# ADVANCED MATERIALS, ECONOMIC EVALUATION

## 1. Introduction

The emergence of the advanced materials industry, beginning in the late 1970s, represents one of the most important and dynamic chapters in U.S. and international technological development. These materials possess new and different types of internal structures and exhibit a variety of novel physical and chemical properties that have a wide range of industrial and commercial applications.

The advanced materials industry encompasses such product areas as: biochemicals (including genetic-based materials); bioengineered materials; catalysts; ceramics and clays; coatings; composites; crystal materials; fuels; fullerenes; metal alloys; nanometarials (eg, nanotubes, nanopowders, nanospheres, nanofibers); optical and photonic materials; polymers (eg, plastics, rubber, fibers) and polymer matrices; powdered metals; sensor materials; superconducting materials; and thin films (1,2).

While advanced materials are highly diverse with respect to structure, physical and chemical characteristics, and applications, they form a coherent industry due to a number of criteria, including common processes and technical and economic interrelationships. The importance of the industry resides in the fact that its materials diffuse into and impact virtually all of the major industrial sectors, including aerospace, automotive, biomedical, construction, consumer electronics, defense, energy, food processing, healthcare, materials processing, mining, packaging, petrochemical, security, telecommunications and utilities.

Because the advanced materials industry impacts the economic well being of a growing range of businesses and industries within the United States and internationally, it will ultimately rival the traditional chemical, pharmaceutical, and metals industries in terms of revenue, diversity, and economic importance. The advanced materials field is fundamentally altering how, and even what, the world's leading industries produce, and how they structure themselves and perform their basic operations. Indeed, very few major new technologies can emerge without the application of advanced materials. Accordingly, an examination of the advanced materials industry is also a study of technological change in general in the modern age.

## 2. The Historical Context

Today's advanced material technology follows and expands upon what is generally considered the first material revolution that emerged during and following World War II. Beginning in the mid-nineteenth century, the German chemical industry dominated advanced chemical materials. German firms, including Bayer, Badische, and Hoechst, revolutionized industrial chemistry by synthesizing from coal tar materials a broad range of commercial organics (including dyes), pharmaceuticals, and plastics. In the years leading up to World War II, the United States began to compete with Germany in the commercialization of new materials. As the largest oil-producing country in the world, the United States substituted petroleum for coal as the dominant feedstock for its advanced material products. Some of these petroleum-based materials, notably synthetic rubber, toluene (for making explosives), and advanced fuels, served critical strategic purposes during World War II (3–5).

The postwar period, building upon these earlier achievements, ushered in the age of synthetic "materials by design." The large, established chemical companies and petroleum refiners—Dupont, Dow Chemical, Exxon (Jersey Standard), Sun Oil and, increasingly, the specialized process engineering firms—created and controlled this revolution because they had the means, engineering talent, and the mass production facilities to do so. The new technology at this time included the mass manufacture of the new synthetic rubbers, fibers, resins, and plastics, such as nylon, polyethylene, and the like. These novel materials percolated rapidly throughout the U.S. economy, transforming a wide range of industrial operations, including transportation, metals production, packaging, construction, electronics, biomedical, etc (6–8).

By the 1970s and early 1980s, shrinking returns from innovation due to overproduction, the global energy crisis, and declining technical possibilities from petroleum, put a brake on new material development. The large, integrated petrochemical producers, now shying away from new product development, focused on improving and modifying existing processes and products as their major competitive strategy. This retreat by the traditional chemical industry from more revolutionary technology provided an opportunity for newcomers to explore the commercial potential of a new generation of innovative materials. This encroachment by "upstart" R&D firms led the way to the new materials revolution of the 1980s and 1990s (6,9).

## 3. The New Materials Revolution: 1980s—Present

The current generation of new materials, in part, has evolved from earlier advanced material technology. For example, new types of "high performance" polymers derived from, and are an improvement over, such first generation materials as polyethylene (and polypropylene), nylon, etc. This is true as well for new types of catalysts, metal alloys, pharmaceuticals, and biochemicals.

But important technical and economic differences exist between earlier, post World War II technology and the newer generation of materials. Rather than relying on a single feedstock (ie, petroleum), the new and emerging processes consume a variety of raw materials: ceramics, clays, crystals, minerals, coal, petroleum, natural gas, graphite, and agricultural by-products. In contrast to earlier production technology, advanced materials technology does not depend on large, integrated plants and are not inexorably linked to mass production methods. This is so because they often become critical additives in a wide range of composite materials and therefore do not have to be made in the massive quantities typical of new petrochemical products in the past. For example, a small quantity of carbon nanotubes can be added to a relatively large volume of an already existing polymer material to make commercial quantities of a totally new type of composite material. Similarly, a relatively small amount of a particular element or compound, integrated into a mass of steel or aluminum, produces large quantities of advanced alloys (1,9).

These trends mean that the current generation of advanced materials depends to a greater extent than previously on creative laboratory investigation, venture capital funding, and extensive licensing arrangements, rather than on in-house, large-scale engineering capability. Accordingly, the established petrochemical firms, once the dominant player in creating new materials, increasingly find themselves competing with the university and government laboratories, and the start-up operations and spin-off firms that license promising inventions for advanced material markets.

## 4. Process Flow and Technology

While the advanced materials industry creates a wide range of products, common patterns emerge that characterize the process flow of the industry. First, the manufacturing processes that transform raw materials into advanced materials are generally chemical in nature. Typically, the processes employ thermal energy through various means—eg, thermal furnaces, laser technology, and high temperature reactors—To effect the requisite chemical reactions. Then too, an advanced material, once produced, generally requires subsequent processes to modify and prepare the material for market. Nanotubes, eg, need to be made into a composite materials, coatings have to be applied to the surfaces of components, and so forth in order for the advanced material to be useful in various applications. Depending on the industry involved, additional processing steps may include assembling components or parts containing an advanced material into a final product to be distributed and sold to an original equipment manufacturer (OEM) (1,6).

Currently, separate firms perform these processes for the advanced material companies. Increasingly, the latter resides near to the assorted downstream plants that serve it, thus forming tightly knit manufacturing complexes. This clustering of production provides essential economies in developing and manufacturing advanced materials through the regular movement of raw materials, energy, labor, knowledge and technology between companies. Over time, as they grow and diversify and integrate operations, the advanced material companies themselves undertake some or all of these operations in-house (9,10).

## 5. Industry Structure: Competition, Diversity, and Geography

The advanced materials industry exhibits a high degree of competitiveness. While one company may dominate a new material for a short time, companies offering competing technology—whether a new product, process, or both—emerge rapidly thereafter. Also, product lifecycles tend to be short as new companies and products regularly enter the market. New materials must also compete against older products that serve the same markets. The inevitable push of new technology is not always the case since markets, generally conservative in nature, do not readily accept novel materials over more familiar and tested products. Consumers of the older materials understand the advantages and limits of the established products and have adjusted their processes accordingly. They also are aware that adopting new materials can be costly, such as in retooling of plants and retraining of personnel. Further, the price of advanced materials cannot initially compete against the offerings of established producers, who attempt to maintain their markets by reducing unit prices. Such dynamic competition, coupled with the fact that production processes for advanced materials achieve greater economies over time, means that unit prices for these products tend to decline steadily over time (8,9).

Within the industry, there are “captive” producers and “open” producers. The former produces advanced materials—eg, nanotubes—for internal use. They may also purchase advanced materials on the open market. Captive producers include universities and government and industrial laboratories. They may also include the larger, multinational corporations, such as Honeywell. On the other hand, "open" companies produce and sell their materials on the open market. Purchasers of these materials may want to conduct experiments on them or incorporate them into proprietary production processes. Suppliers of advanced materials to the market may be small start up firms, large corporations, or academic and government laboratories.

The advanced materials industry encompasses a wide variety of companies in terms of size, diversity, and the degree of integration. These companies range from the large, integrated chemical, petrochemical, and process engineering firms who employ tens of thousands of people worldwide and post annual sales in the billion of dollars, to the small start up and spin-off companies who rarely employ $>100$ persons and who may record annual sales revenues $<1$ million dollars. The former type of company generally supports its research and development activity with internally generated funds and obtains patents on the technology it creates in-house. It may, in time, license its technology to outside companies in exchange for royalties. The large corporation offers a wide range of products, both established, well-know materials as well as new types of materials that often are modifications of existing commercial products. For its part, the small start up and spin off firm usually takes out licenses on promising material processes from university and government laboratories. In time, they then sublicense to other firms in order to expand manufacturing capacity or exploit locational advantages, ie, nearness to raw materials or markets. The start up firm typically obtains funds for development and commercialization activities from outside sources—venture capitalists, government grants, etc (9,11–13).

While certain of the large corporations, such as Dow, General Electric, Xerox, 3M, Motorola, and IBM, continue to develop new material technologies, the established corporation typically has turned away from developing the most radical technologies. This is so for a variety of reasons including increasing development costs; decreasing returns on investment in R&D (due in part to the need to utilize an extensive R&D department and the high costs of retooling and restructuring existing, large-scale plants); the growing likelihood that new technology must compete against the innovating company's own existing products; and the difficulties and costs involved in establishing new supply lines and distribution networks (and the possible alienation of existing suppliers and customers). Moreover, the growing professionalization of corporate management blunts the desire and capability of companies to undertake new technological development. This is, in part, due to the rise of intellectual and cultural boundaries between managers that reflect the greater degree of specialization that characterizes corporate management professionals. Such specialists, embracing their own particular professional goals, problems, and even language, hinder the close cooperation and free flow of information between different departments, which is often required in successfully undertaking major technological projects (5–8,14).

In contrast, the small, start-up and "spin-off" firms enjoy a greater degree of flexibility in pursuing new technology. They are not burdened with an existing system of plants nor do they have to support an extensive supply, distribution, and R&D infrastructure. They do not have established products that could compete with new material technologies nor do they need to cosset an established network of suppliers, distributors, or customers. Indeed, commercializing radically new materials is absolutely critical to their existence since doing so distinguishes them from their competitors, both large corporations and other smaller newcomers, and is the key to capturing new markets. In addition, the organizational structure in these firms is more loosely organized. As a result, the lines separating specialties and departments tend to be highly porous and even blurred. Often, individual executive managers undertake a wide range of functions, including engineering, procurement, and marketing. This informal organizational structure facilitates a free flow of information, know how, and insight throughout the company and permits decisions involving new technology development to be made quickly and efficiently (6–8,11,14).

The geographical distribution of advanced materials companies, whether in the United States or internationally, depends on a number of economic, political, intellectual, and demographic factors. These factors include the local availability of raw materials, potential markets, knowledge-based institutions (ie, universities, industrial and government laboratories, incubator facilities), government support and incentives (eg, tax breaks, R&D subsidies, technology development programs), and funding sources (eg, venture capital) (4,10–13).

The advanced materials industry is active in different parts of the United States and internationally. Within the United States, particularly dynamic areas include the Southeast, Southwest, and West Coast. Internationally, western Europe, and particularly Germany and the United Kingdom, conduct extensive research and development work. Now that much of eastern Europe is part of the European Union and can benefit from information, technology, and markets of the western European countries, this region is likely to expand its role in the field over the next few years. Within the Pacific area, Japan is a major participant in advanced materials, including advanced ceramics, since the 1980s, and Australia continues to increase its presence in the field. China, India, and certain Middle Eastern countries (eg, Israel), continue to develop as centers of advanced materials, a trend that will continue over the next 10–20 years. United States advanced materials companies continue to establish links with foreign firms through partnership arrangements, especially with European and Asian countries. These arrangements serve U.S. producers through information and technology transfer and ready access to foreign markets (9).

## 6. The Commercialization Process

Commercialization is the process by which a laboratory invention enters into the market arena. Commercialization involves a number of closely interrelated tasks, including product and process development, and marketing and distribution strategy. Patterns of commercialization for advanced materials differ, depending on whether the company is a large, integrated corporation or the small start-up or spin-off firm.

The large, integrated corporation generally controls all (or at least most) phases of commercialization. The corporation's research department investigates the technical and economic viability of new materials. The patent department, staffed by both technical and legal personnel, arranges the application of the patent with the U.S. Patent Office and determines the terms and conditions for licensing. The engineering department perfects the production process, which usually requires the development of continuous (semicontinuous) mass production systems, and often sees to the coordination between supply and production schedules. The marketing department then secures customers for the new material. These may be independent processors who further shape the material into some form (eg, molders), original equipment manufacturers (OEMs) that incorporate the material as a component in an assembled product (eg, automobile, airplane, computer, appliance) or, in certain cases, the final consumer who purchases the material directly from the manufacturers (or from distributors). The marketing department often works closely with—or is part of—technical services. The latter, a hybrid engineering and marketing service, instructs customers as to the proper use and possible application of new materials and the components derived from them. Technical services personnel, many of whom have engineering backgrounds, also examine possible ways in which materials require modification in order to attract potential customer sources. In doing so, technical services works together with the company's research, engineering, and marketing departments (6,9).

For the large, integrated corporation, commercialization proceeds in-house using the resources of the entire organization. With increasing frequency, however, commercialization of advanced materials takes place through the close interaction and cooperation of the university and government laboratory and the small start-up firm. The university and government technology transfer offices play an instrumental role in steering promising new materials from their organizations to the commercial sector. As part of their responsibilities, these offices work with in-house university and government researchers to patent inventions in a timely manner and to help license technologies to outside businesses. State (and federal) governments also provide assistance to the commercialization process. Federal R&D programs, such as the Small Business Research Initiative (SBIR), provide grants to firms commercializing promising new technology. The Departments of Energy (DOE), Commerce (DOC), and Defense (DOD) operate various programs to aid the development of advanced material products and processes. Also, certain states facilitate the transfer of advanced materials technology from universities and government laboratories to selected firms through such organizations as centers for innovation and technology, regional technology councils, and incubator facilities. Within Virginia, examples of such organizations include Virginia's Center for Innovative Technology (VACIT) and the Hampton Roads Technology Council. These agencies offer a number of functions, including the funding (eg, through grants) of research and development, providing research facilities, and identifying and bringing together potential strategic partners in joint technology development arrangements (9–13).

Once the start-up firm secures license rights to a patent, it continues to develop the technology through commercialization and, eventually, market development. The innovating university or government laboratory typically supplies technical assistance through much of the process. Often the original inventors retain some role in the new firm, possibly as technical consultant or lead

R&D person. To continue financing the project prior to the creation of significant sales revenues, the start up firm usually depends on government money in the form of federal and state grants and contracts. This money supports a small core staff of managers, engineers, and production crew. At some point, the firm approaches outside investors, usually in the form of venture capitalists. Investors participate in the commercialization process at a distance (ie, through lending funds only) or more intimately by taking part in the operations of the firm. In the latter case, they actively guide the progress of the enterprise by participating as members of the Board of Directors or Executive Committee (11–13,15).

Typically, the start-up firm does not generate revenue until it actually starts selling the advanced material on the open market. Reaching this stage typically requires 3–5 years from the time of first obtaining licensing rights since time is needed to undertake further research and development on the technology to improve the process, achieve commercial-grade material and lower production costs (9,14).

As the new material diffuses through markets, the firm expands production to meet the growing demand. With increased production, economies of scale come into play through the adoption of fully (or semi) continuous process technology and better coordination of the company's supply, processing, distribution, and marketing functions. These economies create a downward pressure on prices and, in turn, the further expansion in market demand. From this point, demand for the new material increasingly depends on price, as well as quality, as the process technology strives to dislodge the existing materials from their market positions. As production expands, the firm broadens the management team by hiring additional and diverse personnel to handle the increased volume and coordinate material flow, process technology, and market development. It is at this point that the material achieves economic prominence (9,14,16,17).

## 7. Evolutionary Patterns and Market Strategies

The evolution of an advanced material generally adheres to the classical product life-cycle model. In the first (or "creation") phase of an advanced material's life-cycle, the new material is not yet in its final commercial form. It undergoes frequent and significant alterations in its physical and chemical properties. Because the material is not yet standardized, the production process tends to be inefficient and generally makes the material in batches rather than continuously. As a consequence, unit prices remain high. Markets for the new material tend to focus on specialized, niche applications, such as for defense needs. Market strategies in this phase of the cycle hinge on the superior characteristics of the product rather than on competitive pricing. By necessity, inputs are limited to generally available materials and energy sources, facilities are often small scale and located near user or source of technology, and labor costs tend to be a large percentage of the total costs of production (9,14).

In the second (or "formative") phase of a new material, technical considerations and preferences of the marketplace determine which variation of the new material becomes the one, dominant design. This stabilization of design means that the production process can become fully continuous thus permitting the rapid scale up to high volume production. As the mass production process evolves, "islands of automation" appear in the production line. The production process then requires increasing volumes of specialized raw material and capital inputs. The production process becomes more rigid in that it is specifically designed for the large-scale production of the single type of material. In this second phase of the material's life cycle, the percentage of total costs consumed by labor decreases since the manufacturing facility generates an increasing output of materials per unit of man hours. As volume of output expands, other factors of production play a more important part in the cost equation. These include raw materials, capital expenditures (ie, such as on equipment and buildings), and energy usage (9,14).

During this period of initial production expansion, the advanced material company expands its present capacity, both by adding onto a current plant as well as building new facilities. Employees of the company begin to grow in number but not in proportion to output. Economies of scale and greater efficiencies come into play thus limiting the number of new production workers required. The firm continues to rely on the initial group of engineers and technical personnel since they possess a clear understanding of the nature of the material and its production technology. However, the company begins to bring in new engineering, marketing, and managerial talent in order to meet the increasing scale and diversity of operations (9,14).

In the third (or "ascendant") phase of the product life cycle, the market for the advanced material undergoes rapid growth as costs per unit of product decline. The company then undertakes aggressive marketing strategies. It looks to sublicense to other, secondary enterprises. These secondary companies may specialize in certain product categories (eg, nanospheres of certain diameter range, particular types of fullerenes, etc) or on particular markets and applications. The initial start-up firms then begin to earn income from both its own sales and from royalties collected from its secondary companies (ie, its licensees). Competition now focuses as much on economic—ie, low unit price—as well as product quality. As this third phase proceeds, patent protection and leaning curve advantages provide the advanced material firms and their licensees cover from competition. Nevertheless, prices continue to fall as production processes improve in order to maximize market growth (9,14).

The material eventually enters its fourth, or "developed", phase. At this time, competition from other firms increases as both patent protection and the learning curve advantage come to an end. Market strategies now strive toward incremental product and process changes and cumulative improvements as the original producer and his licensees struggle to retain market share. Firms now compete on the basis of product differentiation, marginal price reductions, and creative marketing techniques. They attempt to fully integrate supply, production, and marketing functions to gain the maximum economies as possible from their operations (9,14).

Finally, the material reaches its fifth, or "mature", phase. At this point, the material has become and established, "impacted" technology. Now, the process of "creative destruction" proceeds swiftly as the next generation of advanced materials comes to the fore and edges these older and once-dominant technologies out of critical markets (9,14).

At any one time within the industry, there exists a pool of advanced materials at differing phases of their product life cycles. Some materials, such as superconducting materials and molecular computers, remain at the research or laboratory phase and have not yet gone past the “critical divide” to commercialization. In contrast, other types of materials have just crossed over that barrier and have reached that point of initial production. These include such materials as piezoelectric ceramics and certain types of nanomaterials. Other materials—including thin films, ceramic composites, bioengineered synthetics, and sensors—are further along in the cycle and have begun to scale up for full mass production. More developed materials—eg, advanced structural alloys, ceramics, and polymer–metal composites—already in mass production mode, now pursue expanding markets and, thus can be considered fully formed commercial products. Finally, there are those materials, such as high performance polymers, in full commercial production for a number of years and well known in their markets. Now in their mature years, these materials have undergone a series of modifications in order to retain market share in the face of increasing competition from newer material technologies (9,14).

## 8. The Market: United States and International

As an advanced material proceeds along its product life cycle, its market grows in volume and diversity. Market volume expands as unit price contracts—due to the increased adoption of continuous, mass production methods—and the technical capabilities of the product increases. Moreover, market diversity broadens as researchers learn how to modify the material in order to take advantage of different commercial applications. Over the next few years, certain advanced materials, such as nanospheres and nanotubes, will find application across a wide range of industries including aerospace, appliances, biomedical, defense, electronics and telecommunications, automotive, construction, electrical products and systems, petrochemicals, portable energy systems (ie, batteries and fuel cells), security systems, power generation, electro-optical systems, and textiles (1,2,9,15–19).

This process of market entrance and diffusion ultimately determines the projected rate of growth of a new material. Overly optimistic forecasts must be adjusted to take into account the various difficulties that often arise when attempting to introduce a new material into the market place. While comprehensive data on the size of the U.S. advanced material industry are not currently

Table 1. **U.S. Market Trends for Advanced Materials, $\times 10^9$ \$**[a,b]

| | 2002 | 2005 | 2012 |
|---|---|---|---|
| direct economic impact | 10.0 | 12.75 | 21.5 |
| total economic impact[c] | 41.5 | 46.2 | 77.2 |

[a] Refs. 1,2,9,15–19.
[b] Includes all advanced materials; excludes sales of final products incorporating advanced materials.
[c] Includes direct + indirect + induced impact.

Table 2. **World Market Trends for Advanced Materials, $\times 10^9$ \$[a,b]**

| | 2002 | 2005 | 2012 |
|---|---|---|---|
| direct economic impact | 38.50 | 45.36 | 65.6 |
| total economic impact[c] | 72.10 | 98.45 | 262.40 |

[a] Refs. 1–3,3,9,15–19.
[b] Includes all advanced materials; excludes sales of final products incorporating advanced materials.
[c] Includes direct + indirect + induced impact.

available, an in-depth analysis of the industry indicates that all sales of advanced materials in the United States can reach \$21.5 billion annually by 2012. Further, the full economic impact of the industry—taking into account the direct, indirect and induced effects of new materials production—is likely to be between \$77 and \$78 billion by 2012 (1,2,9,15–19) (Table 1).

On a global scale, World markets are expected to closely shadow U.S. sales in terms of growth. By 2012, total sales of advanced materials will be ~\$66 billion, representing a full economic impact worldwide—ie, the sum of direct, indirect, and induced impacts—of ~ \$262 billion (Table 2).

## 9. The Emerging Advanced Materials

The following sections examine specific advanced material areas. Industry specialists consider these products as the most important advanced materials that have recently entered the market, are on the verge of commercialization, or may be commercialized over the next few years. As a group, these materials account for the bulk of current and projected advanced materials sales within the United States and worldwide for the 2002–2012 period.

**9.1. Bioengineered Materials (9,20–24).** Biochemicals play an increasingly critical role in the advanced materials industry. An important biochemical technology that is just beginning commercialization is the so-called bioengineered materials. These materials bridge the biochemical and synthetic organic fields and promise to provide large volumes of synthetic materials over the next few years.

Bioengineering technology involves the biochemical transformation —in so-called "biorefineries"—of agricultural feedstock, by-products, and wastes into useful synthetic materials. Biorefineries are directly comparable to the petrochemical plant in that both petroleum and biomass refineries use a particular raw material to produce a wide range of synthetic products varying greatly in their chemical properties and physical characteristics and serving a diversity of markets. These products include synthetic plastics and packaging, clothing, fuel additives, chemicals (eg, alcohols, polymers, ethylene, phenolics, acetic acid, etc), biologics, food products, adhesives and sealants, and a variety of commodity and industrial products (22).

An important advantage of bioengineered materials is that they conserve on energy and provide additional markets for the products and wastes of the farming industry. Also, processing costs are low because the technology uses known methods and does not require complex and expensive bioreactors and associated facilities for upstream production. Scale-up of biorefineries appears to be rapid and relatively inexpensive. From the environmental viewpoint, these materials degrade more readily than traditional synthetics. They also generate fewer greenhouse gases and require less energy, water, and raw materials to produce compared to petroleum-based materials (20–22).

In general, the production of bioengineered materials occurs near to agricultural areas. Recent advances in bioengineering technology involve cellulosic-based feedstocks, including vegetable crops, starch-producing crops, oil seeds, wood and other lignocellulosic biomass. Current research in the field focuses on three major production technologies: fermentation (including enzyme processing), pyrolysis, and low temperature technology. Of these possible processes, fermentation, in conjunction with such operations as distillation and polymerization, appears to offer the most promising commercial method (20–22).

Bioengineering research is international in scope. Besides the United States and Canada, such European countries as Austria, Denmark, Germany, Iceland, and Switzerland pursue particularly active programs in the field. In addition international companies are emerging that specialize in the construction and operation of advanced biorefineries.

Within the United States, a variety of agencies and organizations actively pursue bioengineering research and development. For example, the Department of Agriculture, through the Economic Research Service, has established a wide range of programs and grants to support the research and development of biorefineries for the purpose of converting biomass materials into commercial products (eg, fuels, chemicals) and energy sources (eg, electricity). Similarly, the Department of Energy—through the National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), and other DOE-affiliated laboratories—administers a variety of research and development programs related to the development of biorefineries for the purpose of creating a wide range of bioengineering materials. For example, NREL provided the company Genencor International with a $17 million contract to find a process to convert biomass to alcohol. Also, the U.S. DOEs Idaho National Engineering and Environmental Laboratory (INEEL) is partnering with universities and industry (eg, National Association of Wheat Growers) to find biorefining technology to efficiently convert wheat and other crops into chemicals, fuels, and industrial and consumer products (20–22).

The most significant U.S. commercial venture into bioengineering technology to date involves a several hundred million dollar facility built in Blair, Nebraska by Cargill Dow, a joint venture between Cargill Inc. (Minnetonka, Minnesota), an agricultural corporation, and Dow Chemical Company (Midland, Michigan). The facility, which began semi-commercial operations in 2002, is designed to eventually consume 40,000 bushels of locally produced corn to produce synthetic materials. Through fermentation, distillation, and polymerization processes, the Cargill's technology synthesizes polylactide (PLA) and related compounds from corn by-products. The polylactide (PLA) compounds, in turn, provides the building block for a variety of synthetic products, including fiber materials with superior characteristics, such as wear resistance and insulation. The costs of production of the PLA fibers are relatively low since the production

Table 3. **U.S. Market Trends for Advanced Bioengineered Products, $\times 10^9$ \$[a,b]**

| | 2002 | 2005 | 2012 |
|---|---|---|---|
| direct economic impact | 0.010 | 0.046 | 1.3 |
| total economic impact[c] | 0.058 | 2.3 | 5.5 |

[a] Refs. 20–22.
[b] Includes all advanced materials.
[c] Includes direct + indirect + induced impact.

process uses inexpensive agricultural waste, including corn stalks, wheat straw, rice hulls, and even sawdust and prairie grass. Dow Cargill plans to incorporate PLA materials in furnishings, containers, packaging, and numerous industrial applications (20–21,23).

A number of other chemical companies plan to enter into bioengineering of synthetics. Dupont in particular has formed a partnership with the sugar producer Tate & Lyle plc to build biorefineries to utilize genetically-engineered microbes in transforming naturally occurring sugars into a synthetic material useful in making clothing, packaging and plastics. Other chemical companies—including Celanese, BASF and Chevron—may soon follow Dupont and Dow in entering into the field (21–22).

The future prospect of bioengineered materials hinges on a number of factors. Most importantly, biorefineries need to achieve continuous, full-scale production to effectively compete in price against existing synthetic materials. Moreover, the companies involved in the technology must accelerate their technical services programs in order to locate and capture increased market share. This depends as well on finding new applications for the materials. Stricter environmental regulations at the federal and state levels promise to increase the interest in and demand for bioengineered materials (20–22,24).

Bioengineered materials face considerable competition from the synthetic materials traditionally made from petroleum and natural gas. It is expected that, with the backing of some of the large chemical companies, bioengineered materials production will find markets for their products over the next 10 years. By 2012, it is estimated that total U.S. sales of these materials could reach in excess of \$1 billion. This means that the total economic impact—direct, indirect, and induced—within the United States of bioengineered materials will be between \$5 and \$6 billion (Table 3). Much of this impact will be focused in the Midwest and other agricultural regions throughout the United States.

**9.2. Advanced Ceramics (9,25–27).** Ceramics are inorganic and nonmetallic materials. There are three major forms of ceramics: amorphous glasses, polycrystalline materials, and single crystals. Ceramics are generally made from powders and additives under high temperatures. Traditional types of ceramics includes bricks, tile, enamels, refractories, glassware, and porcelain. Advanced ceramic materials, developed more recently, possess superior physical, mechanical, and electrical properties. They are made from metal powders that undergo innovative processing methods.

Advanced ceramics increasingly enter into a wide variety of applications. In general, advanced ceramics extend equipment life, decrease fuel costs, and increase power and performance. One of their major markets is in electronics, which accounts of $\sim$ 66% of the total demand for advanced ceramics. Important ceramic products in electronics applications include both the pure and mixed oxides—alumina, zirconia, silica, ferrites—and doped barium and lead titanates. The important electronic application of these materials includes their use in substrates and packaging, capacitors, transformers, inductors, and piezoelectric devices and sensors. Approximately two-thirds of total electronic ceramic consumption goes into integrated circuit packages and capacitors. Japan is particularly active in developing advanced ceramics for these applications. (9,26–27).

Advanced ceramics are also used in structural applications due to their resistance to corrosion and high temperatures. Ceramics perform very well as a material for equipment components or as an industrial coating. Such ceramics are important materials for infrastructural applications, such as power plants, construction, and bridges as well as in industrial equipment, eg, bearings, seals, cutting tools. The automotive industry employs advanced structural ceramics in catalytic converters and for certain under-the-hood components. Important advanced structural ceramics include various forms of aluminum oxide, zirconia, silicon carbide, and silicon nitride.

Recent developments involve the creation of new types of advanced ceramics and production processes. One of the most important lines of research within the United States and internationally includes the development of ceramic metal matrix composites incorporating reinforcing materials such as carbon fibers. These materials possess superior mechanical properties, excellent thermal stability and a low friction coefficient (to serve as a superior lubricant). Examples of such materials include silicon carbide fibers in silicon carbide matrix and aluminum oxide fibers in aluminum oxide matrix. Research in the field continues to find a wider range of new composites and to reduce unit costs (25–27).

A second major area of advanced ceramics research involves new techniques to make ceramic powders. For example, the use of thermal plasmas may prove a superior process to generate very fine powders, such as aluminum nitride, silicon carbide, titanium carbide, and aluminum oxide. In this process, the plasmas operate under very high temperatures that vaporize raw materials and speed reactions and, then cause rapid quenching of the particles, thus forming ultrafine powders. The process produces high purity powders as well as eliminating intermediate production steps currently employed in traditional manufacturing methods, thus conserving on time and costs, and minimizing wastes (9,25–27).

A third line of research centers on the development of advanced ceramic coatings technology that allows the deposition of a thin layer of ceramic on complex surfaces at low costs for improved resistance to corrosion, mechanical wear, and thermal shocks. These processes impart superior properties without industry needing to go through the time and expense to make entirely new parts and components. An important example of an advanced coating system is zirconium oxide coating for gas turbine engines. These coatings provide a thermal barrier that allows engines to run hotter by protecting underlying metal. In turn, the coating extends component life, increases engine efficiency, and reduces fuel consumption. Research in advanced ceramic coatings focuses on improving adhesion of the coating to surfaces, increasing the properties of the coatings, and reducing the costs of the coating process. The various coating processes currently employed or being investigated include plasma and flame spray, high velocity oxy-fuel deposition, and electron beam techniques (9,26).

Overall, the market for advanced ceramics within the United States and internationally is growing at between 3.0 and 4.0% annually. Advanced ceramics accounts for the largest portion of the total advanced materials market and will continue to dominate the advanced materials field throughout the 2002–2012 period. In 2002, the world market for advanced ceramics stood at \$21.4 billion. By 2005, the global market will be \$23.4 billion, and by 2012 nearly \$29 billion. In 2002, the U.S. market accounted for 40% of world demand for advanced ceramics, or \$8.6 billion. This translates into a total economic impact within the United States of > \$34 billion. By 2005, the U.S. market will stand at \$9.5 billion. In 2012, the U.S. advanced ceramics industry will see a market of \$12.2 billion, or 42% of total world demand. The total economic impact of advanced ceramics in the United States at this time will be \$48 billion (9,25–27) (Table 4).

Two advanced ceramic material areas appear particularly promising: nanoceramics and piezoelectric ceramics. While these materials currently account for a relatively small percentage of the total advanced ceramics market, they attract a disproportionate amount of research and development activity. As a result, they represent the cutting edge in the advanced ceramics field and promise further development, increased production, and a growing range of applications through 2012 and beyond.

*Nanoceramics (9,28–30).* One of the most promising developments in the development of advanced ceramics is in the area of nanoceramic materials. In this technology, free-flowing nanopowders, processed under intense thermal conditions and elevated pressures, form a variety of parts and components. Properties and applications of nanoceramic materials generally depend on the type and average particle size range of the metals.

Nanoceramics provide both cost savings and new material applications to industry. Traditional ceramics tend to be hard and brittle thus making parts made of the material difficult to machine, and, in turn, significantly limiting markets. In contrast, nanoceramics, characterized by very small internal grain size, provide to parts a mechanical flexibility that allows greater ease in forming, shaping, and finishing (eg, grinding and polishing) in lower temperature environments. Nanoceramics also possess superior structural characteristics exhibiting high strength and excellent abrasion, deformation, and wear resistance, even under high temperatures. Cost savings to industry result from lower energy use,

Table 4. **U.S. Market Trends for Advanced Ceramic Materials, $\times 10^9$ \$**[a,b]

| | 2002 | 2005 | 2012 |
|---|---|---|---|
| direct economic impact | 8.6 | 9.5 | 12.1 |
| total economic impact[c] | 34.4 | 38.0 | 48.4 |

[a] Refs. 9,25–27.
[b] Includes all advanced materials.
[c] Includes direct + indirect + induced impact.

reduced time to complete operations, and material savings from fewer damaged parts requiring replacement (28,29).

There are a variety of nanceramic materials. These include titanium nitride, silicon nitride, aluminum nitride, zirconia (and zirconia–aluminua), yttrium–aluminum compounds, and ceria and gallium oxides. Other countries, in addition to the United States, are actively engaged in developing and commercializing these compounds. Germany and Japan represent the most serious competitors to the United States in such materials as silicon nitride and electronic grade aluminum nitride. Other countries active in the filed include Russia, Austria, and Poland. Nevertheless, the United States dominates in most of the other nanoceramic materials, in part due to the greater economic growth of the United States in the 1990s compared to Europe and Asia. The added impetus from military spending after the 9/11 attacks has also aided nanoceramic development with the United States. Currently, the powders used for producing nanocermaics are available from a range of United States and international companies in laboratory, semicommercial, and commercial quantities (28–30).

Applications for nanoceramics include a wide range of structural and industrial uses, such as in machine tools, electroplated hard coatings, and thermal barrier coatings. In the automotive area, research focuses on the use of nanoceramics for "under-the-hood" automotive applications (eg, use in automotive engine cylinders providing greater retention of heat and more complete and efficient combustion of fuel). Small, light weight sensors that incorporate nanoceramics help to measure air/fuel ratios in exhaust gases. This in turn leads to more efficient cars and aids in curtailing environmental pollutants. Potential use for nanoceramics includes applications in appliances, industrial machinery, and petrochemical and power plants. Nanoceramics will see growing application as well in liners and components for appliances, heat exchange systems, industrial sensors, electric motor shafts, gears and spindles, high strength springs, ball bearings, and, potentially, thousands of additional structural parts and components (9,28,29).

Due to its unique internal structure—ie, possessing a large number of molecular-sized "holes"—nanoceramics can serve as advanced molecular sieves and catalytic carriers for a variety of chemical, refining, and biotechnology operations. Because of their generally nonhazardous nature, chemical inactivity, and biocompatibility, nanoceramics can supply materials for industrial, chemical, and biochemical ultrafiltration equipment, "delivery" systems for more efficiently and effectively introducing bioactive agents into the body, and equipment and apparatus for chemical and biochemical research and manufacture. Promising biotechnology applications include the use of nanoceramics in new bone implantation systems, and as implanted medical prostheses (29,30).

Nanoceramic materials also possesses superior electrooptical properties that have applications as materials for semiconductors, electronic components, and related technology and systems including optical filters, capacitors, floppy discs and tapes, magnetic media, fiber optics, and superconducting products (eg, flexible superconducing wire). Nanoceramics, in the form of alumina, ceria, zirconia, and titania oxides, can be used in industrial micropolishing operations since ultra fine abrasive particles provide for superior mechanical polishing of dielectric and metallic layers deposited on silicon wafers. Nanoceramic materials demonstrate unique translucent properties useful in advanced lighting systems. In particular, translucent alumina-based ceramic tubes can operate in high pressure sodium lamps and metal halide lamp tubes for indoor lighting. Nanoceramics also promise increased use in critical energy-related technology including advanced fuel and solar cells and new generation microbatteries (9,28,29).

In 2002, the largest share (53.4%) of the nanoceramic market went into electrooptical applications, followed by chemical/environmental applications (40.1%). The remaining 6.5% of the market for nanoceramics entered into a variety of structural applications. Over the next few years, it is expected that the electrooptical and structural areas will gain a little ground at the expense of chemical and environmental applications, as indicated in the anticipated average annual growth rates for the various nanoceramic markets: structural (9.6%); electrooptical (7.5%); and chemical/environmental (6.9%) (28,29).

Important issues related to the continued growth of ceramic materials for these applications include the development of new and improved nanoceramic materials and composites and advanced processing technology. For example, a key concern is to improve the strength and fracture toughness of nanoceramics since sudden structural failure hinders wider applications of the material. A novel type of structural composite being investigated involves placing nanosilicon carbide particles inside alumina and in developing silicon nitride composite matrices. These types of composites appear to possess superior wear resistance, chemical inertness, anticorrosion properties, and excellent thermal insulation.

Also of vital interest in the area is development of new processes to make such composites as well as to manufacture existing nanoceramic materials more efficiently and with higher quality (eg, improved compacting and pore size distribution). Innovative processes include new types of powder synthesis technologies involving advanced thermal plasma and laser-based methods. As critically, advances in nanoceramic processing and shaping include such activities as high pressure sintering, ultrasonic compacting and shaping, and advanced "wet" molding (9,28,29).

Overall, the U.S. market for nanoceramic materials is growing, and at a faster rate than for advanced ceramics as a whole. The expansion in the market for nanoceramics is in part due to the declining unit price of nanoceramic powders. In 2002, the average price per pound of nanoceramic powders stood at \$6.6/lb. By 2007, it is estimated that the average price will be \$5.1/lb and by 2012, <\$4.0/lb. In addition to the price issue is the fact that nanaoceramics remains a developing field with a wide range of possible markets that are just beginning to be exploited (28,29).

In 2002, the market for nanoceramic powders stood at \$154 million, or just 1.8% of the total value of the advanced ceramics market. By 2005, sales of nanoceramic powders will be ~ \$194 million, which represents 2.0% of the total advanced ceramics demand. By 2012, that percentage will increase to 2.7%, reflecting the growing importance of nanoceramics in the advanced ceramics markets. At that time, the market for nanoceramics will stand at \$332 million, which translates into a full economic impact within the US of >\$1 billion. After 2012, the market for, and economic impact of, nanoceramics will increase

Table 5. **U.S. Market Trends for Nanoceramic Powders, $\times 10^9$ \$**[a,b]

| | 2002 | 2005 | 2012 |
|---|---|---|---|
| direct economic impact | 0.154 | 0.194 | 0.332 |
| total economic impact[c] | 0.616 | 0.776 | 1.33 |

[a] Refs. 28–30.
[b] Includes all advanced materials.
[c] Includes direct + indirect + induced impact.

rapidly as the material continues to influence the advanced ceramics industry (28–30) (Table 5).

*Piezoelectric Ceramics (9,31–38).* Piezoelectric materials—composed of mixtures or complexes of zirconium, titanium, lead and other metals—create driving voltages when placed under mechanical stress (the "generator effect") and, contrariwise, undergo mechanical movement or deformation when subjected to electrical impulse (the "motor effect"). There are four types of piezoelectric materials: ceramics, crystals (eg, piezoelectric quartz), ceramic/polymer composites, and polymer films. Of the four types of piezoelectric materials, piezoelectric ceramics represents the largest and most mature market segment, accounting for ~90% of the total piezoelectric market. If piezoceramic/polyer composites are included, then piezoelectric ceramic materials have a presence in ~93.3% of the total piezoelectric market (31).

There are a number of piezoelectric ceramic materials, most composed of some form of lead and titanium. Currently, the most common piezoelectric ceramic is lead zirconate titanate (PZT). Other types of piezoelectric materials include barium titanate, bismuth titanate, lead titanate, and lead metaniobate. The various properties that these materials offer depend on the type of production process used and the chemical and operating conditions under which they are formed. The general process by which nonpiezoelectric ceramics are transformed into piezoelectric materials involves heating the ceramic materials in a dielectric oil bath by which the applied electric field aligns the dipole units existing in the material (9,31,34).

Piezoelectric ceramics come in "bulk" and "multilayered" form. The bulk form of the ceramic consists of a single ceramic block from which is produced various shapes: blocks, plates, disks, cylinders, rods, etc. In contrast, the multilayered variety consists of several thin layers of the ceramic material stacked up into rectangular and cylindrical shapes, such as bars, plates, and disks. The quality and performance level of these various forms of piezoelectric ceramics are measured by a number of variables including dielectric constant, dielectric loss factor, electromagnetic coupling factor, piezoelectric load constant, elastic compliance, elastic stiffness, electrical resistance, and thermal coefficient (34).

As with other advanced materials, the United States faces increasing competition from other countries in the piezoelectric ceramic field. Germany and Japan represent the major competition to the United States in piezoelectric ceramics. Other countries in Europe (Denmark, France) and Asia (Taiwan) actively pursue development of new piezoelectric ceramic technology.

Piezoelectric ceramics find application within the United States and internationally in a wide range of industries, including biomedical, aerospace, automotive, industrial, consumer, and marine. While the government dominates the demand for United States produced piezoelectric ceramics, the industrial and consumer markets continue to gain a presence in the field. Industry and government increasingly view these materials as useful in making such general components as electric circuit elements, transformers, actuators, transducers, and energy generators (eg, batteries). These components, such as actuators, allow a large force capability and short response time. This means that, in time, they provide rapid, precise, and carefully regulated displacement of devices, equipment, and systems in response to even small applied voltages. These piezoelectric ceramic components, in turn, find current and potential application in such devices and systems as sensors (medical, pressure, flow, acceleration), sonar equipment and hydrophones, laser positioning, industrial tools and hardware (valves, meters, cutting and polishing machines, displacement gauges), electrical devices (remote control switches, relay contact drivers, electroacoustic devices, microposition actuators, electrical appliances, security alarms, camera shutters), and security systems (9,31,33–38).

One area that is particularly promising for piezoelectric ceramics is their use in vibration control due to the general use of more powerful machinery and equipment in industry. Vibration control is especially important in such areas as aircraft manufacture, hospitals (eg, vibrations due to MRI equipment), and power plants. Another potential market for piezoelectric ceramics is in the manufacture of wireless switching equipment for both residential and business structures. The market in Europe and Asia appears particularly promising for these devices due to the higher cost of installing and replacing wired systems in these regions. The specific uses for piezoelectric ceramics in nonwired applications include switching and lighting systems, appliances, security systems, doorbells, and burglar alarms (9,31,33,35,38).

Future applications of piezoelectric ceramics hinges on their superior power density and cost and size advantage. As a result, they will enter into nonmagnetic transformer components in radiofrequency (RF) transmissions systems and remote control devices to power back lighting for computer screens and, in the form of ceramic fibers, as critical material in the monitoring of stresses and strains in aircraft bodies, automotive engines, and building structures (9).

Investigation into more advanced piezoelectric materials and production processes continues at a rapid rate within the United States and internationally. Attempts to find alternative materials that do not depend on lead result from stricter environmental policy. Denmark, eg, has been investigating the Alkaline Niobates as a possible substitute for PZT. Work is also underway in various countries on a new variety of porous piezoelectric ceramics that promise superior performance for transducers operating underwater (eg, in hydrophones). Finding new ways to fabricate piezoelectric ceramics also has a priority. Significant work in the United States, England, and other countries centers around “net shape fabrication” and the process of “plasticising” the powder-binder mixture in order to limit sintering and, in turn, the structural defects and high production costs associated with the sintering operation (31–33).

As with nanoceramics, the rate at which piezoelectric ceramics gain markets in the United States, Europe, and Asia depends on the ability of the production process to reduce unit costs. The cost of ceramic-based raw materials—which currently represents approximately one-fifth of total manufacturing costs—remains a bottleneck to commercialization. However, it is likely that his percentage will decline to 5% or less as the production process achieves mass production status Currently, the unit price for advanced ceramics is about $75 per wireless ceramic element. By 2005, this is expected to decline to ~$50 and by 2012 ~$20 per element (9).

As the unit price contracts, and the technology advances, new markets for piezoelectric ceramics will emerge. The annual rate of growth for piezoelectric ceramics is expected to remain at 8.9%. The material commands a somewhat greater role in the advanced ceramics market compared to nanoceramics, and will continue to do so throughout the 2002–2012 period. The U.S. market for piezoelectric ceramics stood at $237 million in 2002, representing 2.8% of the total advanced ceramics market. By 2005, sales of piezoelectric ceramics will be $306 million, or 3.2% of that market, and by 2012, $556 million, accounting for 4.6% of advanced ceramics demand. The increase in the direct sales of piezoelectric ceramics between 2002–2012 represents a growth in total economic impact in the United States l from $948 million to $2.2 billion (31,33) (Table 6).

**9.3. Advanced Coatings.** Advanced coatings provide a vital and growing area in the new materials field. These advances emerge from recent research in surface chemistry and solid state physics. Technical and economic growth of these materials continues to accelerate.

The advanced coatings field consists of an increasing number of smaller firms specializing in manufacturing particular types of coatings and coating application technology. Many of these firms are start up operations that license technologies from the university and government (eg, NASA, DOE, DOD) and who carryout their own R&D to further commercialization. These firms create novel coating materials that provide new ways to protect surfaces from the environment—ie, heat, impacts, erosion, and chemical degradation—thus increasing the life and performance of components, equipment, and systems across a wide range of industries and technologies. The more advanced coatings impart to surfaces and objects heightened ability to sense and respond to the full range of changes in the environment. Consequently, advanced coatings promises to be a central component in the development of the so-called "smart" materials that are expected to revolutionize twentieth century technology.

Table 6. **U.S. Market Trends for Piezoceramic Materials, $\times 10^9$ \$**[a,b]

| | 2002 | 2005 | 2012 |
|---|---|---|---|
| direct economic impact | 0.237 | 0.306 | 0.556 |
| total economic impact[c] | 0.948 | 1.22 | 2.22 |

[a] Refs. 31,33.
[b] Includes all advanced materials.
[c] Includes direct + indirect + induced impact.

*Thermal Barrier Coatings (9,39–42).* Thermal barrier coatings protect surfaces in one of three ways: providing a simple physical barrier to thermal energy ("passive" heat control); dissipating, dispersing or reflecting heat; or minimizing heat-producing friction. A new generation of thermal barrier coatings promises to protect surfaces from very high temperature environments by affecting all three modes of heat management.

Thermal coatings are produced in a variety of forms, including paints, tapes, and vacuum deposited metals. Currently, thermal coatings tend to be passive in nature in that they simply act as a barrier to protect surfaces from a given thermal environment up to a certain temperature. Above this limit, degradation to the coating and, in turn, surface takes place. Advances in coating technology allows the materials to be "active" agents that sense changes in outside temperatures and, through electronic means, adjust their internal molecular structure to optimally reflect, absorb, or dissipate thermal energy and, in effect, be able to withstand far higher temperatures than currently possible. The ability to create "smarter" thermal coatings depends on an increasing understanding of the structure of coatings and their behavior in high-temperature environments (9).

A growing range of thermal coating materials is currently being developed. Such materials include a variety of aluminum alloys and metal matrix composites, ceramic-based materials, the aluminum oxides, titanium alloys, zirconia–yttria compounds, and molybdenum plasmas. One of the more promising passive thermal coating material that is emerging comes from advances made in polymer technology, and in particular, polyimide chemistry. Polyimide coatings withstand temperatures of up to 700$^{\circ}$, or $\sim$50% more than current coating materials. The polyimide materials, which are made in thermal reactors under relatively low pressures, also provide surfaces with superior resistance to corrosive agents (9,39,41).

An important part of thermal coating technology involves the method of applying the coating material to the surface. Thermal spray technique, in particular, represents the state of the art in applications technology. It employs a combination of thermal and kinetic energy to direct particles evenly and at desired thickness onto a surface. Improvements to the technology—including the development of high velocity oxygen fuel systems and incorporation of robotics—will increase productivity and lower overall costs (9,41,42).

One of the more advanced applications techniques currently being investigated and developed includes electron-beam–physical vapor deposition by which vaporized metal coating is directed onto a surface. This process allows the formation of tailored, composite coatings on surface substrates by coevaporating different coating materials and alternating layers of the different materials onto the surface. Additional processes that appear promising include vacuum plasma spray and arc and flame spray technologies (9,41,42).

The potential market for advanced thermal coatings range from the automotive, aerospace, and defense industries to high temperature microelectronic circuit boards, industrial motors, electric and nuclear power production, biomedical systems, chemical and petrochemical plants, and composite materials for construction applications and machine tools (9,39).

Currently (2002), prices for the more advanced coatings remain relatively high. For example, the unit price for polyimide thermal coatings is around

$350/lb. Over time, the adoption of mass production techniques will force prices down. Thus, by 2005, the price for polyimde coating material will decline to $172/lb and be at only $20–25/lb in 2012. By this time, market penetration for the new generation of thermal barrier coatings will stand at ~20% (9).

*Conductive Coatings (9,43–47).* Conductive coatings consist of an electrically conductive material mixed into, or bonded onto, some nonconductive medium through such means as vapor-phase deposition or electroplating. In this sense, conductive coatings can be termed composite materials. Currently, conductive coatings exist commercially in three main forms, defined by the type of medium employed: conductive paint, metal plating (or cladding), and synthetic resin (eg, epoxy, urethane, acrylic). With respect to metal-based conducting coatings, current technology utilizes metals such as copper, nickel, and silver as the conducting agents, either separately or in combination. In terms of cost, silver paint tends to be the most expensive type of coating, nickel paint the least expensive, and copper-nickel cladding an intermediate cost conductive coating material (43).

A fertile area for recent and future research is in the area of conductive resins. This field evolved from Nobel Prize winning work that showed that plastic materials could be made electrically conductive. Researchers in the United States and internationally are investigating a number of potentially useful polymers and their particular conductive coating applications including: polythiopene derivatives (antistatic agents, photography), polypyrrole and polyaniline (electrostatic speakers, computer screens), polyphenylenevinylene (phone displays), and the polydialkylfluorenes (advanced color screens for video and TV) (9,43).

As the case of conducting polymer shows, emerging conductive coatings, both metal and polymer, find potential use in a wide variety of electrical and optoelectronic applications. Conducting coatings, when incorporated into a battery's current collector, enhance the power and life of batteries. The coatings impart portability, compactness, and lower costs as well. Adhesives made from conducting coatings (eg, epoxy medium) appear excellent for repairing printed circuits and replacing metallic solder. Conductive coatings embedded onto glass substrates promise commercial development of two-dimensional antenna systems for use in automobiles and telecommunications equipment. Transparent conducting films offer the prospect of increased application in optical systems, dielectric mirrors, and holographic devices (43–46).

One of the most important applications for metal-based conductive coatings is in electromagnetic interference (EMI) shielding, which is so because conductive coatings absorb, emit, or reflect certain optical and radio frequencies. Moreover, they create a magnetic field or three-dimensional geometry that scatters radar signals or reduce aircraft and ship signature. The coating protects equipment from interfering signals and sudden and potentially disruptive electromagnetic pulses. Conductive coatings can shield entire rooms containing electronic equipment or replace plastic as the packaging material for printed circuits and electronic components and devices (eg, computers mobile phones). Industries currently or potentially using conductive coatings in shielding systems include the aerospace, defense, electronics, security, health care, financial, and communications sectors (9,43,45).

Attempts by researchers to find superior alternatives to current conductive coatings result from limitations inherent in the existing technology and the need to extend the range of application. While silver is a superior conductor and anticorrosion agent, it is expensive, which restricts its use to only the most specialized applications. On the other hand, copper and nickel, while relatively inexpensive, do not offer the same level of conductivity as silver and, for example, cannot adequately shield entire rooms from electromagnetic interference. Moreover, copper tends to oxidize, which further reduces its conductivity, while nickel poses environmental problems. The increasing power required in electronic and telecommunications components, devices, and equipment also call for more advanced conductive materials in batteries, optical equipment, and EMI shielding systems. Advanced research within the United States and internationally seeks to develop new conductive coating materials to solve these problems and extend markets. These novel materials consist of special alloys, composites, and polymer compounds (43,45).

The current unit price of certain of these coatings—as high as \$1200/gal—prohibit a significant market for the more advanced conductive coatings. However, as production processes improve, the industry expects unit costs to contract significantly. By 2005, it is expected that the price of advanced conductive coating material will stand at ~\$650/gal and by 2012 will be as low as \$40/gal. As a result, by 2012 market penetration could reach between 6 and 7% (3).

*Anti-Corrosion Metallic Coatings (9,48–51).* Anticorrosion coatings prevent oxidation reactions from taking place at a metal's surface. Currently, anticorrosion coatings are solvent-based and employ both inorganic metals and organic resins. Specifically, coatings make use of metal-based primers (eg, zinc, aluminum, nickel) with polymer coatings used for intermediate (eg, epoxy) and top (eg, urethane) layers. A number of companies produce anticorrosion coating materials. In the United States alone, there are ~ 100 manufacturers of anticorrosion coatings providing specialized products to small geographical areas (48,50).

A variety of processes exist to apply coatings to surfaces. A typical application technology is thermal (flame) spray process by which a metal is melted in an oxy-acetylene flame and atomized under compressed air to form fine particles that are then sprayed onto a surface. On contact with metal, the metal spray solidifies to form a uniform coating. Other spray processes include powder and plasma thermal spray methods.

A number of problems continue to plague current anticorrosion coating technology. Current coatings tend to cause environmental problems and require expensive and time-consuming preparation of the surface. Also, coatings degrade over time, resulting in flaking and peeling. Current research in the field focuses on the development of coating materials to meet stricter environmental standards, do not require expensive surface preparation, and have good adhesion—superior bond strength and uniformity—and longer life under rigorous climatic conditions. Promising materials under investigation are nonsolvent-based coatings incorporating advanced polymer materials including polyester, polyaniline, and silcone and silicon–glycol resins (9,48–50).

A potentially revolutionary line of research being conducted in the United States and Europe concentrates on certain organic films that form tightly bound multilayers on a surface through electrolytic action. These materials are gel-like films of alternating layers of positively and negatively charged molecules. As opposing charges pair up, they hold adjacent layers together tightly while, at the same time, a positively charged bottom electrolyte layer adheres to negatively charged metal surface, thus avoiding degradation and flaking over a long period of time (51).

Also being investigated are purely metallic anticorrosion coatings, in particular a complex of aluminum, a rare earth metal (eg, cerium) and a transition metal (eg, iron or cobalt) combined in various proportions. The nature of the alloy itself, produced in an innovative thermal process, allows quenching of the molten metal at a relatively low rate (as measured in degrees cooled per second) compared to current aluminum alloy materials. This less radical quenching process, undertaken in a thermal furnace, produces an amorphous alloy without structural damage to the metal. This noncrystalline structure serves as both an anti-corrosion and anti-deformation coating (9).

Researchers within the United States and Europe are also examining new forms of applications technology. These efforts include finding ways to improve the more traditional thermal and plasma spray methods, especially in applications involving metal-based coatings. Since thermal techniques tend to weaken a metal's surface thus resulting in early degradation and coating failure, research work looks to reduce the need for heat during spraying. One alternative is the recently developed cold plasma spray, which offers an advanced alternative that retains the integrity of the host metal (9).

In addition, development efforts are now underway to commercialize totally new processes, notably a process based on the creation of ionic self-assembled coating layers. In this technology, a charged substrate is dipped into an aqueous solution of a cationic material followed by dipping in an anionic solution. Adsorption to the surface of the substrate results from electrostatic attraction of "interlayer charges", with each layer of uniform thickness. Multilayers of several microns thickness are easily fabricated via repeated dipping process and are rapidly dried and fixed at room temperatures. The low-cost process produces an ultra thin, impermeable, and tightly bound coating. The process produces specific coatings, depending on the applications involved, through molecular manipulation (9,48).

Continued innovation, and the decreasing costs over time in producing the coating material and in applying the coating to a surface, promise expanding markets for anticorrosion coating technology. In addition to making further inroads into such traditional markets as shipbuilding and repair, public infrastructure (bridges, buildings, etc), public utilities, machinery, buildings and construction, the new generation of anticorrosion coatings technology is expected to find increased applications in such industries as aerospace, automotive, electronics, industrial gases, telecommunications, and petrochemicals. (9,49,50).

*Multifunctional Coatings (9,49,52,53).* Multifunctional coatings, which first emerged in the 1990s, perform a number of operations—anticorrosion protection, conduction, electromagnetic shielding, thermal protection—simultaneously. Their development, both within the United States and internationally, results from exploiting the commercial potential of surface engineering. Typically, small R&D and start-up firms license multifunctional coating technology from the government and universities. In addition, certain large corporations (eg, Dow corning) look to expanding their product capability in advanced multifunctional coating technology (49).

Multi-functional coatings incorporate a number of new materials, either separately or in combination. These materials include fluoropolymer composites, the urea–formaldehyde resins, multicomponent pigments, and the carbides, nitrides, and borides of certain metals (eg, titanium). These materials can be incorporated into different media such as paint, ink, and adhesives. Multifunctional coatings may be composed of one material capable of performing different functions, or, more commonly, be a multilayered composite of different materials. Increasingly, work in the field focuses on the synthesis of nanocomposite coatings with multifunctional properties that impart a wide range of surface qualities, including transparency, surface hardness, reflectivity, etc. The use of diamond films doped with certain metals also offers a promising route for the custom-design of multifunctional coatings with desired electrical, mechanical, and optical properties (49,52,53).

A number of process technologies currently being developed in the creation of multifunctional coatings include thermal vaporization, electrospark alloying, laser heat processing, ion implantation, plasma deposition, magnetron sputtering, and solution-phase ionic self-assembly. In addition to these technologies, fluidization technique, typically used in refining or power generation, may provide a route to the mass encapsulation of anticorrosion agents for use in multifunctional coating systems (9,52).

Numerous applications exist for multifunctional coatings. In the automotive sector, multifunctional coatings meet increased demands for strength and thermal and corrosion protection of steel surfaces. In the textile industry, research in the United States and Germany looks to development of “smart” hybrid polymeric coatings for fibers that allow fibers and textiles to switch or tune their properties in response to external stimuli. In the metallurgical industries, multifunctional coatings provide superior hardness, anticorrosion properties, thermal protection, abrasion resistance, and chemical “inertness”. Accordingly, they enter into a variety of metallurgical operations, such as pressure die casting operations. For its part, the defense and aerospace industries require multifunctional coatings in its defense systems and aircraft for sensing, conductivity, energy absorption, and thermal dissipation. Such coatings increase the performance capability and lifetime of components, equipment and systems (9,52,53).

One of the most promising areas for multifunctional coatings involves the development of new types of sensors. An emerging application for multifunctional sensors is in a new generation of micro electromechanical systems (MEMS) requiring the simultaneous detection of temperature, pressure, radiation, gas concentrations, electromagnetic fields, and so forth. Multifunctional coatings also act as sensors for detecting and monitoring structural defects in buildings, bridges, and aircraft, and to carry and deliver chemical agents to strengthen critical points in the structures. In one variation of the technology, the sensing system uses small synthetic spheres arrayed in a crystalline lattice and imbedded within a coating material. As the coating shifts or otherwise changes its configuration due to structural distortion, the internal lattice also

Table 7. **U.S. Market Trends for Advanced Coating Materials, $\times 10^{9a,b}$**

| | 2002 | 2005 | 2012 |
|---|---|---|---|
| direct economic impact | 0.085 | 0.170 | 1.80 |
| total economic impact[c] | 0.034 | 0.680 | 6.50 |

[a] Refs. 9,52,53.
[b] Includes all advanced materials.
[c] Includes direct + indirect + induced impact.

changes its structure. An optical system then monitors these changes over time. These spheres also contain various anticorrosion agents and deliver them to pivotal sites (9).

The market for advanced coatings—including thermal conductive, anticorrosion, and multifunctional—is increasing at a rapid rate. In the decade 2002–2012, thermal and anticorrosion coatings will continue to dominate the advanced coatings group, accounting for well > 90% of sales throughout the period. However, during this time conductive and multifunctional coatings will gain ground as technology advances and unit costs decrease. These two coatings will exhibit the largest growth rate during the latter part of the period and in the decade to follow.

The production of advanced coatings as a whole in terms of dollar sales is expected to accelerate rapidly after 2005. By 2012, total U.S. production of advanced coatings will stand at $1.8 billion million, producing a total economic impact within the United States of ~ $6.5 billion (9,52,53) (Table 7).

**9.4. Nanopowders and Nanocomposites (9,54–60).** In recent years, powder metal technology has emerged as a major segment of the metals industry. It is a growing presence in a variety of commercial and industrial applications. Most recently, this field has been advancing into the still new area of nanotechnology. Nanopowders are typically composed of metals or metal mixtures and complexes with particulate sizes in the micron ranges. The potential markets for these materials depend on the fact that they can be formed into diverse shapes and forms possessing a variety of important mechanical, electrical, and chemical characteristics. Nanopowders are composed of a broad range of metals and their compounds. These include (but are not limited to) the oxides of aluminum, magnesium, iron, zinc, cerium, silver, titanium, yttrium, vanadium, manganese, and lithium; the carbides and nitrides of such metals as tungsten and silicon; and metal mixtures, such as lithium/titanium, lithium manganese, silver/zinc, copper/tungsten, indium/tin, antimony/tin, and lithium vanadium (9,57–59).

As with a number of other advanced materials, including nanotubes, nanopowders come from a relatively small number of companies worldwide, including the United States, Europe, Asia, and the Mideast (eg, Israel). These companies range from large international corporations with diversified operations to small start-up firms, licensing technology from academic and government laboratories and specializing in a narrow range of nanopowder products. Nanopowder producers are either captive, ie, making powders for their own internal research and commercial use, or "open," ie, producing powders for sale to research organizations and commercial facilities (9,54).

Companies produce nanopowders through a number of processes, including furnace and laser-based technologies. Plasma chemical synthesis (PCS), eg, employs microwave methods to produce nanoparticulates through the creation and consequent rapid quenching of hot ionized gas plasma. Another process, a modification of the Xerox "emulsion aggregation" technology, utilizes emulsion polymerization technique. The resulting powders produced by these various processes possess narrow particle size distribution, high purity and energy efficiency, and superior metallic and ceramic properties. One of the more active areas in the nanopowder field is nano-based coatings. These coatings possess more tightly packed structures than exists in the case of traditional coating material. This structure, in turn, imparts to the surface a high degree of transparency, hardness, and abrasion and scuff resistance. These materials, when added to a resin base, produces superior paints and varnishes (9,54).

Additional applications for nanopowders include their use as abrasives for polishing silicon wafers and chips, hard disk drives (for higher data storage capability), and optical and fiber optical systems; an advanced catalyst for petroleum refining and petrochemicals production, as well as in automotive catalytic converters (providing more complete conversion of fuel to nontoxic gases); as pigments in paints and coatings; and as an additive to plastics in a new generation of semiconductor packaging (9,54,60).

One of the most important applications of nanopowders is in the manufacture of nanopowder–plastic composites. Typically, nanopowder composites contain under 6% by weight of nanometer-sized mineral particles embedded in resins. One of the first such composite used nylon as the plastic medium. More recently, other plastics have come to the fore, such as polypropylene and polyester resins. A new generation of plastics with superior properties is currently being developed for future application. In addition to a number of smaller R&D companies, a few of the larger corporations within the United States and internationally continue to develop advanced nanocomposites, including Bayer, Honeywell, and GE Plastics. In addition to the United States, Germany, China, Korea, and Japan are particularly active in the field (60).

Nanocomposites offer a range of beneficial properties including great strength and durability, shock resistance, electrical conductivity, thermal protection, gas impermeability, and flame retardancy. New and more sophisticated processes can manufacture composite powders with a uniform, nanolayer thick metallic or ceramic coating for high density parts with superior thermal, mechanical and electrical properties (54,60).

As a result of their superior properties and advancing manufacturing technology, nanocomposites face new market opportunities. For example, in the automotive area, General Motors recently entered into production of the first polymer nanocomposite part for the exterior of a car. The biomedical field also appears a particularly promising area for nanopowder composites, especially as delivery systems for the application of bioactive agents into the body, as materials for dental and medical micro abrasion applications, and for use in orthopedic implants (eg, artificial bones for hips) and heart valves (9,54,58–60).

Additional potential applications for nanopowders and nanopowder composites include electrodes for more efficient and longer lasting portable power sources (batteries, solar cells); superior materials for military weapons (eg, as armor and in projectiles); advanced instrumentation (eg, for automotive applications) and biomedical and environmental sensors; materials for stronger, lighter, and more flexible structural shapes and more durable, high performance cutting tools and industrial abrasives; advanced refractory material for chemical, metallurgical, and power generation; ceramic liners (made of zirconia and alumina) in more efficient internal combustion engine cylinders and ignition systems for automotive and aerospace applications; more powerful industrial magnets in magnetic resonance imaging (MRI) systems for medical applications; and a new generation of electrical and electronic components (eg, induction coils, piezoelectric crystals, oscillators) (9,58,59).

**9.5. Nanocarbon Materials.** Nanocarbon materials contain molecular-sized clusters composed of a number of carbon atoms arranged in various configurations. One such group falls into the category of fullerenes. In this case, a series of carbon atoms arranged spherically enclose one or more metal atoms. In the second type of material, the carbon atoms join together to form a tubular-like structure. These structures may or may not enclose metal atoms. These materials, known as nanotubes, have important applications in the advanced composites area. As a group, the nanocarbon materials have begun to enter the marketplace as commercial materials. A number of companies in the United States are particularly active in developing and commercializing nanocarbon materials and composites. These include Carbon Nanotechnologies Inc. (Houston, Tex.), Applied Nanotechnologies, Inc. (Chapel Hill, N.C.) and Luna Innovations (Blacksburg, V.A.).

*Metal Fullerenes (9,61–65).* Fullerenes in general refer to a group of materials composed of carbon structures of 60–90 carbon atoms, each enveloping a single metal atom. Currently, a number of U.S. companies manufacture fullerene materials in varying compositions and amounts. Since the 1990s, research undertaken in the United States has led to the creation of a particular type of fullerene—in which the carbon cage contains three distinct metallic atoms—that is of particular interest commercially. These triatomic fullerenes possess commercially useful properties now being explored by research and industry groups.

Two viable thermal processes produce advanced fullerenes. One technology involves application of the electric arc, using graphite to provide the carbon atoms. The major problem with the process is that it is highly energy-intensive and is therefore expensive if placed on a mass production basis. The second approach, referred to as the “soot-flame” process, is in fact currently utilized to manufacture certain traditional fullerenes. However, it is readily modified to generate commercial amounts of the more advanced (ie, triatomic) fullerene materials by burning a mixture of acetylene (or related hydrocarbon) and the required metals to be “encaged”. The advantage of the soot-flame process is that it is relatively cost efficient and permits carefully controlled production, and therefore more precise product design (9).

Advanced fullerenes offer a variety of potentially important applications. For example, they are at the heart of new types of multi-functional catalyst systems for the petrochemical industry. In this application, the carbon structures encapsulate the different catalytically active metals (eg, iron, platinum, nickel), which are then released in tandem and in a controlled way as the external carbon structure disintegrates during reaction. The unique optical properties of the fullerene material offer additional applications in industrial photovoltaic sensing systems for incorporation into monitoring and automated control technology. The electromagnetic and optical properties of advanced fullerenes will find application in semiconductor, fiber optic, and microelectronic systems (9,61,64,65).

Within the biomedical field, advanced fullerenes appear to be superior "contrasting" agents for use in magnetic resonance imaging (MRI) systems. In this case, the fullerenes, ingested into the body orally, enhance MRI images 50–100 times more than current capability. As a consequence of this improved MRI performance, manufacturers incorporate smaller and less powerful magnets in their machines, resulting in more compact, portable, and cheaper equipment. This advantage, in turn, expands the applications for MRI technology in a number of markets, such as rural, less developed regions, in smaller to mid-sized clinics and hospitals, and in military field hospitals. Further, the smaller MRI equipment, because they operate with less powerful magnetic fields, reduce the costs to the larger hospitals and clinics of housing and maintaining large superconducting magnets. Industry expects the full-scale commercial production of advanced fullerenes for these applications by 2005.

*Nanotubes (9,66–75).* Nanotubes are carbon-based structures with cylindrical shapes and diameters between 0.8 and 300 nm. Nanotubes resemble small, rolled tubes of graphite. As such they possess high tensile strength and can act as an excellent conductor or semiconductor material. There are two main varieties of nanotubes: single-walled and multiwalled. Multiwalled structures are the less pure form of nanotubes and offer only a limited number of applications. The more advanced, purer form of nanotube, ie, defined by a single-walled structure, is the more promising material commercially, especially for incorporation into polymer materials in the synthesis of composites with superior structural, thermal, and electrical characteristics. (9,66,75).

Currently, a handful of companies in the United States and internationally produce advanced fullerenes and nanotubes. In 2002, it was estimated that there were between 20 and 30 captive producers of nanotubes worldwide. These companies included large multinationals (eg, Honeywell) as well as a number of small, independent research firms. In 2002, there were only five "open" companies that produced nanotubes solely for sale in the market. Both captive and open companies sell the bulk of their nanotube production to universities, R&D organizations and other companies, generally for research purposes. A third type of company designs and sells (or licenses) production equipment and systems to other firms to make nanotubes. A current trend in the industry is the formation of international partnerships between United States and foreign—especially Asian—companies to jointly develop and sell nanotubes materials and technologies. These partnership arrangements bring together complementary skills and knowledge and facilitate the sales of U.S.-produced nanotubes within Asian markets. For example, In 2002, the U.S. firm Carbon Nanotechnologies Inc. partnered with Sumitomo Corporation to market carbon nanotubes in Asia (9,66,70,74,75).

The production of nanotubes takes place using one of three major processes: gas-phase catalysis, chemical vapor deposition, and laser-based technology. Chemical vapor deposition involves heating a selected gas in a furnace and flowing the heated gas over a reactive metal surface. This process produces excellent yields with the production of a low concentration of contaminants, but with the nanotubes incurring a large number of defects.

The catalytic process requires acetylene gas to move over a catalyst located within a furnace at high temperatures ($\sim$700°C). In the process, the acetylene molecules decompose and rearrange themselves into nanotubes. This method, which operates on a semi-continuous basis, can generate a significant amount of nanotubes. However, these are typically of the less pure variety and therefore are of limited use commercially. Another problem with this approach is that metal particles from the catalyst tend to attach themselves to newly formed nanotubes. These particles magnetize the nanotubes thus limiting their use for applications in critical electronic components, such as transistors. More generally, both the chemical vapor deposition and catalytic process produce significant amounts of undesired byproducts, eg, carbon black and amorphous carbon. The removal of these impurities from nanotube yields is expensive and limits the economic feasibility of these processes (9,66,68,73).

The laser approach for making the purer nanotubes offers an alternative approach, albeit with its own set of problems. The process involves the use of free electron lasers (FEL). FELs operate at high energy levels and with very short pulses. They produce pure nanotubes by vaporizing graphite-catalyst mixtures. Removal of the impurities (such as spent catalyst and graphite materials), critical in the making of high grade catalysts, involves a solution-based purification process involving dissolution and precipitation of unwanted contaminants. The nanotubes, once purified, are mixed into a polymer host or matrix in various proportions of nanotubes to polymer. Examples of polymers used in nanotube composites include nylon, epoxy and polyester. The extent of dispersal of the nanotubes through the polymer determines the quality and ultimate commercial potential of the final composite. Ultrasonic technology offers one possible commercially viable dispersal technology. The FEL process for making advanced nanotubes is currently under development by government laboratories, universities, and start up companies. The technology produces fewer impurities than other techniques but is energy and capital intensive and offers as yet slow production rates (9).

Research is underway as well in developing other processes, such as improved electric arc technology. In 2002, IBM unveiled its new process for making single-walled nanotubes. The process involves a nanofabrication method centered on silicon crystal technique. The technology, which is still under development, promises minimum creation of by-products and contaminants and little damage to the nanotube structures (73).

Despite advances in nanotube production, process technology currently cannot accurately control the structure and distribution of nanotubes from one batch to the next. This limitation results in nanotube output possessing a high degree of variability in the material's physical and electronic properties. As a result, existing technology cannot as yet satisfactorily custom design nanotubes for particular applications.

One of the most promising large-scale markets for nanotubes involves electronic and optical applications. Because nanotubes have dimensions in the wavelength range of visible light, they can be used directly as active optoelectronic devices. For example, Motorola, Samsung, and other electronics companies are developing advanced electronic displays based on nanotubes. This work is leading to ultrathin screens and flat-panel displays capable of high resolution imaging and high power efficiency, and to a new generation of giant, low cost illuminated signs. A potential market for nanotube display technology is for 20–40 in. television screens since neither LCDs nor other existing display technology has as yet secured a dominant position in the field. A related area is the use of nanotubes in microelectronic devices. In particular, IBM recently succeeded in making microelectronic switches from nanotubes. This device is expected to find a large number of applications in computer and consumer electronic products. The aerospace and defense industries promise markets for advanced nanotube composites as well. These composite materials are both strong and light (20–30% lighter than carbon fibers) and consequently make excellent materials for aircraft components and structures. Current research suggests the possibility that advanced nanocomposite fibers may replace carbon fibers in many structural applications. Additional potential applications for carbon nanotubes include incorporation into thermally conductive fibers for clothing, carpets and fabrics, and into electrical conducting polymers and fibers for use as electromagnetic shielding materials and in various components for wireless communications, micro sensors and monitoring devices. Over the longer term, nanotube composites can provide a superior drug delivery system and advanced storage systems for hydrogen-based fuel cells (9,66,67,70–73,75).

Currently, the price of nanotubes prohibits their extensive commercial use. In 2002, the average price of nanotubes stood at ~\$40–\$50/g, or a number of times more expensive that gold. While the price of nanotubes has declined sharply over the last few years, nanotubes remain too expensive for other than their use in research work and in limited commercial applications (eg, microscope probe tips and membranes). It is estimated that the price of nanotubes would need to drop to ~\$15,000/lb (\$20–\$30/g) in order for their commercial use in flat panel displays for PCs and television sets. The price would then need to reach the \$10,000/lb level for nanotubes to be applied in such applications as microwave devices (eg, antenna) and radar-absorbing coatings for aircraft. A significant drop in price to \$200/lb or less would be required before nanotubes would be used in making fuel cells, batteries, drug delivery systems, and as commercial composites for fabrics, beams, structural members, shielding material for consumer electronics devices, and lightweight automotive and aerospace components (66,68).

The rate at which markets open up to the nanopowder, nanocomposite, and nanotube group of materials depends on the pace of development of production technology and its ability to manufacturer lower priced, high quality, customized materials. Currently, the U.S. market for these materials stands at ~\$25 million. By 2005, it is expected that, as a group, these materials will begin exploiting commercial markets to a significant degree, resulting in total sales of \$250 million. Between 2005 and 2012, the price of the nanomaterials will decline rapidly as their quality and ability to be customized for specific markets increases. By the

Table 8. **U.S. Market Trends for Nanopowders, Nanocomposites, and Nanotubes $\times 10^9$ \$**[a,b]

| | 2002 | 2005 | 2012 |
|---|---|---|---|
| direct economic impact | 0.025 | 0.250 | 2.50 |
| total economic impact[c] | 0.050 | 0.750 | 6.80 |

[a] Refs. 9,66,68,72,75.
[b] Includes all advanced materials.
[c] Includes direct + indirect + induced impact.

end of the period, U.S. sales will reach \$2.5 billion, representing a total economic impact accruing to the United States of ~\$6.8 billion (9,66,68,72,75) (Table 8).

**9.6. Nanofibers (9,78–83).** Nanofiber technology refers to the synthesis by various means of fiber materials with diameters less than 100 nm. Nanofiber technology remains a new but growing field with promising applications. In general, advantages of nanofibers depend on their high flexibility and therefore their ability to conform to a large number of three-dimensional configurations. They also have a very high surface area allowing a myriad of interactions with chemical and physical environments. Recent research suggests possible industrial applications as ceramic ultrafilters, gas separator membranes, electronic substrates, medical and dental composites, fiber reinforced plastics, electrical and thermal insulation, structural aerospace materials, and catalyst substrates for petrochemical synthesis. Nanofibers also may be applied in advanced optical systems, according to the shape, number, and composition of the fibers (9,81,82).

Nanofiber materials may also be incorporated into new types of textiles. In addition to the United States, South Korea is particularly active in this field. Nanofibers potentially can impart beneficial properties to both natural and synthetic fibers, such as superior thermal insulation, durability, strength, resilience, texture, wrinkle resistance, and flexibility. Nanofibers may become the fiber itself through polymerization or, in the form of ultra-thin whiskers, be added to a traditional fiber to modify its properties. Currently, Burlington Industries (Burlington, N.C.), partnering with Nano-Tex (Greensboro, N.C.), leads research in this latter approach. Formed into shirts, pants, and other forms, these whisker-modified fabrics just recently entered the market. Advanced research also points to the possibility of polymerizing textile-grade nanosized fibers through the self-assembling of acetylene-based molecules or through biosynthesis that effects various polymeric combinations of protein materials (9,78).

One of the most promising areas of nanofiber technology involves applications in the biomedical area. Nanofibers potentially can be integrated into advanced drug delivery systems. Even more importantly, nanofibers can produce three-dimensional collagen-based matrices or "scaffolds." When these scaffolds are "seeded" with specific types of human cells, blood vessels of small diameter are formed. These vessels can then be transplanted into a patient. This application of nanofiber technology offers one of the most promising routes to manmade blood vessels. The market for this technology continues to grow rapidly. Currently, nearly 1.5 million hospital operations requiring arterial prostheses are performed in the United States annually, including one-half million coronary by-pass operations. Since no acceptable synthetic arteries currently exist, implanted arteries need to be harvested from the patient, a procedure that often results in complications (and failure), extends recovery time, and is limited to certain patients with usable vessels (9,79,80,83).

The process of making nanofiber collagens involves the use of "electrospinning" technology, similar to the first such method used by DuPont in making its early synthetic fibers. The modern process produces nanofibers from collagen (polylactic and poly glycolic acids) and various human protein materials. An electrical charge is placed on a syringe containing the collagen. The electrical field forces the collagen liquid through the syringe in a thin stream which dries once in the air and is collected on a spool as a fibrous material (9,83).

For this application, the electrospinning process, in a redesigned and computerized form, creates fibers with the necessary "layering" and orientation so that the nanofiber matrix has similar properties to naturally occurring blood vessels. Following synthesis and spinning, the nanofibers are then weaved into a cloth matrix (ie, the scaffolding), which exhibit high porosity and large surface area. The process also uses an innovative bioreactor designed to maintain the matrix structure and hinder necrosis during the cell growth process. Because the fibers closely resemble naturally occurring tissue, cells readily grow in the man-made scaffold. Over time, the technology promises to find application in the synthesis of organs, nerves, muscles, and other tissues. In the near term, the synthetic nanofiber collagen mats may serve as an innovative bandage to stop bleeding during surgeries and to act as scaffolding in order to speed growth of new tissue at the wound site (9,79,80,83).

The company NanoMatrix, Inc. (Irving, Tex.), which licensed its process from Virginia Commonwealth University (Richmond, Va.), is currently developing a process to synthesize bandages and eventually arteries and organs from collagen-based nanofibers. Researchers anticipate that nanofiber bandages to be on the market by 2005 and nanofiber arteries (and other organs) by 2010 (9).

Production of nanofiber materials as a whole is growing as unit prices continue to decline. Total sales of nanofibers in the United States are likely to reach ~$89 million by 2005. By 2012, estimates place sales at >$350 million. This means that, by 2012, the total economic impact in the United States due to the production of these materials will be between $1 and $2 billion (9,78,79,83) (Table 9).

**9.7. Thin Films (9,84–92).** Advanced thin film materials represent one of the newest and most promising of the emerging material technologies. In general, thin film materials are composed of different advanced materials—polymers, metals, and polycrystals—layered a few tenths of an Angstrom deep onto a foundation or substrate, such as glass, acrylic, steel, ceramics, silica, and

Table 9. **U.S. Market Trends for Advanced Nanofibers, $\times 10^9$ \$**[a,b]

| | 2002 | 2005 | 2012 |
|---|---|---|---|
| direct economic impact | 0.033 | 0.089 | 0.350 |
| total economic impact[c] | 0.132 | 0.356 | 1.40 |

[a] Refs. 3,78–79,83.
[b] Includes all advanced materials.
[c] Includes direct + indirect + induced impact

plastics. Whereas coatings are applied to surfaces, thin films often operate as stand alone components in a variety of products and systems including consumer electronics and electronic components, telecommunications devices, optical systems (eg, reflective, antireflective, polarizing, and beam splitter coatings), biomedical technology, sensor systems, electromagnetic and microwave systems, and energy sources and products (eg, batteries, photovoltaic cells) (9,84,91,92).

While a variety of thin film systems remain to be commercialized, certain types are currently in production and have entered into particular markets. A number of companies within the United States and internationally produce various types and amounts of thin film materials. Thin-film companies tend to be relatively small (eg, <200 employees) and specialized (eg, concentrating in optical thin films). Some companies focus only on the process technology; others synthesize the coating materials themselves, as well as manufacture the thin film unit (ie, film materials-substrate composite). These companies typically sell their products to original equipment manufacturers for incorporation into final components and devices. A number of these companies continue to pursue R&D on new thin film technology. These efforts are often supported by government agencies in the form of grants. The Departments of Energy and Defense remain particularly active in the thin film field (9,84–86,88–90).

The future success of thin-film technology depends to a large extent on the viability of the production process. One possible approach involves a thermal laser-based deposition technique. Also known as pulsed laser deposition (PLD), this method involves hitting a target composed of the desired film material with a laser beam of short pulse. The laser's thermal energy causes single atoms or atom clusters to project up at a right angle to the beam onto the desired substrate, forming a homogeneous thin film. This process avoids the formation of unwanted particulates that can cause defects in, and hinder performance of, the final film. Adjusting various parameters of the laser, as well as modifying the target and substrate materials, permits the custom design of a broad range of thin films. The PLD process is often associated with metallic thin film materials. A similar process, called chemical vapor deposition, takes place in a vacuum and involves the diffusion and adsorption of the film material in the form of vapors onto the surface of the substrate. Variations of this process have yet to be fully developed. These processes include plasma enhanced chemical vapor deposition, ultraviolet injection liquid source chemical vapor deposition, and metallorganic chemical vapor deposition (9).

The second general type of process in the manufacture of thin films, known as electrostatic (or ionic) self-assembly (ESA), offers a superior technique in the production of organic, as well as metallic, thin-film materials. The process, using chemical solution (or liquid-phase) deposition, depends on repeatedly dipping the selected substrate— which is cleaned and left with an electrical charge—into alternate aqueous solutions containing anionic and cationic metallic materials. The ESA process conserves on costs because it does not require an ultraclean environment and is not energy intensive. The process also permits scale up for mass production manufacture through the use of automatic dipping machines and robot-controlled fabrication stations. In this process, the electrically charged substrate is repeatedly "dipped" into the solution. As this occurs, thin layers of materials form on the foundation. The material itself, as well as the number and types of layers, determine the optical, electrical, magnetic and mechanical properties of the final thin-film product. Other process technologies appear promising. These include magnetron sputtering, which allows the deposition of different materials only a few atoms deep. In this process, the magnetic field of a magnetron acts on a plasma material, which is transported to the substrate through the sputtering action to the substrate (9,86).

Following the formation of a thin film on a substrate, a variety of film patterning techniques come into play, especially to pattern electronic circuits onto the film. Recent advances in nanolithographic (etching) techniques in particular allow more rapid and precise thin film patterning. These techniques, including X-ray lithography and electron and ion beam lithography, are critical for the economic production of complex thin-film circuitry (9).

Thin-film technology brings together different advanced materials as the primary film substance. In general, these film materials can be organic polymers (eg, organic polymer electronic—OPE—synthetic resins), metals and alloys, or crystals of various sorts (eg, titanium dioxide, magnesium fluoride). The 3M Corporation, eg, is developing a new generation of fluoroacrylate polymers that possess both electronic and anticorrosive properties. These polymers can form ultra-thin transparent coatings on a number of substrates, including copper, aluminum, ceramic, steel, tin, or glass. Possible applications for these types of materials include their use in wireless telecommunications systems, liquid crystal and electrochromatic display technology, reflective or light-emitting (smart) windows, advanced sensors, magnetic and laser devices, piezoelectric products and systems, biomedical devices and implants, antistatic electronic packaging (eg, for use in packaging and protecting microchips), photovoltaic systems, corrosion protection, and xerographic applications, It is expected that, in time, OPE thin films may replace silicon in a number of the most important electronic applications. In part, this is because the process of producing the OPE thin film is potentially significantly cheaper than the vacuum-deposition processes required in silicon technology (9,92).

Metal-based thin films also appear close to achieving a reduction in the size of circuits and circuit components for electronic applications and may, in fact, compete against the polymer thin films in these markets. Metal-based thin films offer greater purity and durable interconnections between microcircuit components. These advantages allow future computers to be made much smaller and to operate faster than current technology. Metal-based thin films promise to advance a new generation of microelectronic and electromagnetic components including capacitors, resisters, thermistors, transducers, inductors, and related elements. Specific types of metals, metal compounds, and alloys used in advanced thin films include alumina, tantalum, nickel, nickel-aluminum alloys, copper, silver, silver-palladium alloys, platinum, and zinc (9,84,85).

Both polymer- and metal-based thin films also provide a route to “printed” low-cost antennas for attachment onto different surfaces. These antennas possess large surface areas for capacitive coupling and may compete against certain types of metallic conductive coatings. Additional potential markets for thin film materials include applications in more efficient photovoltaic systems, thermally and electrically conductive adhesives (for adhesives for chip-to-substrate bonding or for connecting materials in electronic enclosures), thin-film transistors, carpets

Table 10. **U.S. Market Trends for Advanced Thin Film Materials, $\times 10^9$ \$[a,b]**

| | 2002 | 2005 | 2012 |
|---|---|---|---|
| direct economic impact | 0.056 | 0.24 | 0.725 |
| total economic impact[c] | 0.112 | 0.96 | 2.9 |

[a] Refs. 9,84,88,90–92.
[b] Includes all advanced materials.
[c] Includes direct + indirect + induced impact.

and fabrics, wireless identification tags, electrodes for ultrasmall electronic devices (replacing traditional materials such as indium tin oxide), future fuel cell components, and less expensive, smaller, and more advanced microelectromechanical systems (MEMS) that combine computers with tiny mechanical devices such as sensors, valves, gears, mirrors and actuators embedded in semiconductor chips (9,84–88,91,92).

Despite a wide range of possible applications, a number of technical and economic risks exist as advanced thin film materials attempt to broaden their market base. These problems include uncertain interface control; physical degradation of the polymer material in the presence of high temperatures, high electric fields, and exposure to solvents used in the circuit printing process (which limits the types of circuits that can be designed); uncontrolled charge leakage between thin film-based devices and circuit elements resulting in lower operating life and increased signal interference; reduced electrical performance and mechanical degradation due to impurities in the polymer or metal (9).

Beyond these technical issues are industry and market barriers. For example, the suppliers of silicon represent a particularly difficult market in which to compete since they are well entrenched in the industry and enjoy strong customer loyalty. Moreover, they compete vigorously against new competition by improving quality and lowering the price of their technology. Costs remain a concern as well for thin film producers. Currently, thin-film materials vary widely in cost, from <\$50/m$^2$ to in excess of \$1000/m$^2$, depending on the type of thin-film system involved. The higher costs of thin film technology complicate fibers attempts by producers to compete against the more traditional materials. However, as production processes enter into full mass production, unit prices for thin films as a whole will continue to decline, resulting in increased market penetration and sales. While U.S. production of advanced thin films will remain relatively modest through 2005, production will expand rapidly after that. By 2012, total U.S. sales are estimated at ~\$700 million. At this time, the total economic impact of advanced thin films will be nearly \$3 billion (9,84,88,90,92) (Table 10).

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Sanford L. Moskowitz
Villanova University