter, are noted next. The corrosion-resistant application sector for chemical storage, process tanks, pipe systems, cooling tower components, wastewater treatment, pressure vessels, and pollution control equipment grew 5.9% in 1993. This is because of their ties to capital spending and substitution for other materials, and another 3.7% gain is likely in 1994. Electrical and electronic application usage grew at 5.7% in 1993 (plus 5.5% more in 1994). Power poles and fiber optic cable splice boxes are examples of growing areas here. The appliance, business equipment, and consumer product markets gained only 3.0% (plus 3.7% more in 1994) and 2.2% (with another 4.2% in 1994) respectively, mainly from material substitution. Lastly, the 'other' category grew at 7.1% in medical equipment such as orthopaedic appliances and dental materials. The Composites Institute (CI) represents over 415 firms in the composites industry and is the SPI's largest division.

**Table 43.10** USA composites shipments: 1984–1994 (in million lb)

<i>Markets</i>	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994 <i>projected (revised)</i>
Aircraft/aerospace/ military	29	32	37	36	39	41	39	38.7	32.3	25.4	24.6
Appliance/business equipment	123	133	137	141	150	151	153	135.2	143.2	147.5	153.0
Construction	430	445	456	506	495	470	468	420.0	483.0	530.0	575.0
Consumer products	143	142	149	167	169	158	165	148.7	162.2	165.7	171.2
Corrosion-resistant equipment	310	295	291	329	349	335	350	355.0	332.3	352.0	365.0
Electrical/ electronic	189	191	201	214	230	229	241	231.1	260.0	274.9	290.0
Marine	309	335	340	413	452	405	375	275.0	304.4	319.3	332.8
Transportation	540	563	585	656	695	677	705	682.2	750.0	822.1	890.0
Other	80	82	83	75	80	76	79	73.8	83.4	89.3	93.9
Total	2153	2218	2279	2537	2659	2542	2575	2360	2551	2726	2895.5

Includes reinforced thermoset and thermoplastic resin composites, reinforcements, and fillers.  
Source: SPI Composites Institute, 1994 Semi-annual statistical report, February 8, 1994

#### 43.6 PREDICTIONS

Much of the long-term growth for composites is likely to come from this miscellaneous sector of the business. The most likely segments to experience large unit growth rates are CNG tanks, flywheels, industrial rolls, distribution and lighting poles, civil structures, consumer and medical products and some other oil and gas or transportation components. Composites have a low market share in many industries, and commercial and industrial applications should continue to experience well above average growth compared with other composites, other material systems, and the total economic growth rate on a worldwide basis. Such growth over the long term is believed likely to exceed the 5–8% growth rate expected for 1994 over 1993 shipments for these composites markets.

#### 43.7 CONCLUSIONS

Because these sectors of business and technology are highly fragmented many smaller producers are likely to participate. The scale of production is often not well suited to large producers. Also, the cost for large producers to pursue such fragmented businesses, pieces of which may not be very large, could be higher per unit or unit weight than for their huge composites commodity businesses such as automotive, marine and others. Much of the innovation in material forms and process technology also resides in this group of markets.

Thus, one should look to these markets not only for growth but also for technology and new ideas.

#### REFERENCES

Most of the information provided in this chapter was generated through attendance at trade shows, interviews with industry participants, review of press releases, other extensive reading of publications, and the experience of the author over 30 years. Therefore, since most paragraphs would have required almost a reference per sentence, we elected to list below the best generic and reliable USA-based sources available to research these applications and markets or to track their future activities, participants and prospects.

- Composites Institute of the Society of the Plastics Industry, New York, NY.
- Composites News: Infrastructure and Advanced Material* newsletters. Loud, Steve, (ed.) Solana Beach, CA: Composites Worldwide, Inc.
- Composites Industry Monthly* and *ACM Monthly* newsletters. Burg, Martin, (ed.) San Diego, CA: Composite Market Surveys.
- Composites Technology* and *High-Performance Composites* magazine. Hazen, Judith Ray, (publisher), Denver, CO: Ray Publishing, Inc.
- Performance Materials* and *Fleets & Fuels* newsletters. Piellisch, Richard, (ed.) San Francisco, CA: August Pacific Press.
- plasticsBRIEF Reinforced Plastics Newsletter*. Best, James R., (ed.) Toledo, OH: Market Search, Inc.