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PREFACE

The U.S. International Trade Commission (USITC) Office of Industries has researched the commercialization of new manufacturing processes for materials since 1993. The National Critical Technologies Panel, appointed by the President's Office of Science and Technology, and the Council on Competitiveness, an association of private-sector chief executives representing business, higher education, and labor, identified new processing technologies as crucial to improving competitiveness of U.S. industries. The results of the USITC research on developments related to these technologies have been published periodically as individual articles in the *Industry, Trade, and Technology Review* (ITTR), a quarterly staff publication of the Office of Industries. These articles are reprinted in this staff research study, and, in most cases, include a section describing recent developments. An overview of the research objectives and executive summary of the key findings derived from the research are provided at the outset. In addition, several other published ITTR articles covering materials technology are included to provide an understanding of the scope of advanced technologies that have potential future implications for U.S. industrial competitiveness.

The information and analysis in this staff study are for the purpose of this report only. Nothing in this report should be construed to indicate how the Commission would find in an investigation conducted under other statutory authority. For additional information, please direct inquiries to David Lundy, Project Leader at (202) 205-3439 or electronic mail at lundy@usitc.gov.

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OVERVIEW AND EXECUTIVE SUMMARY

"Critical technologies" are those that are considered crucial for the development of innovative, high-quality, cost-competitive products. New manufacturing processes for materials (NMPM) was identified as such a technology by the National Critical Technologies Panel and the Council on Competitiveness during the early 1990s. Several studies also linked the development of advanced materials and processing technologies to the competitive posture of industries.[1]

Assessing the importance of critical technologies in improving the competitiveness of U.S. industries requires a base of information to evaluate how the United States compares with the rest of the world in developing and adopting these technologies. The adoption of NMPM likely will have an important effect on the ability of many U.S. industries to compete in the global marketplace, not only industries that will use these processes but also downstream industries that will use products made by these processes.

The USITC Office of Industries initiated formal research on NMPM in October 1993 to develop expertise and report periodically on emerging developments in this complex and rapidly evolving subject area as part of a long-term research agenda. Eleven articles have been published in the *Industry, Trade, and Technology Review* (ITTR), a quarterly staff publication. Each of these articles is reprinted in this report. Except for articles published since October 1997, updated information has been added to reflect recent developments in the subject areas.

The objective of the research by the USITC was to analyze the development and adoption of new manufacturing processes related to the production of ceramic, metal, polymer, composite, and other materials, and parts fabricated from these materials. The research specifically attempted to develop information in the following areas:

- NMPM at various stages of development and commercialization, and factors affecting their adoption.

- Benefits and drawbacks of using these processes in place of conventional processes.

- Industries potentially or actually using the processes as well as industries that

[1]*Report of the National Critical Technologies Panel* (Washington, DC: Office of Science and Technology Policy), Mar. 22, 1991; U.S. Department of Commerce, *Emerging Technologies: A Survey of Technical and Economic Opportunities* (Washington, DC: U.S. Department of Commerce), Spring 1990; The Council on Competitiveness, *Gaining New Ground: Technology Priorities for America's Future* (Washington, DC: The Council on Competitiveness), Mar. 1991; and *Advanced Materials in High Technology and World Class Manufacturing*,) New York, NY: United Nations Industrial Development Organization, Mar. 1995.

could use products made by the processes, and the characteristics of the companies in these industries.

- Interactions between the entities involved in commercialization and types of collaborations that are most often successful.

- Role of government institutions in funding research, development, and adoption of these processes.

- Extent of adoption of these processes in the United States and foreign countries, and the factors contributing to NMPM development.

Information related to the commercialization of NMPM is not readily available from government agencies or other sources, and published information is scattered, incomplete, or outdated. To develop current information, USITC staff conducted extensive interviews with industry/company representatives, including site visits. Information on foreign companies and comparable developments among global competitors was particularly limited, but was supplemented to some degree by technical conferences, trade journals, and other literature as sources. Despite such limitations, a number of findings emerged from the research. These findings are summarized below.

The scope of NMPM

- NMPM cover a wide assortment of materials and applications. NMPM are used for producing conventional materials, such as steel sheet, as well as for producing advanced materials.[2] In addition, NMPM encompass processes for adapting conventional materials to new uses, such as aluminum in automobile frame applications.

- The intensity and ramifications of intermaterial competition are also apparent in NMPM; for example, advances in steel processing that allow for the production of thin, high-quality sheets have made it more difficult for aluminum to capture certain automobile applications.

- There is a significant emphasis on processes to produce composites combining, for example, metal and ceramic material to create a substance that has the advantageous properties of its constituents. One such process combines aluminum with a ceramic material; the resulting metal matrix composite appears poised to achieve significant commercialization in automobiles.

- Adoption of NMPM may also create the need for advancements in supporting technologies, such as new joining methods for aluminum and composite materials.

NMPM industries and structure

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[2]An advanced material is one that exhibits superior physical properties (e.g., strength, strength-to-density ratios, hardness, durability, etc.) as compared with conventional materials. Advanced materials are also referred to as "new," "high-tech," or "high-performance" materials.

- The automobile sector is a major target market for the materials produced using new processes. This is because it is one of the largest consumers of metal, ceramic, and polymer materials, and because the industry is attempting to improve the efficiency and minimize the environmental effects of its products.

- Foreign competitors are undertaking initiatives and efforts to commercialize NMPM, such as direct ironmaking and processes to produce composite materials for automobiles. This underscores the need for sustaining U.S. efforts to ensure future competitiveness in these technologies and end-use industries.

- The adoption of NMPM can have significant effects on the structure of industries. For example, new processes for thin-slab casting of steel have allowed steel sheet production by minimills, eroding the market share of integrated steel companies.

Environmental aspects (including energy conservation)

- Environmental concerns are driving the development of many processes, from cokeless iron-making (avoiding the pollution problems associated with coke production) to producing automobiles that are more efficient and generate fewer harmful emissions. Light weighting of automobiles is a major near-term solution to increase efficiency, and producers are considering a host of new materials or new applications of conventional materials to decrease vehicle weight.

- Many NMPM create products that have energy savings benefits. For example, sol-gel processing produces insulation material that can save significant energy as compared with using conventional insulation material.

Cooperation and collaboration

- Government involvement in research and development of materials technology is centered in Federal laboratories. Much of this work was initially related to the development of new materials for military systems during the Cold War era. Since that time, new laws allow for cooperation and collaboration between labs and private industry. Indirect government involvement is achieved by funding technology development through agency appropriations.

- Collaboration appears to be increasing as organizations attempt to shorten development horizons and decrease risk. Collaboration between private firms and Federal laboratories is common. Domestic competitors in the private sector also collaborate--Chrysler, Ford, and General Motors, for example, have formed a partnership for developing basic technology for the next generation of automobiles. Collaboration between U.S. and foreign companies also is growing.

Barriers to commercialization and outlook

- The commercialization of NMPM is a formidable task, with substantial economic, technical, and other barriers. Improving cooperative and collaborative links between organizations (private companies, government, and universities) is considered an important method of overcoming barriers. See the first article for a detailed discussion of commercialization barriers.

- The organizations involved with NMPM have expended substantial resources in commercialization attempts. In general, the outlook for commercialization of these processes depends on reducing processing costs to expand market potential, speeding the commercialization effort, and developing other markets.

The first article in part I summarizes many of the factors generally acknowledged affecting development and adoption of NMPM. The second article in part I examines the Government's expenditures on research and development programs related to technology development, particularly in advanced materials and processing technologies. The remaining articles provide specific case studies of a process or processes at various stages of commercialization, from initial development to full commercialization. Articles in part II concern developments related to other materials technology research. These articles are focused on specific materials rather than processes, and examine the use of advanced materials or the use of conventional materials in new applications, as well as the state of development of these materials and competitive implications for consuming industries.[3]

Much of the research on these topics to date has emphasized developments in the United States, although insights are provided on initiatives by foreign competitors to the extent information has been obtained from industry contacts and trade sources. The longer term research agenda of the Office of Industries, will concentrate on developing more detailed information on the adoption of advanced technologies by global competitors. Emerging processes and research findings will be published periodically in the quarterly report, *Industry, Trade, and Technology Review*.

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[3]Articles in this study examine industry-specific technologies and do not include discussion of the broader economic effects related to benefits and costs of government funding for private sector research and development. In assessing impacts of commercializing innovative technologies, articles focus specfically on industry segments or individual firms; conclusions about broader effects on U.S. competitiveness or U.S. economic welfare overall should not be projected from these examples.

PART I

NEW MANUFACTURING PROCESSES FOR MATERIALS

Factors Affecting the Commercialization of New Manufacturing Processes for Materials

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Commercializing innovative processing technologies to enhance industrial competitiveness has become an important consideration among both private-sector representatives and policy makers. By producing materials more efficiently or with superior properties, new manufacturing processes for materials (NMPM) may boost the competitiveness of a wide range of materials-using sectors of the economy. The economic potential of innovative technologies, and policy and regulatory actions promoting their commercialization, provide significant incentives to private firms considering NMPM as a means of keeping pace in an increasingly competitive marketplace. However, barriers to developing and adopting NMPM can be formidable because of economics, technical factors, corporate culture, and regulations. This article examines how these various factors promote or impede NMPM commercialization; highlights the diverse efforts of private industry, government, and academia to overcome existing barriers; and presents both public- and private-sector recommendations to improve the commercialization process for NMPM.

This article was originally published in the Industry, Trade, and Technology Review *(ITTR) of January 1998. ITTR articles cited in footnotes are included in this report.*

Note: A glossary of technical terms (highlighted within the article by ***bold italics***) appears at the end of this article.

New manufacturing processes for materials (NMPM) encompass both innovative manufacturing processes for producing materials and advanced materials that can result from such processes, and may be developed by a private firm, through collaborative efforts of several firms (***internal technology development***), or adopted from outside sources (***external acquisition of technology***). For example, sol-gel processing technologies produce materials with specialized mechanical and thermal properties from the gel state for various architectural and automotive applications.[1] NMPM also include improved production techniques for conventional materials, such as direct ironmaking technologies

[1]For additional information, see Vincent DeSapio, "Sol-Gel: Industry Seeks to Commercialize Energy-Saving Technology for Existing and Emerging Markets," *Industry, Trade, and Technology Review*, USITC, Dec. 1995, pp. 13-26.

that avoid the increasingly costly and hazardous coking process for steelmaking.[2] NMPM can even spur further technological advancements, as when increased use of aluminum, polymer composites, and other specialized lightweight materials in automobile designs prompted development of new bonding and joining technologies.[3]

Commercialization of innovative technologies is driven by two different, but related forces. Where firms seek technical solutions to specific needs, ***market pull*** provides the force for an invention to find a commercial application. For example, nylon was developed by the DuPont Chemical Co. primarily in response to demand by hosiery manufacturers for a more plentiful and less-costly substitute for silk. In contrast, where innovators seek suitable end-use markets for innovations, ***technology push*** provides the underlying basis from which entirely new applications or markets are possible. DuPont successfully applied its Teflon polymer to numerous end uses, the two most familiar being nonstick surfaces on cookware and water-resistant but breathable material for outdoor clothing.

Advances in NMPM have revolutionized entire industries, often with dramatic impact upon markets and international trade. In the steel industry, for example, continuous casting of molten steel into slabs, as an alternative to the more capital- and labor-intensive conventional ingot-casting, was first commercialized around 1960; today, more than 80 percent of all molten steel produced in the Western world is continuously cast.[4] Refinement of continuous casting and scrap-based electric-arc furnace steelmaking technologies enabled lower-cost "mini-mills" to displace the conventional large-scale integrated mills in many bar, rod, and light-structurals markets by the late 1980s.[5] More recently, further process improvements to continuous casting enabled mini-mill penetration into the higher value-added plate, sheet, and coil markets, once the sole domain of the integrated mills.[6] Recognizing that invention, application, and dissemination of innovative technologies have an important role in enhancing growth in industrial productivity, both public-[7] and private-

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[2] See, e.g., Cheryl Badra, "Direct Ironmaking: a Case Study in Government and Industry Cooperation to Commercialize New Manufacturing Processes for Materials," *Industry, Trade, and Technology Review*, USITC, May 1995, pp. 31-42.

[3] See, e.g., Susan H. Lusi, "Alternative Materials in the U.S. Automotive Industry Promote Development of Joining and Bonding Technology," *Industry, Trade, and Technology Review*, USITC, Oct. 1997, pp. 13-23.

[4] Donald F. Barnett, "Harnessing New Technologies: Key to Winning," *Steel Survival Strategies XII, World Steel Dynamics* (Paine Webber, New York, NY, June 17, 1997), pp. 213-238.

[5] Mini-mills' shares of long-products shipments in the U.S. steel industry in 1990 were estimated at 83 percent for wire rods, 65 percent for merchant bars, 35 percent for cold-finished bars, and 100 percent for light-structural shapes. By 1997, estimated mini-mill shares for these products rose to 95 percent for wire rods, 78 percent for merchant bars, 55 percent for cold-finished bars, and 100 percent for structural shapes. Ibid.

[6] Mini-mill shares of flat-product shipments in the U.S. steel industry in 1997 were estimated at 40 percent for plate, 30 percent for hot-rolled sheet, 10 percent for cold-rolled sheet, and 12 percent for hot-dipped galvanized sheet. With the exception of plate, mini-mills shipped only 2 to 4 percent of these products in 1990. Ibid.

[7] Richard J. Brody, *Effective Partnering, a Report to Congress on Federal Technology Partnerships*, Office of Technology Policy, U.S. Department of Commerce (Washington, DC, Apr. 1996); Executive Office of the President, Office of Science and Technology Policy, *Total Materials Cycle, the Pathway for Technology Advancement, 1995 Federal Research and Development Program in Materials Science and Technology, a Report by the Materials Technology Subcommittee, Committee on Civilian Industrial Technology, National Science and*

(continued...)

sector agencies[8] identified commercialization of NMPM as enhancing growth in industrial productivity.[9]

Incentives for Developing and Adopting NMPM

The incentives encouraging the use of innovative materials processing to maintain long-term competitive ability arise from both outside and within the firm. The marketplace is increasingly competitive, as the pace of technological innovation accelerates with shrinking product life-cycles and with the rapid diffusion of capital and technology.[10] Commercialization of innovative technologies is also encouraged by government policy and regulatory changes. Since the 1980s, the Federal Government's role in strengthening the nation's technology development has evolved from a customer relationship toward a partnership with the private sector. Some important actions reflecting this shift include a formalized Federal policy that actively promotes transfer of government-funded innovations from Federal agencies to the private sector; changes to patent regulations to allow industrial partners exclusive ownership of patentable government-funded innovations; and changes in antitrust regulations to allow for collaboration on pre-competitive research and development (R&D).[11]

A firm's primary consideration in developing and adopting innovative technologies is their potential to enhance corporate economic performance. For example, numerous process technology improvements, taken together, have enabled steelmakers to reduce their operating costs and improve product quality (table 1). Other innovations, such as cokeless ironmaking technologies and conversion of furnace dusts and rolling-mill sludges into pig iron,[12] are designed to reduce costs of pollution control, waste disposal, and site remediation. Mini-mills with thin-slab continuous casting technologies can be constructed at one-fifth the cost of integrated mills with conventional casting technology and incur about 10-percent lower annual operating costs.[13] By enhancing economic performance, firms are

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[7](...continued)
Technology Council (Washington, DC, Dec. 1995); and U.S. Congress, Office of Technology Assessment (OTA), *Innovation and Commercialization of Emerging Technologies,* OTA-BP-ITC-165 (Washington, DC, Sept. 1995).

[8] Paul Allaire, Jack Sheinkman, and Thomas E. Everhart, *Endless Frontier, Limited Resources, U.S. R&D Policy for Competitiveness*, Council on Competitiveness (Washington, DC, Apr. 1996).

[9]In assessing impacts of commercializing innovative technologies, this article focuses specifically on industry segments for individual firms; conclusions about broader effects on U.S. competitiveness or U.S. economic welfare overall should not be projected from these examples.

[10] Ibid.

[11] The changing roles of the Federal Government in encouraging U.S. industry to innovate were reviewed in the first article in this series: Dana Abrahamson, "New Manufacturing Processes for Materials: Government Policies and Programs Towards Commercialization," *Industry, Trade, and Technology Review,* USITC, Mar. 1995, pp. 5-13.

[12] Badra, "Direct Ironmaking."

[13] The investment required for a mini-mill of minimum efficient scale (about 2 million tons per year capacity) can be constructed for about $200 per annual ton of production capacity ($400 to $500 million per mill) for producing flat-rolled steel products. In contrast, construction of an integrated steel mill of minimum efficient scale (3 to 6 million tons per year capacity) is estimated to exceed $1,000 per annual ton of production capacity ($4 to $5 billion per mill). Charles Yost, "Thin-Slab Casting/Flat-Rolling: New Technology to Benefit U.S. Steel Industry," *Industry,*
(continued...)

Table 1
Advancements in process technology and product quality in the steel industry

Process step	Integrated-mill 1987	Integrated-mill 1997	Mini-mill 1987	Mini-mill 1997	Selected improvements to steelmaking technologies
Steelmaking—					
Tons per day (*per furnace*) . .	3,000	4,500	2,150	2,800	1970 Bottom blowing—basic oxygen furnace 1985 Direct current—electric arc furnace
Electricity use (*kwh/ton*)	25	25	485	430	1985 Advanced ladle refining 1986 Ultra-high pressure oxygen injection—electric arc furnace 1990 Liquid iron in electric arc furnace
Continuous casting—					
Tons per day (*per strand*) . . .	2,000	3,500	2,100	2,750	1960 Conventional casting 1988 Slim-slab casting (100-mm minimum thickness) 1989 Thin-slab casting (50-mm minimum thickness)
Yields (*percent*)	97.0	97.5	97.5	98.0	1994 Thin-slab casting squeeze (20-mm minimum thickness) 1997 Strip casting (10-mm minimum thickness), stainless steel 2000(p) Strip casting (10-mm minimum thickness), carbon steel
Hot-strip rolling mill—					
Tons per day	10,500	12,000	2,000	4,700	1975 Quick-change rolls 1988 Light gauge (<1.7 mm)
Yields (*percent*)	95.5	96.5	95.5	97.5	1994+ Ultra-light gauge (<1.0 mm)
Cold-rolling mill—					
Tons per day	5,000	6,800	950	1,950	1995 Two-stand reversing cold-rolling mill 1994+ Ultra-light hot-rolled as cold-rolled substitute

(p) - projected.

Source: Donald F. Barnett, "Harnessing New Technologies: Key to Winning," World Steel Dynamics, Paine Webber Inc. (New York, NY, June 17, 1997), pp. 215-238 and telephone interview with A. Cramb, Jan. 1998.

more able to strategically position themselves in the marketplace. Adoption of thin-slab casting enabled Nucor Corporation to be the first company world-wide to build a new, flat-rolled mini-mill in the United States in the late 1960s, reportedly from a perception that this technology provided a means of overcoming the large-scale capital and production entry barriers to an industry segment dominated by the integrated mills.[14]

Confronting the Barriers to Commercializing NMPM

Numerous barriers hinder commercialization of innovations (table 2). Among the most significant barriers are the long time-horizon and high costs, which limit profitability and

[13](...continued)
Trade, and Technology Review, USITC, Oct. 1996, pp. 21-29.

[14] Ibid.

make it difficult for a firm to recoup its investment in successful projects. This is most likely when patent protection expires near the end of development, or in industry sectors with short life-cycles.[15] The experience of AlliedSignal Incorporated in commercializing a new product made with amorphous metals demonstrates how a combination of approaches may be necessary to address the numerous barriers that can simultaneously impede the commercialization process (see text box). Likewise, the magnitude of investment often required to bring an innovation to commercialization may be more than a firm can feasibly finance alone, given the anticipated rate of return; many firms have scaled back "in-house" research efforts or closed down their R&D facilities entirely.

Table 2
Barriers to commercialization of new manufacturing processes for materials

Source of barrier	...to developing NMPM	...to adopting NMPM
Time horizon	Failure to recognize lengthy R&D period needed (often a decade or more) to develop a market for an innovation.	Lengthy learning and adjustment period needed to achieve desired product quality.
Technological	Resulting material's properties are not entirely suitable for existing market application; underdeveloped markets in some cases.	Resulting material's properties are not entirely suitable for specific industry application. NMPM may be more suitable for a new state-of-the-art facility and retrofit may not match scale production economies.
Financial or economic performance	Magnitude of required investment, given anticipated returns. Resulting products with high unit cost may be suitable only in industries requiring specific material properties. Limited initial production capacity or market demand, especially for improved or new materials.	Capital cost exceeds anticipated returns. Resulting products with high unit cost may be suitable only in industries requiring specific material properties. Existing process technology may embody sunk costs or possess lengthy remaining economic life.
Corporate culture	Organizational separation among units involved in R&D process; differences in attitudes and values among units. Territoriality among organizational units; suspicion of projects originating outside of unit.	Risk-adverse or risk-neutral approach to decision making; receptive to innovative NMPM but adopts wait-and-see approach.
Regulatory environment	Inflexible codes and standards preclude use of resulting material. Antitrust regulations inhibit collaborative R&D.	Inflexible codes and standards preclude use of resulting material. Strategic considerations prevent NMPM from being acquired by economic rivals or hostile foreign powers.

Source: Compiled by USITC staff from various government documents and industry publications.

[15] Thomas W. Eagar, "Bringing New Materials to Market," *Technology Review*, Feb./Mar. 1995, pp. 43-49.

Producing amorphous metals using the rapid solidification process: 20 years to commercialization.

The rapid solidification process cools molten metals extremely quickly to an amorphous metal (AM) in which the atoms are randomly spaced, as opposed to the ordered structure of conventionally cooled metals. Given the excellent magnetic properties of iron-based AM alloys, electrical distribution transformer cores made of these alloys consume 60 to 70 percent less energy than those with the most efficient conventional silicon-steel cores. If all U.S. distribution transformers used AM alloy cores, the annual operating cost savings could exceed $3 billion (based on the average residential rate for electricity), according to AlliedSignal (AS) Incorporated, the developer of this technology.

Processing technology was the most significant barrier identified in developing rapid solidification; perfecting the process took AS almost 20 years. Many other potential barriers were avoided because AS received development assistance from a Federal laboratory, had regulatory agency support, and had close cooperation from the industry's standards-setting organization. The technology, when applied to making distribution transformers, was accepted by end users (electric utilities) in the United States with minimum reservations, and AM transformers captured 12 percent of the U.S. market during 1990-95. Recently, however, utilities have been reluctant to switch to these transformers because energy costs are decreasing in real terms, and the economic incentive for installing AM transformers (which cost 10 to 15 percent more) is decreasing.

Source: Compiled by USITC staff from company publications and interviews of company representatives.

Corporate culture also may contribute to delays and cost overruns because of organizational separation between technical and business units, and differences in goals and values.[16] Private firms use various combinations of approaches to overcome such cultural tendencies, employing cross-functional teams and enhancing communication between functional units were most commonly reported.[17] Mobil Oil Company relies extensively upon both strategies to develop and maintain its core technical competencies, including advanced catalytic processing for refining petroleum and synthesizing chemicals.[18] Another approach to encourage interaction between technical and business units is centralizing technological functions.[19] For example, by centralizing new-product development and integrating representatives from all functional units into development teams, production and marketing difficulties at Chrysler Corporation can be anticipated before finalizing product designs. Because the design of a product determines a large share of production costs, Chrysler anticipates significant reductions in both final product costs and development time through this approach.[20] Likewise, the existence of formalized project plans and written procedures, which provide early agreement between the business and research units, eliminates false starts and defines responsibilities that would otherwise take time to evolve.

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[16] For example, an innovation is successful to a technician if it can be produced in a laboratory, but for management, if it can be manufactured and survive in the marketplace.

[17] See: John J. Wise, "An Evolving Partnership, Mobil has Adopted a Number of Innovative Practices Designed to Strengthen its Technology/Business Partnership and Expedite the Transfer of Its Technology," *Research-Technology Management*, vol. 38, No. 6, Nov./Dec. 1995, pp. 37-41; Charles E. Bosomworth and Burton H. Sage, Jr., "How 26 Companies Manage their Central Research," *Research-Technology Management*, vol. 38, No. 3, May/June 1995, pp. 32-40; and Derek L. Ransley and Jay L. Rogers, "A Consensus on Best R&D Practices," *Research Technology Management*, vol. 37, No. 2, Mar.-Apr. 1994, pp. 19-26.

[18] Wise, "An Evolving Partnership."

[19] Mobil found that previously separate product laboratories and technical service units often slowed the transfer of technological developments to business divisions, and were duplicative at a time when it was under pressure to cut costs. Ibid.

[20] Steven W. Irwin, *Technology Policy and America's Future* (St. Martin's Press, New York, NY, 1993).

Incorporating lessons learned from past project plans also contributes to success; Mobil relies extensively on formal mechanisms for reviewing project progress, including post-project auditing to learn from its experiences.[21]

In addition to these factors, technical barriers may hinder the adoption or commercialization of NMPM. New materials may be initially unsuitable for existing market applications because they exhibit significantly different specifications or physical properties than conventional materials, or because of their high initial unit costs. For example, despite considerable weight savings and long-run cost savings of aluminum metal matrix composites (MMC), the automobile industry was hesitant to substitute this advanced material for steel and cast iron in drive shafts and brake rotors because of significantly higher initial per-unit material costs, higher machining costs, and the large amount of capital investment necessary to retrofit process lines. To commercialize this new material, Duralcan approached the U.S. automotive industry to try aluminum MMC in limited production runs to demonstrate the material's reliability and potential long-run cost-effectiveness (see text box).

Producing aluminum metal matrix composites using the stir-casting process: technical and economic barriers delay commercialization.

Metal matrix composites (MMC) consist of a metal or metal alloy (matrix) with a reinforcing material (usually ceramic) dispersed throughout. Duralcan, a subsidiary of Alcan Aluminum Limited, developed a proprietary stir-casting technique to produce aluminum MMC, which are reinforced by particles of silicon carbide or aluminum oxide. Aluminum MMC offer comparable stiffness, corrosion resistance, and abrasion resistance as conventional steel or cast iron, but with considerable weight savings. In automobile drive shaft and brake-rotor applications, aluminum MMC save 18.0 and 7.5 pounds, respectively.

However, automobile manufacturers have been reluctant to adopt this new material for technical and economic reasons. Aluminum MMC cost $1.50 to $2.00 per pound (depending on production volume) compared with $0.90 per pound for aluminum, $0.50 per pound for steel, and $0.20 per pound for cast iron. Fabrication costs are higher than for conventional materials because parts made of aluminum MMC must be finished with diamond tools. Entire assemblies would have to be redesigned to fully exploit the advantages of this advanced material. Also, manufacturers are particularly sensitive to product-safety concerns, which limit use for brake components.

To commercialize aluminum MMC, Duralcan sought closer links with the U.S. automotive industry by approaching manufacturers directly, setting up a marketing arm in the Detroit area, and even relocating production facilities. A decade after Duralcan was formed to manufacture and commercialize this advanced material, General Motors and Chrysler Corporation are trying aluminum MMC parts in limited production runs of drive shafts and brake rotors; such trials will allow aluminum MMC parts to prove their reliability and long-run cost-effectiveness. Other industry sectors have turned to aluminum MMC for specific applications, including specialized bicycle frames, sporting goods, and even snow tire studs. These applications present less volume potential but nevertheless encourage sales and market development of aluminum MMC.

Source: Compiled by USITC staff from industry publications and interviews of company representatives.

Collaboration between private firms—

Direct firm-to-firm collaboration is ideal for resolving the classic risk-associated problem of hesitancy on the part of materials producers to invest in expanding production capacity for a new high-performance product where its potential market niche is small, and likewise, the hesitancy of materials users to invest in switching to such products with limited availability. To speed up commercialization, U.S. Steel worked closely with Chrysler

[21] Wise, "An Evolving Partnership."

Corporation to fine-tune its newly developed steel sheet with an iron-zinc coating to be compatible with the latter's painting system. In anticipation of a major market for its output, U.S. Steel could justify the expenditure for substantial modifications to its electrogalvanizing process to produce the new iron-zinc steel sheet. Furthermore, the time span from concept to full-scale manufacturing was 3 to 4 years, compared with 10 or more years to commercialize new products in the past.[22]

To side-step the time and expense of the earlier stages of the R&D process, private firms may elect to adopt innovations developed by outside sources in either a partially or fully commercialized state. Two well-established mechanisms are ***licensing*** and ***strategic partnerships***. For a license-granting firm, licensing its technology can be an alternative to expending resources to develop new markets and scale up to full commercial production. The mutual benefits attendant with licensing are illustrated by the Boeing Company's 1993 agreement with Grumman Corporation to apply Grumman's patented electromagnetic forming process for torque-tube joints in commercial aircraft, a deal that could be worth $10 million over the next 10 years.[23]

In a strategic partnership, two firms agree to share marketing and commercialization of a product or process created by one firm but developed by the other. This arrangement enables the originating firm to commercialize an innovation despite lack of technical expertise, skilled personnel, sufficient funding, or adequate capital equipment. Martin Marietta used a strategic partnership to commercialize high-strength aluminum alloys and metal matrix composites, as the company's core business is not materials production.[24] For this case, important considerations for selecting a strategic partner were that the two firms should compete in different market segments and have similar organizational cultures, a high level of management commitment, a defined strategy to aggressively develop and commercialize the technology, and the technical ability to work closely together. With both licensing and strategic partnerships, the acquiring firm receives access to a technological innovation with less investment in R&D, but must finance fine-tuning the innovation for application, and must develop detailed marketing plans. A significant positive feature of such partnerships is that commercial applications are developed concurrently with technical development. For Martin Marietta's technologies, markets may be already partially developed by strategic partners who are often major customers.[25]

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[22] John Schriefer, "Increasing R&D's Productivity," *New Steel*, vol. 12, No. 6, June 1996, pp. 72-78.

[23] Torque tubes are aluminum and steel drive-shaft assemblies that are part of the control system that raise and lower the flaps and slats on aircraft wings. The Grumman process extends the service life of the torque tube by strengthening the joint between the tube and fittings. Grumman has used electromagnetic forming for more than 20 years in the production of military aircraft, although this is the first commercial application of this technology. Grumman also offers this process for automotive and other high-stress, rotary-motion applications. Anthony L. Velocci, Jr., "Ventures Rife with Marketing Pitfalls," *Aviation Week and Space Technology*, vol. 139, No. 19, Nov. 8, 1993, pp. 59-61.

[24] John A.S. Green, John Brupbacher, and David Goldheim, "Strategic Partnering Aids Technology Transfer, Martin Marietta Finds Technology Transfer Through Strategic Partnerships a Rapid, Effective and Successful Tool for Developing Novel Engineered Materials," *Research Technology Management*, vol. 34, No. 4, July/Aug. 1991, pp. 26-31.

[25] Ibid.

An alternative to adopting from outside a firm is pre-competitive collaboration with other firms. This approach to commercialize NMPM enables participants to spend R&D funds more efficiently and helps reduce duplication of expenditure and effort, especially in the early phases of a project.[26] Private firms may form ***horizontal consortiums*** to tackle problems common to an entire industry, although the firms remain competitors in the marketplace. An increasing number of ***vertical consortiums*** are being formed among firms from the various stages of production, as manufacturers increasingly interact with suppliers and customers to develop innovative technologies. For example, the 5-year Advanced Process Control Research Program, coordinated by the American Iron and Steel Institute, includes steelmakers, industry suppliers, and Federal laboratories[27] collaborating in the development of advanced sensor and process-control technologies to improve steelmaking efficiency and reduce energy consumption and emissions.[28] Factors for successful consortiums include long-term commitment and active participation of members (including management), access to members' marketing and manufacturing capabilities, and a focused technology strategy.[29] Furthermore, potential benefits are maximized with partners whose R&D capabilities are complementary.

Looking to R&D institutions as sources of innovative technologies—

Collaboration with Federal laboratories and research universities rather than competitors may be preferable to some firms, especially due to intense interfirm rivalries and problems of sharing intellectual property rights. In addition, R&D institutions offer access to technical expertise and advanced facilities that would be too expensive for most firms to build and operate (e.g., high-powered computational and sophisticated analytical capabilities).

The abilities of the 700+ Federal laboratories to develop and commercialize NMPM depend to a great degree on the mission of the supporting agency and past experience. A notable example is the extensive collaborative effort between the U.S. polymer industry and the National Center for Agricultural Utilization Research to develop less expensive, more versatile, advanced superabsorbent polymers. The results of this research not only enabled the polymer industry to regain its domestic market share from foreign competitors, but also to enter new markets abroad (see text box). Although collaborative mechanisms range from informal sharing of information (through laboratory publications, workshops and seminars, and technical consultations) to the use of Federal laboratory facilities, employee

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[26] Eagar, "Bringing New Materials to Market."

[27] Schriefer, "Increasing R&D's Productivity."

[28] Potential annual energy savings for the U.S. steel industry anticipated from the six projects are estimated at 16.5 trillion BTUs, which could cut costs to the industry by $103 million. Furthermore, potential NO_x emissions could be cut by an estimated 13,000 metric tons, SO_x by 80,600 metric tons, and particulate matter by 33,100 metric tons. National Renewable Energy Laboratory, *Technology Partnerships, Enhancing the Competitiveness, Efficiency, and Environmental Quality of American Industry*, for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of Industrial Technologies, DOE/GO-10095-170 DE95004086 (Washington, DC, Apr. 1995).

[29] Tim Stevens, "Success in Numbers: A Research Consortium Can Yield Big Payoffs to Member Companies, If They Do It Right," *Industry Week*, vol. 243, No. 7, Apr. 4, 1994, pp. 45-48.

exchanges, and licensing, three mechanisms were most frequently cited as promising future payoffs: industry-sponsored research, contract research, and cooperative R&D.[30]

Superabsorbent starch-based polymers: commercializing Federal laboratory innovations for revival and expansion of domestic industry.

Superabsorbent polymers are used in air filters, to mop up spills and absorb wastes, to reduce watering requirements of crops, and in numerous products in the construction, electrical, petroleum, and chemical industries. The specific absorbency of polymers allows some mixed liquids to be readily separated, for example, extracting water from diesel fuel or gasoline.

In the 1980s, the U.S. polymer industry was losing its market share to foreign competition in the $1-billion-a-year domestic market, particularly to producers of petroleum-based synthetic absorbents. Scientists at the Department of Agriculture's National Center for Agricultural Utilization Research (NCAUR) revisited past research and relied upon extensive links with industry to identify existing and potential applications; product performance requirements; and production, equipment, and market needs. Industry engineers and researchers were invited to observe and comment during laboratory preparation of the polymer, and NCAUR scientists collaborated with industry to resolve technical problems during scale-up to commercial production.

This public-private collaboration resulted in improved starch-based polymers that are more absorbent, effective for a broader range of substances, and less expensive than other absorbent polymers. As a result, the domestic polymer industry regained its standing in the domestic market, and opened new markets as U.S. manufacturers began selling overseas.

Source: George Fanta and William Doane, "Researchers Starch Up Soggy U.S. Polymer Industry," *Winners in Technology Transfer* (Federal Laboratory Consortium for Technology Transfer, Washington, DC, 1994).

The use of ***cooperative research and development agreements*** (CRADAs) has mushroomed since their inception in 1986 because of unique advantages over other forms of industry-Federal laboratory collaboration. These advantages include exclusive ownership of patent rights for the industrial partner, protection of proprietary information, and royalty shares for government researchers. To some critics, the CRADA program is too generous to industrial partners who essentially pay half the R&D costs,[31] and some industry officials have criticized the long delays for CRADA approval.[32] In contrast, supporters have

[30] Based on two surveys of chief technical officers and laboratory directors of industrial firms by the Georgia Institute of Technology. There was less enthusiasm for licensing agreements because many laboratory innovations needed further development at initial licensing to bring them to commercial success. Cited in: David Hughes, "Industry Seeks Expertise in Federal Lab Interaction," *Aviation Week & Space Technology*, vol. 139, No. 19, Nov. 8, 1993, pp. 56-58; and J. David Roessner and Alden S. Bean, "How Industry Interacts with Federal Laboratories," *Research Technology Management*, vol. 34, No. 4, July/Aug. 1991, pp. 22-25.

[31] Both partners provide relatively equal amounts of resources (facilities, equipment, personnel, expertise, and funding) to the agreement, but the Federal laboratory cannot provide appropriated funds. Dan Cordtz, "Bye-Bye, Dr. Strangelove, Threatened with Extinction by Politicians, U.S. Weapons Labs are Dying to Help Business," *Financial World*, vol. 164, No. 2, Jan. 17, 1995, pp. 32-37.

[32] From quarterly surveys of its CRADA partners, Sandia National Laboratory found that the program was responsive to industry queries, and technical goals and milestones were being met, but the time required to conclude agreements needed to be reduced. William B. Scott,

(continued...)

questioned the wisdom of firms paying the entire cost, which would reportedly turn laboratories into "job shops," a shortcoming the CRADA program was designed to discourage.[33]

Industry also has a long history of interaction with research universities. Although universities are capable of long-range basic research, it is on a relatively small scale compared with the Federal laboratories, and is usually confined to specific academic disciplines. These factors, plus academia's emphasis on freedom of inquiry, can be problematic in meeting private industry's need for multi-disciplinary, applied R&D assistance. To bridge these cultural differences, many academic institutions have developed technology transfer centers to coordinate and facilitate customized assistance. This type of collaboration is most common for incremental improvements to existing technologies or products.[34]

Taking advantage of government technology-commercialization programs—

At all levels of government, there are programs to promote the transfer of technology from R&D institutions to private industry, particularly to small- and medium-size business.[35] At the state and local level, for example, there are some 390 technology-commercialization programs.[36] These vary in structure, focus, and range of services, from providing technical assistance to small businesses, promoting industry collaborations, and offering literature search capabilities, to financing small businesses and giving start-up assistance to small technology-based firms or regional industries. Despite successes, these efforts reportedly are sometimes criticized not only for lacking expertise, but also for wasting funds because of inefficiencies, program overlap, and bureaucratic snarls.[37] Awareness of local technology-commercialization resources was reported to be low among small manufacturers, but use increased with extent of prior use.[38] It also has been reported that small firms generally are in greater need of "off-the-shelf" technologies, particularly

[32](...continued)
"Technology Transfer Support Wavers," *Aviation Week & Space Technology*, vol. 143, No. 17, Oct. 23, 1995, pp. 57-60.

[33] Charryl Berger, deputy director of the Los Alamos National Laboratory Industrial Partnerships Office, cited in: Cordtz, "Bye-Bye, Dr. Strangelove."

[34] Robert Killoren, "University-Industry Interactions, Room for Diversity," *SRA Journal*, vol. 25, No. 2, June 1994, pp. 31-35.

[35] Federal-agency programs encouraging U.S. industry to innovate were reviewed in Abrahamson, "New Manufacturing Processes for Materials: Government Policies and Programs Towards Commercialization."

[36] U.S. Congress, OTA, *Innovation and Commercialization of Emerging Technologies*.

[37] Paul Proctor, "Regional Agencies Help Small Firms Get Foothold," *Aviation Week & Space Technology*, vol. 143, No. 17, Oct. 23, 1995, p. 62.

[38] Based on a study of survey results from 120 small manufacturing firms in middle Tennessee. John Masten, G. Bruce Hartmann, and Arief Safari, "Small Business Strategic Planning and Technology Transfer, the Use of Publicly Supported Technology Assistance Agencies," *Journal of Small Business Management*, vol. 33, No. 3, July 1995, pp. 26-37.

computer-aided drafting and manufacturing software, and applying computerized techniques to the factory floor for statistical process control and inventory control.[39]

Outlook: Further Actions for Effective Commercialization of NMPM

Despite considerable progress toward commercializing innovative materials technologies, observations of key participants in the process suggest that continued efforts are needed to promote development and adoption of NMPM. Standards for test methods and materials design should be developed,[40] taking into account factors such as increased performance of advanced materials and degree of risk for the application. For example, given the stronger, more fracture-resistant steels that are now readily available, materials specifications for pressure-vessel boilers are currently over-specified, being nearly the same as they were 50 years ago.[41] In those cases where a single firm cannot afford to underwrite extensive testing of an advanced material, pooling the cost of risk assessment may be helpful.[42] Evaluation of NMPM also could be improved by increased standardization of design-related, materials-property databases.[43] For certain materials R&D areas that are seldom tied directly to commercial applications, it is reported that the government may need to take the lead, especially in supporting research to characterize and understand new materials, and in developing advanced computational tools for new-material design methods, and life-cycle performance analysis techniques.[44]

For private industry, reported recommendations focus on developing and expanding markets for advanced materials.[45] Collaborations to tailor an advanced material to meet specific end uses and increase production and market capacity include:

- Establishing direct links with the ultimate end users of a material rather than just the immediate customer.

- Increased mutual sharing of proprietary technical information and marketing strategies between materials suppliers and users. Also, increased joint ventures between materials suppliers and users.

- Incremental introduction strategies to improve existing products and build market demand for an advanced material.

[39] William H. Miller, “Federal Help, Don’t Laugh, The Commerce Dept’s. Expanding System of Manufacturing Technology Centers is Trying to Show That the Feds Can be Useful,” *Industry Week*, vol. 242, No. 14, July 19, 1993, pp. 55-61.

[40] Materials Advisory Board, *Commercialization of New Materials for a Global Economy*.

[41] Eager, “Bringing New Materials to Market.”

[42] Ibid.

[43] Materials Advisory Board, *Commercialization of New Materials for a Global Economy*.

[44] Office of Science and Technology Policy, *Total Materials Cycle, the Pathway for Technology Advancement.*

[45] Eager, “Bringing New Materials to Market;” and National Materials Advisory Board, *Commercialization of New Materials for a Global Economy*.

To the extent that partnerships with private industry continue, results reportedly can be improved through a number of specific policy changes by the Federal Government:

- Improve the continuity of Federal R&D resources to reduce fiscal unpredictability.[46]

- Reform export-control regulations on **dual-use technologies** that may unnecessarily interfere with interactions between U.S. firms and foreign partners, restrict access to foreign technical bases, or limit U.S. firms' access to international markets (see text box).[47]

> **Extremely fine metallic-membrane filters: posing a $2 billion dual-use technology dilemma.**
>
> Martin Marietta was interested in applying metallic membrane technology to commercial filtration applications ranging from effluent treatment to purification of orange juice, with an estimated potential of $2 billion in commercial business by 2000. This technology has been developed by Oak Ridge National Laboratory for use as extremely fine filters in the gaseous diffusion process for purifying uranium. Declassification of this technology was halted by concerns about the Iraqi government's efforts to upgrade its nuclear processing capabilities.
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> Source: Thomas G. Donlan, "The Price of Progress, Scientific Advances Require Sound Investment Policies and Clear Goals," *Barron's*, vol. 74, issue No. 26, June 27, 1994, p. 62.

- Improve the speed, flexibility, and predictability of negotiating, implementing, and funding industry partnership agreements with Federal laboratories.[48]

- Promote timely and wide dissemination of information on Federally funded innovations and R&D partnership opportunities[49] by establishing a centralized materials database.

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[46] Allaire, Sheinkman, and Everhart, *Endless Frontier, Limited Resources*.

[47] National Materials Advisory Board, *Commercialization of New Materials for a Global Economy*. Private firms also impose barriers deliberately for strategic considerations, especially to preserve trade secrets and protect economically valuable innovations from competitors. Likewise, foreign economic rivals also screen the acquisition of economically valuable innovations by U.S. firms.

[48] Brody, *Effective Partnering*.

[49] National Materials Advisory Board, *Commercialization of New Materials for a Global Economy*; and Brody, *Effective Partnering*.

- Pare agency bureaucracies and decentralize decision making to allow laboratory directors to implement their own strategies and be accountable for supporting commercial applications.[50]

- Increase partnerships with small- and medium-sized technology firms.[51]

- Coordinate Federal programs with State programs,[52] especially to improve the effectiveness of small business in commercializing innovative NMPM[53] and to reduce overlap in State programs.[54]

For research universities, reported recommendations specific to NMPM focused on disseminating updated knowledge about advanced materials:[55]

- Include advanced-materials selection and design in the materials engineering curriculum.

- Promote continuing education for materials engineers on technological advancements and practice-oriented training for materials technicians.

- Promote programs for faculty and graduate students to gain experience in industrial laboratories as a means of promoting links between university and private-sector R&D.

- Increase partnerships with small- and medium-sized firms specializing in technology.[56]

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[50] Allaire, Sheinkman, and Everhart, *Endless Frontier, Limited Resources*; and National Materials Advisory Board, *Commercialization of New Materials for a Global Economy*.

[51] Lewis M. Branscomb, Aetna Professor Emeritus of Public Policy and Corporate Management Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, *Testimony, Hearing of the Subcommittee on Science, Technology and Space of the Senate Committee on Commerce, Science and Transportation*, Apr. 16, 1997.

[52] Federal partnerships with State programs are essential because states are much closer to the practical need of local businesses through the efforts of State colleges and universities and State commerce and transportation agencies. At their 1997 meeting in Washington, DC, the State Governors created a formal structure for linking Federal and State research teams in partnership. John H. Gibbons, Assistant to the President for Science and Technology, *Technology Partnering: Can You Count on the Government?* (Federal Technology Report, McGraw-Hill Companies, Inc., Washington, DC, Mar. 3, 1997).

[53] Brody, *Effective Partnering*.

[54] Walter H. Plosia, Executive Director, North Carolina Alliance for Competitive Technologies, “State and National Strategies for Promoting Innovation and Stimulating Economic Development,” *Trends in Industrial Innovation, Industry Perspectives and Policy Implications*, 1997 Sigma Xi Forum, Arlington, VA, Nov. 20-21, 1997.

[55] Allaire, Sheinkman, and Everhart, *Endless Frontier, Limited Resources*; and National Materials Advisory Board, *Commercialization of New Materials for a Global Economy*.

[56] Branscomb, *Testimony, Hearing of the Subcommittee on Science*.

Private industry, government, and academia continue to commercialize innovative NMPM in response to economic and regulatory incentives. The numerous interactive and often interlinked approaches devised by these participants have evolved through time to address many of the barriers that impede development and adoption of such innovative technologies. The extent to which the above suggestions can be implemented will have significant bearing upon the pace of technological innovation, which, in turn, impacts industrial competitiveness in a rapidly changing and increasingly globalized marketplace.

Glossary of Terms

Consortium	A joint R&D agreement among private firms to develop a technology of common interest to participants. Government agencies and research universities also may participate in or organize such ventures.
Cooperative research and development agreement (CRADA)	A formalized joint R&D agreement between private industry (either a single firm or multiple firms) and a Government agency, national laboratory, or research university.
Defense conversion	Reorienting an institution's R&D efforts from defense-related to commercial, non-defense-related applications.
Dual-use technology	Innovations with both commercial and military applications.
External acquisition of technology	Innovations brought into a firm from an outside source. Also referred to as "technology acquisition." Contrast with *internal technology development*.
Horizontal consortium	An industry *consortium* whose member firms normally compete in the same or related markets. Contrast with *vertical consortium*.
Internal technology development	Innovations developed by a firm from within, through successive functional units involved in the R&D process. Contrast with *external acquisition of technology*.
Licensing	An agreement granting an acquiring firm access to the licensor's technology.
Market pull	Technology development spurred specifically when a solution is sought by the market to meet an existing technical need. Contrast with *technology push*.
New manufacturing processes for materials (NMPM)	Any manufacturing process that can produce materials more efficiently than can conventional processes, or can produce materials with superior properties compared with conventional materials, or both. NMPM also could result in entirely new materials.
Strategic partnership	A joint R&D agreement between two private firms to commercialize a technology initially developed by one, but in need of further development by the other to bring the technology to the marketplace.
Technology push	Technology for which there is currently no commercial market, but developers seek commercial applications after its development is under way or completed. Contrast with *market pull*.
Vertical consortium	An industrial *consortium* whose members do not all compete in the same or related marketplaces, but rather are drawn from the various stages of production (e.g., materials suppliers, finished-product manufacturers, etc.). Contrast with *horizontal consortium*.

New Manufacturing Processes for Materials: Government Policies and Programs Towards Commercialization

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This article examines the Government's increasing involvement in research and development activities, with a particular focus on the development and eventual commercialization of advanced materials and processing technologies. Since the early 1990s, the administration has emphasized Government-industry cooperation in technology development as an important priority. Indeed, several mechanisms have been established to facilitate cooperation between the private and public sectors. In addition, significant legislation has been passed promoting technology transfer that has benefited the development of advanced materials and processing technologies. Finally, the article discusses several factors that will likely impact Government involvement in such activities in the future.

Since this article was first published in the Industry, Trade, and Technology Review *of March 1995, policy mechanisms directing Government coordination of materials R&D have been phased out. However, budget allocations to the relevant agencies have not decreased significantly, suggesting that materials development efforts supported by the Federal Government will continue relatively unhindered. In addition, there has been significant legislative activity supporting R&D efforts that could affect the Government's R&D activities in materials. The concluding section of this article elaborates on recent developments and provides current funding estimates for certain programs.*

The development of advanced materials and processing technologies directly affect a nation's economic prosperity, environmental health, and quality of life. The importance of these related areas has been highlighted by numerous U.S. and foreign government and private studies, all of which have reached similar conclusions.[1] Materials processing

[1]Within the United States, the National Critical Technologies Panel (appointed by the Office of Science and Technology Policy (OSTP)), the Department of Commerce, and the Council on Competitiveness (a private organization of representatives from business, higher education, and labor) have all identified materials and associated processing technologies as critical for U.S. competitiveness and economic prosperity. *Report of the National Critical Technologies Panel* (Washington, DC: Office of Science and Technology Policy), Mar. 22, 1991; U.S. Department of
(continued...)

technology is a vital enabling technology; with each advancement, the potential for advances in other fields increases. This is because advances in processing technologies can result in increased efficiency and productivity, lower production costs, and improved material characteristics. This article examines the role the U.S. Government plays in the development and precommercial stages of materials-processing technologies, outlining shifts in government focus, the framework for government involvement, and the outlook for future government involvement.

Shifts in Government Focus

The U.S. Government has a long history of involvement in the materials and materials-processing fields. For many years, Federal research and development (R&D) efforts in these areas centered on defense- and space-related technologies used by the Department of Defense and the National Aeronautics and Space Administration (NASA). Advances in military and space systems often require the use of new materials or new processing techniques where unique combinations of properties or specific characteristics are necessary. As the principal consumer of military and aerospace technologies, the U.S. Government has a vested interest in their development. As a result, the Government has been willing to underwrite the risk and expense involved in developing these areas.

In the post-Cold War era, military threats have decreased and concerns about economic competitiveness have become increasingly important. Accordingly, the U.S. Government has, to a degree, shifted its focus from development of defense-related technologies to development and transfer of technologies applicable in the commercial sector as well. In addition, a trend towards greater cooperation and coordination of public/private efforts is being embodied in current initiatives.

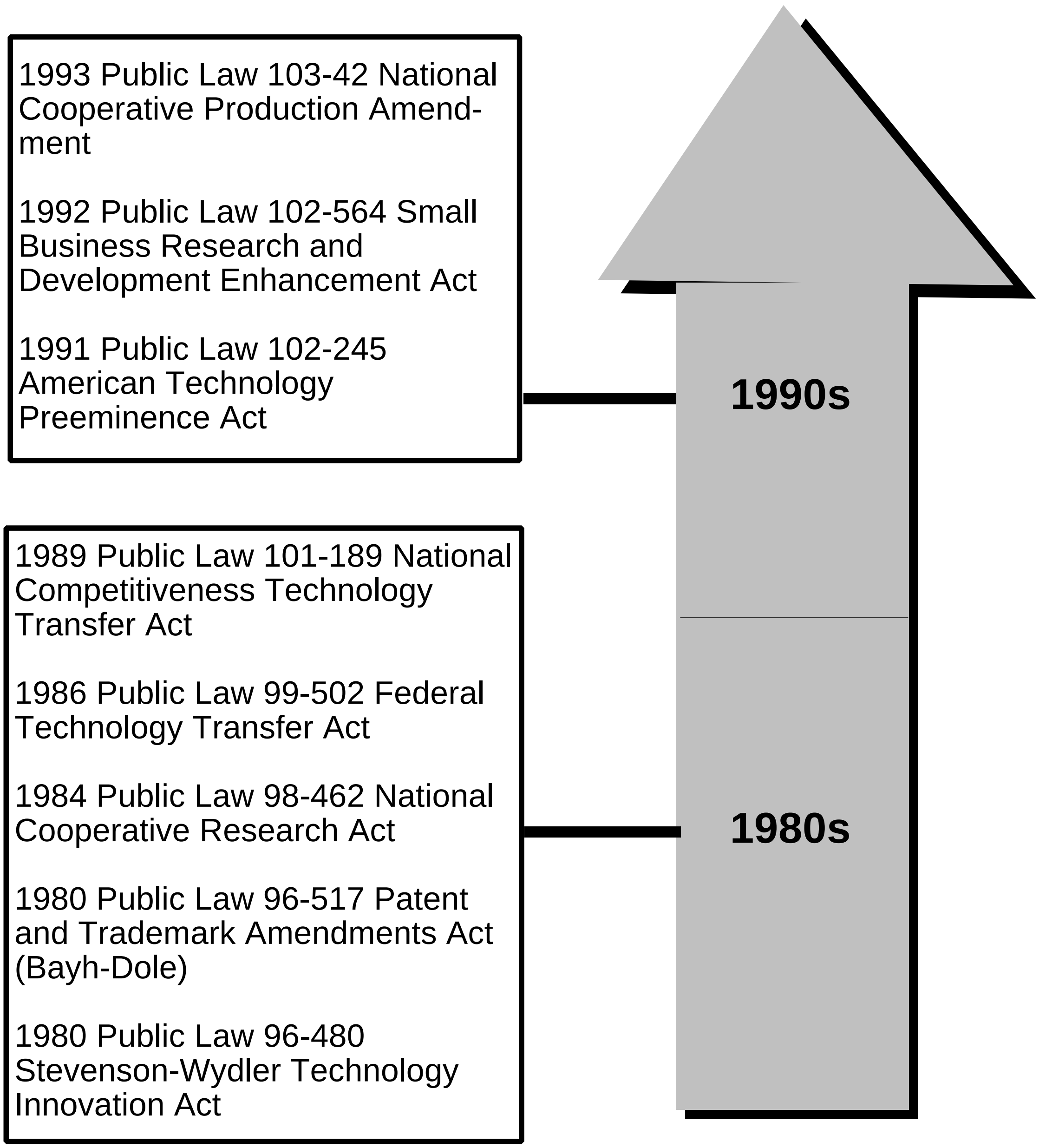
This recent administration's increased emphasis on technology transfer and government-industry cooperation has been a continuation of legislative initiatives enacted since the 1980s (figure 1).[2] Relevant statutes include the Stevenson-Wydler Technology Innovation Act (1980), which formally made technology transfer a policy of the Federal Government by mandating that 0.5 percent of each national lab budget be spent on technology transfer;[3] the Patent and Trademark Amendments Act (1980), which gave Federal agencies authority to grant licenses to small businesses and nonprofit organizations (including universities) for inventions made at government- and contractor-operated national labs; and the National Cooperative Research Act (1984), which limited the potential application of antitrust laws in order to foster cooperative research among companies.

[1](...continued)
Commerce, *Emerging Technologies: A Survey of Technical and Economic Opportunities* (Washington, DC: U.S. Department of Commerce), Spring 1990; and The Council on Competitiveness, *Gaining New Ground: Technology Priorities for America's Future* (Washington, DC: The Council on Competitiveness), Mar. 1991.

[2]Committee on Science, Engineering, and Public Policy, *The Government Role in Civilian Technology: Building a New Alliance* (Washington, DC: National Academy Press, 1992).

[3] In addition, Offices of Research and Technology Applications (information offices on laboratory products and services) were established in every national lab.

Figure 1
Legislative initiatives promoting technology transfer enacted since the 1980s



Source: Compiled by USITC staff.

More recently, the Federal Technology Transfer Act (1986) amended the Stevenson-Wydler Act, delegating authority to national labs to enter into cooperative research and development agreements (CRADAs) with non-Federal parties (i.e., private businesses). The National Competitiveness Technology Transfer Act (1989) included technology transfer in the mission of the national labs. Further, the American Technology Preeminence Act (1991) aimed to strengthen programs promoting U.S. economic competitiveness at the various agencies. The Small Business Technology Transfer Act (1992) outlined specific rules for technology transfer. And finally, the National Cooperative Production Amendment (1993) amended the National Cooperative Research Act, further modifying antitrust laws to increase research joint ventures in the private sector. In addition, many Federal agencies have specific legislation governing technology transfer.

Framework for Government Involvement

As part of the U.S. Government's new focus on technology, in 1993 the Clinton administration enunciated a new emphasis on public/private cooperation in technology development.[4] Federal agencies are to facilitate civil technology development in precommercial areas, to foster cooperative efforts between the Government and the private sector, and to transfer new technologies developed in Government facilities to all sectors of the economy. These changes are expected to increase the ability of private industry to leverage its R&D expenditures with Federal monies as well as to gain access to the vast array of technology already under development at the national labs. Moreover, the U.S. Government will be able to leverage taxpayer funding of the national labs with private R&D expenditures.

This change in emphasis was formally stated in *Advanced Materials and Processing: The Fiscal Year 1993 Program* (AMPP), a supplement to the President's budget request for fiscal year 1993. The AMPP provides a framework to promote interaction and cooperation among all players in the technology development field (government, industry, and universities) and to facilitate the progression from technology innovation to application. One stated goal of the AMPP is to improve the performance and manufacture of materials to enhance the quality of life, security, industrial productivity, and economic growth in the United States.[5] Agencies participating in the AMPP and significantly involved in materials technology include the Department of Commerce, Department of Defense, Department of Energy, Department of the Interior, Department of Transportation, Environmental Protection Agency, Department of Health and Human Services, NASA, National Science Foundation, and Department of Agriculture. Table 1 lists AMPP funding levels for these agencies.

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[4]Clinton, William J., and Albert Gore, Jr., *Technology for America's Economic Growth, A New Direction to Build Economic Strength* (Washington, DC, Feb. 22, 1993).

[5]Office of Science and Technology Policy, *Advanced Materials and Processing: The Fiscal Year 1994 Federal Program* (Washington, DC: Office of Science and Technology Policy, July 1993), p. 6.

Table 1
Funding levels under the Advanced Materials Processing Program, 1992-94

(*Million dollars*)

Agency	1992	1993	1994
Department of Agriculture	36.3	37.4	45.8
Department of Commerce	2.6	48.4	56.7
Department of Defense[1]	530.9	557.7	421.7
Department of Energy[1]	862.5	914.0	941.5
Department of the Interior	5.2	24.9	21.5
Department of Transportation	1.0	14.9	12.7
Environmental Protection Agency	0.5	4.5	4.5
Health and Human Services	79.6	85.9	92.9
National Aeronautics and Space Administration	76.3	102.8	131.1
National Science Foundation	265.6	303.6	328.0
Total	1,933.5	2,094.1	2,056.4

[1] This figure does not include classified research and development activities.

Note.--Data for 1992 are actual expenditures, 1993 are congressional appropriations, and 1994 are the President's budget request.

Source: Office of Science and Technology Policy, *Advanced Materials and Processing: The Fiscal Year 1994 Federal Program* (Washington: Office of Science and Technology Policy, 1993), p. 13.

During 1994, the U.S. Government allocated over $75 billion in R&D expenditures.[6] Of the total budget, approximately 60 percent was allocated to military and defense technology projects, with the remaining 40 percent directed at civilian or commercial projects. However, with the shifting focus to economic competitiveness, the administration has stated that it would like to see this ratio reach 50-50 by 1998.[7] To reach this goal, agencies are increasing their outreach programs to the private sector and developing a wide range of mechanisms to facilitate public-private partnerships.

The national labs affiliated with the various Federal agencies offer private industry R&D projects a source of funding, research, and technical advice. There are over 700 national labs, which spend $35 billion to $40 billion annually on research and development efforts, with generally 5 to 10 percent spent in R&D partnerships with industry.[8] The administration has stated that this portion should be increased to 10 to 20 percent of the budget of each laboratory.[9]

A wide range of mechanisms are available to facilitate public-private partnerships. They include personnel exchanges, data exchange agreements, use of specialized facilities, cost-shared procurement, cooperative agreements, patent and software licensing,

[6]Gore, Albert, Jr., "*From Red Tape to Results: Creating a Government that Works Better & Costs Less*," Report of the National Science Foundation and Office of Science and Technology Policy (Washington, DC: Office of the Vice President), Sept. 1993, p. 5.

[7]Clinton, William J., and Albert Gore, Jr., *Technology for America's Economic Growth, A New Direction to Build Economic Strength* (Washington, DC, Feb. 22, 1993), p. 8.

[8]According to the Stevenson-Wydler Act (1980), 0.5 percent of each national lab budget was allocated to technology transfer activities.

[9]Clinton, and Gore, *Technology*, Washington, DC, Feb. 22, 1993, p. 9.

reimbursable work for others, technical assistance, and cooperative research and development agreements.

CRADAs represent one of the main mechanisms for technology transfer from the Federal agencies and nationals labs to the private sector.[10] Under a CRADA, one or more Federal agencies, through its laboratories, may provide personnel, services, facilities, equipment, or other resources (not including funds), with or without reimbursement, to one or more non-Federal parties. In turn, private parties may provide funds, personnel, services, facilities, equipment, or other resources toward the conduct of specified R&D that is consistent with the laboratory missions. CRADAs are designed to limit paperwork requirements and to allow flexible implementation. For example, agencies can streamline procedures or shorten approval times, which can range from a few weeks to over 18 months, and have some discretion in entering any agreement.

Legislation encouraging industry to participate in CRADAs includes an exemption for participating parties from antitrust regulations, thereby allowing large segments of an industry to cooperate in Federally funded research efforts. For example, the Partnership for New Generation Vehicles (PNGV) is an initiative between the U.S. Government and the "Big Three" auto manufacturers (General Motors, Ford, and Chrysler) that focuses on developing a new generation of fuel-efficient vehicles. The Government part of the partnership is an interagency effort headed by the Department of Commerce and includes the Departments of Defense, Energy, and Transportation, the Environmental Protection Agency, NASA, and the National Science Foundation.[11]

In addition, CRADA legislation allows private entities to obtain rights to intellectual property developed within a CRADA while protecting any existing patents a company or lab brings to the project. Moreover, the Federal Technology Transfer Act established royalty sharing for Federal inventions and directed agencies to promote technology transfer via a cash awards incentive program for Federal employees.

As of December 1, 1994, 3,220 CRADAs were signed, partnering private industry with national laboratories.[12] The number of CRADAs has increased dramatically in the last few years. For example, as of January 1, 1993, the Department of Energy had 329 CRADAs with private industry. However, by January 1, 1995, this number had risen to 1,157, with a value of $2.1 billion (of which industry contributions accounted for 57 percent).[13]

Examples of CRADAs in the materials processing area include gel casting and precision aluminum forming. The Oak Ridge National Laboratory has signed several CRADAs involving its gel casting technology, including one with AlliedSignal and another with

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[10]Additional information about CRADAs and other technology transfer mechanisms is available from a number of sources including DOE and DOC, and is summarized in DOE's "Technology Transfer Quick Reference: Technology Transfer Mechanisms."

[11]More detail on the PNGV is available from the Department of Commerce.

[12]Stockdale, Grant, president, Technology Publishing Group, Washington, DC, USITC phone conversation, Jan. 20, 1995.

[13]Department of Energy, Washington, DC.

Ceramic Magnetics.[14] In both cases, the companies are providing design and field testing, while Oak Ridge is tailoring its original process technology to each company's needs.[15] The Lawrence Livermore National Laboratory and Sandia National Laboratories have partnered with the Aluminum Company of America (ALCOA) to jointly advance the state-of-the-art in computational analysis of aluminum-forming processes. This development has the potential to reduce manufacturing costs and improve product quality, both of which can reduce the life cycle costs for a variety of U.S. industrial products.[16]

Agencies are also implementing outreach programs, designed to inform the private sector of what facilities and resources are available. Outreach programs include agency participation in trade shows, conferences, expositions, and professional society meetings. In addition, several agencies, including NASA, the Department of Energy, and the Department of Defense, have established databases to assist industry with problems and provide information about available technology and Federal resources. Table 2 outlines the technology transfer mechanisms used by the various agencies.

Outlook for Future Government Involvement

The National Research Council regards faster commercialization of materials technology as critical to ensure U.S. Government ability to specify and procure advanced military and space systems, to obtain maximum benefits from available materials technologies at costs equivalent to those in commercial production, to enhance the competitiveness of the U.S. industries, and to extend U.S. technological leadership.[17]

The commercialization process can be divided into several phases or stages, including basic research/idea development; exploratory development or initial concept validation; pilot development; prototype development; application/demonstration; and commercial use.[18] U.S. Government funding generally is limited to the early stages because of legal constraints and the traditional government policy of limiting involvement in business economic-decision making (figure 2).

The new Agreement on Subsidies and Countervailing Measures in the Uruguay Round Agreement (URA), establishing the World Trade Organization (WTO), addresses generally the subject of subsidies and the remedies that WTO members may take

[14]Gel casting involves creating a gel with ceramic material that is then able to be poured into a mold and hardened. This process allows more intricate parts to be made and has the potential to reduce manufacturing costs of forming ceramic parts.

[15]USITC phone interview, representative of Oak Ridge National Laboratory, Oak Ridge, TN.

[16]Lawrence Livermore National Laboratory, *Industrial Partnerships-The Dual Benefit Story*, Livermore, CA, Oct. 1994.

[17]National Research Council, *Commercialization of New Materials for a Global Economy* (Washington, DC: National Academy Press, 1993), p. 21.

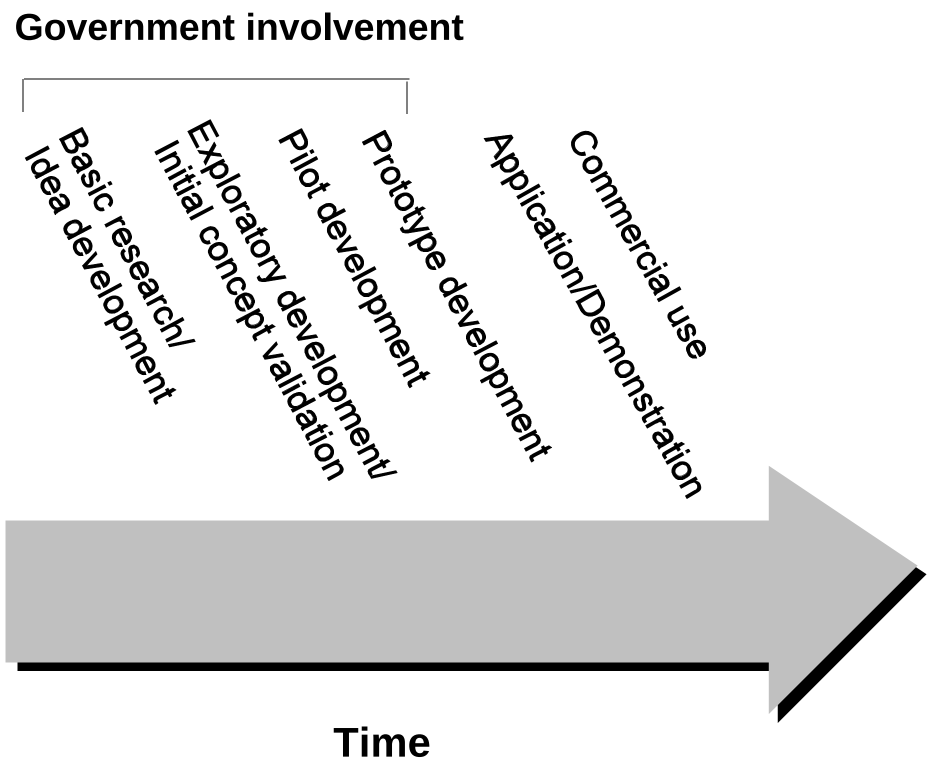
[18]National Materials Advisory Board, "Commercialization of New Materials for a Global Economy" (Washington, DC: National Research Council), 1993, p. 15; and John T. Schofield, Chairman and CEO of Thermatix, Inc., U.S. Department of Energy, background paper on Understanding "Valley of Death" issues in Federal R&D (Washington, DC: U.S. Department of Energy), Dec. 5, 1994.

Table 2
Agency involvement in materials processing R&D and technology transfer

Agency	*Processing Research and Technology Transfer*
Department of Commerce, National Institute of Science & Technology (NIST)	**Carried out in 7 labs, particularly the Materials Science and Engineering Lab (MSEL); MSEL has major programs in advanced ceramics, advanced heat engines, and polymermatrix composites. NIST promotes technology transfer via CRADAs and outreach activities.**
Department of Defense (DOD)	**Carried out by the Army, Navy, Air Force, and the Advance Research Projects Agency (ARPA). Research efforts are geared to providing future military systems, however, dual-use applications of defense technologies are encouraged. Technology transfer occurs primarily through the hundreds of DOD-supported university research centers.**
Department of Energy (DOE)	**DOE has the largest program among the 10 agencies, ranging from fundamental research to demonstrations of materials fabrication technologies. Technology transfer is facilitated through direct grants, research collaboration, industrial use of DOE facilities, CRADAs, and outreach activities.**
Department of the Interior (DOI)	**Materials R&D is carried out through the Bureau of Mines (BOM) and is focused on environmental and conservation issues related to engineered and commodity materials. Technology is transferred via CRADAs and Memorandums of Understanding (MOU) in addition to outreach programs.**
Department of Transportation (DOT)	**Materials R&D is supported by the Coast Guard, the Federal Aviation Administration, and the Federal Highway Administration. Projects are usually directed at transportation technologies. Nearly all DOT research is publicly disseminated because DOT must coordinate its activities with state and local governments and the transportation industry. In addition, DOT provides opportunities for joint research activities with industry and universities.**
Environmental Protection Agency (EPA)	**Research efforts in materials and materials processing are directed at improving the environment. Research is carried out by the Risk Reduction Engineering Laboratory (RREL) and the Air and Energy Engineering Research Laboratory (AEERL). Both labs work closely with industry, via CRADAs and licensing agreements.**
Department of Health and Human Services (HHS)	**Materials R&D is carried out by 12 units of the National Institutes of Health (NIH) and by the Food and Drug Administration (FDA), focusing on improving biomaterials and bimolecular materials for use in medical device implants. HHS maintains extensive communication with academia and industry as most NIH research is conducted by outside investigators via grants and contracts.**
National Aeronautics and Space Administration (NASA)	**NASA materials research revolves around developing advanced materials and processes for use in engines and airframe structures. Technology is mainly transferred through close cooperation with the U.S. aerospace industry. In addition, there is the Technology Utilization Program which fosters liaisons with industry and produces publications. Finally, NASA reaches out to universities and small businesses through its network of 10 university-affiliated Industrial Application Centers and 12 Centers for the Commercial Development of Space.**
National Science Foundation (NSF)	**NSF materials research centers on the synthesis of new materials, fundamental principles, novel and creative approaches to materials processing, applying basic knowledge to materials, and training future scientists and engineers in materials research and processing. NSF transfers technology via projects at multi-user research facilities, which reach out to industry and national labs to optimize the application of new fundamental knowledge. In addition, NSF promotes technology transfer by training students for careers in materials science.**
Department of Agriculture (USDA)	**Materials research at USDA is carried out by the Forest Service, the Agricultural Research Service, and the Cooperative State Research Service. Research activities focus on the use of renewable, nonfood agricultural materials and their derivatives in industrial processes and products. USDA transfers technology primarily through CRADAs and by working directly with the private sector at the point of commercialization of industrial uses of agricultural products, with emphasis on advanced materials.**

Source: Office of Science and Technology Policy, *Advanced Materials & Processing: The Fiscal Year 1994 Federal Program*, Washington, DC, July 1993.

Figure 2
Stages of commercialization and government involvement



Source: National Materials Advisory Board and John T. Schonfield, Chairman and CEO of Thermatix, Inc.

against foreign subsidization.[19] For example, under the General Agreement on Trade and Tariffs (GATT), the U.S. Government can fund only up to 50 percent of the costs of specific precompetitive development activity, defined as "the translation of industrial research findings into a plan, blueprint or design for new, modified or improved products, processes or services whether intended for sale or use, including the creation of a first prototype that would not be capable of commercial use."[20] In other words, Federal funds can be used for first prototypes or models that cannot be used commercially, but not specific direct funding of commercial-ready applications. However, due to such legal constraints, government involvement usually stops short of direct commercialization assistance. Technology is transferred and/or manufacturing problems are ironed out, but the private sector bears responsibility for finding capital, researching markets, developing business plans, advertising, and sales.

Despite these restrictions, government funding in precommercial stages can benefit private industry and impact the U.S. economy as a whole, through expansion and dissemination of basic science and knowledge, job creation, increased industrial output, and improvements in energy efficiency and the environment. Congress and policy makers are increasingly holding agencies to these goals, leading many agencies to develop measures to track the benefits of technology transfer. For example, a recent study looked at the economic benefits derived from many of the Department of Energy's award-winning technologies developed from 1989-1992. The study found that, of the 113 technologies surveyed, 46 percent had transferred technology to the private sector; 10 percent resulted in a new company being formed; 52 percent have created jobs; 22 percent have saved jobs; 12-24 percent have resulted in notable energy savings; and 20-40 percent have resulted in notable environmental improvements.[21]

However, policy makers, academia, and the private sector continue to debate the proper role of government in R&D and the business arena, and the best way to achieve government goals.[22] Proponents of involvement contend that without increased government funding of technology development, within constraints of the subsidies agreement of the URA, U.S. industries are at a disadvantage and thus less competitive globally. A contrasting view is that investment in and development of new technologies should be driven by free market forces, and that government involvement in the process may distort these decisions.[23] Within the private sector, there are still concerns regarding confidentiality and intellectual property rights (IPR) issues, the considerable time commitment required to determine which labs and facilities have the capabilities and the desire to work with them, and the often complex process of

[19]The agreement for the first time defines the term *subsidy* and creates three categories of subsidies: (1) prohibited subsidies; (2) subsidies that may be challenged in WTO dispute settlement proceedings and domestically countervailed if they cause adverse trade effects; and (3) nonactionable and noncountervailing subsidies, if they are structured according to criteria intended to limit their potential for causing trade distortions.

[20]Agreement on Subsidies and Countervailing Measures, Final Agreement Embodying the Results of the Uruguay Round of Multilateral Trade Negotiations, part IV, article 8, 1994.

[21]Department of Energy, "Our Commitment to Change: A Year of Innovation in Technology Partnerships" (Washington, DC: Department of Energy), Sept. 1994, p. 13.

[22]Linda Cohen, "Political Economy and Public Policy: When Can Government Subsidize Research Joint Ventures? Politics, Economics, and Limits to Technology Policy," *American Economic Review*, Vol. 84, Issue 2, May 1994, pp. 159-163.

[23]Larry Reynolds, "Technology Policy Breeds New Era of Cooperation," *Management Review*, Jun. 1993, pp. 50-52.

establishing a partnership. Any further redefinition of the government's role in developing new materials and materials processing technologies also will be subject to limitations outlined in the WTO and regional trade agreements.

The remaining articles in this staff research study discuss specific new manufacturing processes for materials and advanced materials that can result from such processes. To the extent available, information is provided on the status of global competitors, and the role government initiatives and funding (including foreign government programs) have played in the technology development process.

Recent Developments

The administration has identified investment in science and technology as an important priority,[24] and advanced materials and processing technologies has been one of several elements of this policy focus. However, there have been changes in the Government's materials research and development (R&D) policy over the last 2 years, as other science and technology priorities, such as information technology, space exploration, and health research, emerged to dominate the national R&D agenda. The Government's previous emphasis on materials R&D has been affected by the policy re-direction manifested in two forms: the elimination of a policy coordination committee and slightly reduced funding to certain agencies carrying out materials R&D. However, the agency carrying the largest budget allocation for materials R&D, the Department of Energy (DOE), actually received a budget increase from FY 1994 to FY 1996, suggesting that existing priorities have not been altered significantly.

In order to coordinate science, space, and technology policies across the Federal Government, President Clinton established the cabinet-level National Science and Technology Council (NSTC) by Executive Order on November 23, 1993. A stated objective of the NSTC was the "establishment of clear national goals for Federal science and technology investments in areas ranging from information technologies and health research, to improving transportation systems and strengthening fundamental research."[25] The importance of materials R&D was recognized as the NSTC established the Materials Technology (MatTec) Subcommittee to coordinate Federal policy on materials development. The MatTec Subcommittee, which consisted of representatives from nine

[24]Supplement, Budget of the U.S. Government, FY 1998: Chapter 4, "Promoting Research"; and Supplement, Budget of the U.S. Government, FY 1997: Chapter 10, "Promoting Science and Technology," found at Internet address http://cher.eda.doc.gov/BudgetFY97/supp10.html, retrieved on Nov. 18, 1997; and NSTC Executive Secretariat, "Accomplishments of the National Science and Technology Council (NSTC): 1996," found at Internet address http://www.whitehouse.gov.WH/ EOP/OSTP/NSTC/html/1996, retrieved on Nov. 18, 1997.

[25]*1995 The Federal Research and Development Program in Materials Science and Technology, A Report by the Materials Technology Subcommittee, Committee on Civilian Industrial Technology, National Science and Technology Council,* Executive Office of the President, Office of Science and Technology Policy, Dec. 1995, p. ii.

Federal agencies,[26] was overseen by the NSTC Committee on Civilian Industrial Technology (CCIT).[27] However, the NSTC eliminated the CCIT in early 1997. For a time, MatTec's activities were overseen by the Committee on Technical Innovation. However, there is currently a reorganization taking place at NSTC, and the future status of the MatTec subcommittee is unclear.[28]

Significant Agency Activities

The Department of Energy (DOE) continues to represent about 80 percent of the Government's total materials R&D expenditures.[29] Although funding for materials R&D has been declining at a few agencies, DOE's budget for materials R&D has actually increased, from $623.7 million in FY 1994 to $726.9 million in FY 1996.[30] The Defense Department has the second-largest materials R&D budget; however, its allocation has declined steadily since FY 1993, from $563 million to $449 million in FY 1997.[31] The National Science Foundation, which carries the third-largest budget, increased from $283 million in FY 1994 to $293 million in FY 1997.[32]

DOE supports the largest Federal materials R&D program of any agency, and industry collaboration is a key element to its research. For example, DOE has played a major role in the coordination of federal R&D addressing lightweight structural material for automobiles working through both the Partnership for a New Generation of Vehicles (PNGV) and the industry-led U.S. Automotive Materials Partnership. In addition, through its Industries of the Future strategy, DOE's Office of Industrial Technologies (OIT) has identified seven industries for which it is seeking to assist in development of materials that will improve process efficiency and/or products of increased value.[33]

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[26]These agencies include the Department of Commerce (DOC); Department of Defense (DOD); Department of Energy (DOE); Department of the Interior (DOI); Department of Transportation (DOT); Department of Health and Human Services (HHS); National Aeronautics and Space Administration (NASA); National Science Foundation (NSF), and the U.S. Department of Agriculture (USDA). The Environmental Protection Agency, which previously reported to the CCIT, now reports its activities through the NSTC Committee on Environment and Natural Resources.

[27]This was one of several committees that was established to foster improved Government-industry cooperation and facilitate technology transfer and commercialization of new technologies. The others are Committee on Health, Safety, and Food; Committee on Fundamental Science; Committee on Computing, Information, and Communications; Committee on Environment and Natural Resources; Committee on Education and Training; Committee on Transportation; Committee on National Security; Committee on International Science, Engineering, and Technology.

[28]Telephone conversation with Donald Hillebrand, Executive Office of the President, Nov. 21, 1997.

[29]Samuel Schneider, NIST, Executive Secretary, MatTec Subcommittee, Dec. 8, 1997.

[30]Data provided by Dr. Toni Maréchaux, DOE, Interim Chairman, MatTec Subcommittee, Dec. 9, 1997.

[31]Telephone conversation with Andy Culbertson, DOD, Dec. 1, 1997.

[32]Electronic mail message from W. Lance Haworth, National Science Foundation, Dec. 16, 1997.

[33]The seven industries are petroleum refining, chemicals, pulp and paper, steel, aluminum, foundries, and glass.

Other areas of focus include projects to develop high-strength, continuous-fiber ceramic composites capable of operating at high temperatures, novel materials and associated processing techniques for advanced turbine systems, and corrosion- and oxidation-resistant intermetallic alloys.

The National Institute for Standards and Technology (NIST) of DOC and the Defense Department both manage programs specifically geared to materials R&D. The mandate of NIST is to promote economic growth by working with industry to develop and apply technology, measurements, and standards.[34] One of its eight laboratories, the Materials Science and Engineering Laboratory (MSEL), is devoted entirely to materials R&D; its director chairs MatTec. The MSEL carries out about 80 percent of NIST materials R&D.[35]

NIST manages two major complementary programs that support cost-shared industry R&D in key topic areas, including materials. The Advanced Technology Program (ATP) is a cost-shared program that supports multiyear development of a broad spectrum of high-risk, potentially high-payoff commercial technologies, including advanced materials and material-dependent systems.[36] Recent program developments have focused on advanced ceramics and high-performance polymer-matrix composites, advanced processing of materials, and materials characterization; 15 current projects focus on manufacturing of polymer-matrix composites for large, commercial structural applications, such as automobiles and bridges. New focus areas for the ATP include materials processing for heavy industry.[37]

The other program managed by NIST is the Materials Extension Partnership (MEP), which emphasizes NIST role in transferring developed technologies to small- and medium-sized businesses through Government-industry partnerships and extension services. NIST's 5-year technical plan calls for narrowing in on new, interdisciplinary topics with "high potential for significant impact," including: materials theory, modeling, and computation; coatings and interfaces; metal-matrix composites; magnetic materials; photonic materials; nanostructured materials; and precision machining of advanced materials.[38]

Joint industry-Government cooperation plays a significant role in DOD materials development programs, particularly through the Technology Reinvestment Program (TRP), which is based at DOD Advanced Research Projects Agency (ARPA). The TRP promotes development and deployment of new dual-use technologies for both civilian and military applications. The program stresses cost-shared partnerships among government laboratories, industry, and universities. TRP is a joint effort of six agencies (DOC, DOD, DOE, DOT, NASA, and NSF) and is the largest multi-agency

[34]U.S. Department of Commerce, Technology Administration, "Guide to NIST," p. 2.

[35]Other NIST labs involved in materials R&D are the Electronics and Electrical Engineering Laboratory (EEEL), the Chemical Science and Technology Laboratory (CSTL), Building and Fire Research Laboratory (BFRL), Physics Laboratory (PL), and Computing and Applied Mathematics Laboratory (CAML).

[36]U.S. Department of Commerce, "Guide to NIST," p. 10.

[37]*1995 Federal Research and Development Program in Materials Science and Technology*, p. 46.

[38]Ibid.

technology development program ever conducted by the Federal Government.[39] Recent areas of focus include materials processing improvements. For example, ARPA is seeking to develop affordable manufacturing and fabrication techniques for costly advanced structural materials, especially composites.[40]

Legislative Initiatives

With regard to legislative initiatives, The National Technology Transfer and Advancement Act of 1995 (Public Law 104-113) was enacted into law during the 104th Congress. This law amends the Stevenson-Wydler Technology Innovation Act of 1980 and the Federal Technology Transfer Act of 1986, and is intended to improve U.S. competitiveness by speeding commercialization of inventions developed through collaborative agreements between government and industry. It specifically seeks to promote partnership ventures with Federal laboratories and the private sector and creates incentive in laboratory personnel for new inventions.[41]

Following enactment of this law, Rep. Constance Morella (R-MD) introduced the Technology Transfer Commercialization Act of 1997 (H.R. 2544) in September 1997. The goal of H.R. 2544 is to remove the legal obstacles to effectively license Federally-owned inventions. The bill seeks to provide agencies with two new tools for effectively commercializing federally-owned technologies--either licensing them as stand-alone inventions, or including them as part of a larger package under a CRADA.[42] Also, H.R. 2544 removes language requiring public notification procedures in the current law, recognizing that speedy time-to-market commercialization is a critical factor for the successful introduction of new products in a competitive marketplace.[43] The bill has been referred to the Intellectual Property Subcommittee of the Judiciary Committee and the Technology Subcommittee of the Science Committee for consideration; hearings may follow in early 1998.[44]

[39]Ibid., p. 15.

[40]Ibid, p. 66.

[41]Hon. Constance A. Morella, Extension of Remarks in the House of Representatives upon introduction of H.R. 2544, The Technology Transfer Commercialization Act of 1997, Sept. 25, 1997, found at http://thomas.loc.gov/cgi-bin/query/D?r105:1:./temp/~r105BPrR; retrieved on Nov. 19, 1997.

[42]HR 2544, Technology Transfer Commercialization Act of 1997, introduced in the House of Representatives, Sept. 27, 1997, found at http://www.fedlabs.org/flc/ftpsrc/h2544.htm; retrieved on Nov. 14, 1997.

[43]Ibid.

[44]Telephone conversation with aide to Congresswoman Constance Morella (R-MD), who as Chair of the House Science Committee's Technology Subcommittee, introduced the bill, as well as P.L. 104-113, Nov. 19, 1997.

Alternative Materials in the U.S. Automotive Industry Promote Development of Joining and Bonding Technology

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Joining and bonding technologies have changed as industrial applications for nontraditional materials have expanded. For example, the auto industry has increased its consumption of lightweight materials over the past 20 years as fuel efficiency standards increased and as auto makers responded by producing lighter cars. As the polymer composite and aluminum content of automobiles increased, so did the need for specialized joining technologies. This article examines several joining technologies currently under development that may offer auto makers a competitive advantage as alternative materials make inroads into the auto industry.

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The U.S. automobile industry, the world's single largest car and truck producer, accounted for approximately 21 percent of global production in 1996.[1] During that same year, the Big Three U.S. auto producers captured 35 percent of worldwide sales,[2] largely because of their effective response to market and regulatory demands. Consumer expectations of higher quality, increasingly stringent environmental standards, and heightened safety awareness have raised the intensity level of competition in the market. U.S. producers have responded by reducing costs and improving productivity (often through changes in manufacturing processes).[3]

Auto producers employ many strategies to maintain their competitive position. One strategy designed to meet environmental regulations is the substitution of lightweight materials for steel and other metals.[4] The U.S. automotive industry has increased the polymeric materials[5]

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[1] *Automotive News, 1997 Market Data Book*, May 23, 1997, various pages.

[2] Derived from sales figures in *Ward's Automotive Yearbook, 1997*, p. 126; and *Automotive News*, p. 24.

[3] U.S. Department of Commerce, Motor Vehicle Division, "Drivers of the U.S. Automotive Industry," prepared by Albert T. Warner, director, Motor Vehicle Division, Feb. 27, 1996, found at http://www.ita.doc.gov/ industry/basic/hondsp.html, retrieved July 8, 1997.

[4] For an analysis of the pros and cons of steel versus aluminum and plastic in automobile manufacturing, see Frank R. Field III, and Joel P. Clark, "A Practical Road to Lightweight Cars," *MIT Technology Review*, Jan. 1997, found at http://web.mit.edu/techreview/

(continued...)

and aluminum content of a typical family vehicle (table 1), particularly in applications for nonload-bearing parts, e.g. plastic hoods, roofs, and side panels; and aluminum wheels, brakes, air conditioning compressors, heat exchanger, radiators and engine blocks.[6] Traditionally, these parts have been made of steel.

Table 1
A typical family vehicle, material content and total weight

Material/ year	1976 Pounds	1976 Percent of total	1986 Pounds	1986 Percent of total	1996 Pounds	1996 Percent of total	1976-1996 percent change
Iron and steel	2,785.0	74.1	2,190.0	69.0	1,890.0	61.0	-32.0
Polymeric materials	325.0	8.6	433.0	13.7	642.0	21.0	97.5
Aluminum	85.5	2.3	139.5	4.4	257.0	8.3	200.0
All other	564.5	15.0	407.5	12.9	301.0	9.7	-47.0
Total vehicle weight	3,760.0	100.0	3,170.0	100.0	3,090.1	100.0	18.0

Source: *Recent trends in automobile recycling: an energy and economic assessment*, ORNL/TM/12628, March 1996.

As a means to limit emissions of carbon dioxide, and to meet corporate average fuel efficiency (CAFE) standards,[7] U.S. automobile manufacturers reduced the weight of the steel portion of the average passenger car by 21 percent between 1976 and 1986. The overall weight of the average car declined by 18 percent between 1976 and 1996. However, nearly all of the reduction was achieved by 1986, when auto makers were producing fleets in compliance with CAFE standards (table 1). Since then, the weight of the average car has remained stable, mainly because of the combined effect of unchanging CAFE standards and increased consumer demand for large accessory-laden vehicles.

[4](...continued)
www/articles/jan97/clark.html, retrieved June 17, 1997.

[5]Polymeric materials include all plastics and polymer composites. Plastic is a nontechnical term for "resin system," and polymer composites are resin systems that are reinforced with a fibrous material in order to enhance mechanical and physical properties. Most auto parts that do not have a load-bearing function are made of resin systems although the load-bearing parts must be strong and are made with polymer composites. This article is concerned with the development of joining and bonding methods for polymer composite load-bearing structures for automobiles, such as frames. The term "plastic" will be used to refer to auto parts that are nonload-bearing (such as dashboards) and are made of nonreinforced resin systems.

[6]For details on the use of aluminum in the automobile industry see USITC, "Aluminum Product Development and the Automotive Industry," *Industry,Trade, and Technology Review*, USITC, May 1994, pp. 17-25.

[7]CAFE standards were established in 1975 by the Energy Policy and Conservation Act. According to these standards, automakers are required to meet fuel economy ratings for each fleet of passenger cars they produce. Since 1986, the fleet average has been 27.5 miles per gallon, although industry officials anticipate a higher standard during the next several years. See the data found at http://www.ita.doc.gov/industry/basic/cafe/html, after June 23, 1997.

Since a 25-percent decrease in vehicle weight could save 13 percent in gasoline consumption and reduce carbon dioxide emissions by 101 million tons per year,[8] manufacturers are experimenting with further weight reductions by using alternative materials for auto parts made of steel and other traditional metals. Alternative material candidates include polymer composites reinforced with glass (25-35 percent of the weight of steel), carbon fiber-reinforced polymer composites (50-65 percent of the weight of steel), and aluminum (one-half of the weight of steel).[9] Although CAFE standards have not changed in recent years, auto manufacturers are developing process technology for automobile production with lightweight materials.[10] Manufacturers are more likely to produce a vehicle with improved fuel economy once such technology becomes widely available. A higher CAFE standard would push the development of this process technology and lead manufacturers to increase their use of lightweight materials.

The adoption of alternative materials can also reduce manufacturing costs. Material properties (such as the temperature at which a material becomes malleable) are key determinants of the processing and assembly methods, which directly effect productivity rate and cost. For example, molded polymer composite auto parts cost less to manufacture than stamped steel parts because complex shapes can be formed in one large mold. The process requires less joining, bonding, and machining. Manufacturing costs are further reduced because less labor is required to complete the process. The material switch may also affect the speed of production because less time is needed to assemble consolidated parts.

Automakers are investing in research of joining and bonding technologies for alternative materials. The lack of fully developed joining technologies is considered a barrier to the utilization of advanced lightweight materials to form automotive structures.[11] Traditional means of joining steel parts--welding, brazing, and soldering--do not effectively bond polymer composites, and adjustments to welding and brazing must be made to successfully join aluminum. Mechanical fasteners continue to be a viable joining option, but they are typically used in conjunction with another method. For example, adhesively joined polymer composites may be mechanically fastened (either permanently or temporarily while the adhesive bond sets). The ideal joining methods would have the capacity to bond both similar and dissimilar materials, such as aluminum to steel, or polymer composite to aluminum. One well-known consortium conducting research on joining and bonding polymeric composites and aluminum auto parts is the Partnership for a New Generation of Vehicles (PNGV), highlighted in the text box.

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[8] "Transportation Technologies," found at http:/www.ornl.gov/ornl/energy_Efficiency/trans.html#ctp, retrieved Aug. 13, 1997.

[9] National Materials Advisory Board, *Materials Research Agenda for the Automotive and Aircraft Industries*, NMAB-468 (Washington, DC: National Academy Press, 1993), p. 34.

[10] Toni Marechaux, U.S. Department of Energy, Office of Transportation Technologies, USITC staff interview, June 1997.

[11] "Adhesive Bonding Technologies for Automotive Structural Components," found at http://www.ornl.gov/ orcmt/capabilities/dtin384.html, retrieved June 16, 1997.

Partnership for a New Generation of Vehicles (PNGV)

Research on joining technology for automobile manufacturing is sponsored by private and public collaboration, through the PNGV. The partnership was founded in 1993 between the U.S. Government and the Big Three U.S. car makers to develop the automobile of the future. Each PNGV activity contributes to one of the three goals that guide the program:

- improve U.S. competitiveness in automobile manufacturing
- develop and apply new innovations to conventional vehicles
- develop a vehicle with up to three times the fuel economy of conventional mid-sized sedans while maintaining current performance, safety standards, and cost of ownership

The PNGV strategy to reach the fuel economy goal is the reduction of vehicle weight. The goal is supported by a host of research projects on aluminum and polymer composites conducted in the national research facilities and Big Three laboratories. Materials research, including the development of joining technologies for alternative materials encourages progress toward this objective.

The 1996 PNGV report hailed several research projects on joining methods 'significant technical accomplishments.' A project on *adhesive bonding technologies for automotive structural components* was successful in creating standardized test methods to analyze the durability of bonded joints. Also, the bonding of aluminum to composites and a material surface treating method to improve a bond was addressed. The latter will soon be patented. A project on aluminum laser-welding led to the development of a computer controlled process monitor. No joining technology developed under the PNGV currently is used in the mass production of automobiles.

Ultra-light Steel Autobody (ULSAB) program

The steel industry has mobilized to maintain one of its largest markets. The ULSAB program is a international project initiated by the automotive industry (in this case European) and the steel industry to develop a lightweight steel autobody structure. Its members include 35 steel makers from 18 countries. The ULSAB has addressed the automobile industry's need to reduce the average vehicle weight by using a computer model to design a high-strength steel body and parts.

Auto/Steel Partnership and European Aluminum Association

The Auto/Steel Partnership is a consortium of the U.S. Big Three vehicle manufacturers and major U.S. and Canadian integrated steel mills. Twelve task forces conduct precompetitive research on standardization, cost-reduction, and design issues. Three of the task groups research welding technology and standards. The European Aluminum Association is also active in promoting the aluminum content in European-made automobiles.

Joining and Bonding

A portion of the research and development (R&D) on the future generation of vehicles is focused on surmounting the difficulties associated with bonding polymer composites, aluminum, and steel. More specifically, R&D is underway on less costly and quicker assembly and processing methods (relative to traditional materials) for joining alternative materials.[12] Research in this area is critical to support the application of alternative materials in the automotive industry.[13] The joining technologies described below show promise in facilitating the manufacture and adoption of structural auto parts composed of polymer composites and aluminum.

Although research on new joining technologies is underway, these methods are not yet commercialized. The ability to predict the behavior of a joint is stalled to a large extent by the lack of reliable nondestructive testing methods. Once reliable testing methods are developed and the technology produces satisfactory results, one less obstacle will exist for auto manufacturers who want to make composite and aluminum auto parts. The degree to which the joining and bonding methods described below are adopted can become known only as the auto industry gains greater experience with their application.

Adhesive Bonding

Adhesive bonding is the primary method for joining polymer composites, although metals will also bond with adhesives. The auto industry consumption of adhesives already has been increasing. Plastic has become the dominant material for interior auto parts. The change in bonding technology lowered production costs as the manufacturing process was streamlined and required fewer mechanical fasteners.[14] Adhesive bonds are stronger due to the wider distribution of load at the joint, unlike mechanical fasteners that are stressed at a single point. Auto manufacturers have greater design flexibility with adhesive bonds that have a smooth joint surface. No universal adhesive exists; an adhesive formula is chosen based on the properties of the substrate, the function of the joint, and the environmental conditions that the joint must endure. Three of the most common adhesives used to bond composites are epoxies, acrylics, and urethane.[15]

Aside from determining the best adhesive formula for a composite, a producer must have effective assembly and processing technologies to implement the bonding method. The joining technologies described below address two production challenges faced by the consumers of adhesives; lengthy curing time required to set each bond, and the need to treat the substrate surfaces before bonding. Although not technically joining technologies,

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[12]Research goals for the development of assembly and processing technologies such as joining and bonding are outlined in *Partnership for a New Generation of Vehicles, Report of Workshop on Composite Vehicle Structures,* Sept. 28, 1995, Detroit, MI.

[13]The joining techniques described in this report are intended to bond load-bearing structural auto parts made of aluminum or polymer composites. Joining techniques for load-bearing parts require greater strength than techniques for joining interior nonload-bearing auto parts, such as dashboards.

[14]For additional information, see USITC, "Economics and Innovation Spur Shift from Mechanical Fasteners to Adhesives and Sealants in Certain Automotive Applications," *Industry, Trade and Technology Review,* Aug. 1994.

[15]"Joining Composites," *Machine Design*, Sept. 14, 1995, p. 81.

microwave curing treatment and laser ablation address these joining challenges. Technologies that meet these challenges will offer auto producers a greater choice of materials.[16]

Microwave Curing Treatment

The use of microwave radiation to hasten the curing process of polymer composites joined by an adhesive bond has proven to be successful.[17] Adhesives are conventionally cured with thermal heat, but the microwave process can create an adhesive bond of equal strength and performance in much less time.[18] Microwave radiation requires one-third to one-quarter of the time required to cure with thermal heat.[19] Joining by microwave radiation enables greater flexibility in the manufacturing process since, to a degree, a higher microwave power shortens the required curing time. Reduced processing time leads to energy and labor savings,[20] an effect that not only improves the manufacturing process but also facilitates wider adoption of composites and other alternative materials. Research and development of microwave curing is currently sponsored by the U.S. Department of Energy (DOE) at Oak Ridge and Los Alamos National Laboratories.

Diffusion-Enhanced Adhesion (DEA)

The DEA process was developed at the University of Delaware's Center for Composite Materials and was applied to the development of a composite armored tank vehicle capable of withstanding extreme battlefield conditions. The joining process was used to bond a composite gun projection platform to the body of the vehicle.[21] As a polymer composite layer is co-molded to the gun projection platform, a compatible epoxy adhesive is diffused into the composite layer and a bond is formed. A DEA bond is extremely strong and requires less equipment than traditional steel welding. DEA also requires low pressure, low temperature, and minimal assembly, which translates into lower manufacturing costs.[22] Another potentially cost-reducing aspect of DEA is the elimination of the need to pretreat the composite surface.[23] One difficulty associated with DEA is the length of time required to make the bond. The auto industry is not likely to adopt a technology that slows production. The U.S. Department of Defense funded the project, and reportedly there are no commercialized applications of DEA in the auto industry.

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[16]Adhesives have been used in the automotive industry for years as plastics became the materials of choice for nonload-bearing interior parts, in the 1970s and 1980s. For an analysis of the adoption of adhesives in the auto industry see "Economics and Innovation Spur Shift," USITC, *Industry, Trade and Technology Review*, Aug. 1994.

[17]C. David Warren, R. G. Boeman, and F. L. Paulauskas, "Adhesive Bonding of Polymeric Materials for Automotive Applications," prepared for the Proceedings of the 1994 Annual Automotive Technology Development Contractors Coordination Meeting, Dearborn, MI, Oct. 24-27, 1994.

[18]Thomas T. Meek, "Adhesive Bonding via Exposure to Microwave Radiation and Resulting Mechanical Evaluation," prepared for the Spring Materials Research Society (MRS) meeting, Apr. 1996.

[19]Warren, Boeman, and Paulauskas.

[20]Estimates of costs savings associated with microwave curing treatment are not available.

[21]Melissa Larson, "Quality Gets a Boost From Materials Science," *Quality*, Nov. 1996, p. 32.

[22]Ibid.

[23]Estimates of costs savings associated with DEA are not available.

Laser Ablation

Contaminants on a material surface often inhibit the chemical bond of an adhesive so most composite surfaces must be treated prior to bonding. Laser ablation is a surface treatment that removes the contaminants on the composite surface and also some of the resin. This creates a rough surface area as the fibers (carbon or graphite) characteristic of all reinforced polymer composites are exposed. The resin surrounding the exposed fibers interface with the adhesive, creating a joint that is resistant to cracks. The strength of the bond is attributable to the large surface area contact created as the fibers of one part extend across the joint and intermingle with the fibers of the other part. The production rate of structural auto parts treated with laser ablation would likely increase because of the time savings incurred by the elimination of surface treatment.[24] Glass-fibers of reinforced composites are inclined to split from the intensity of the laser beam, producing a weak bond. The technique appears to work better on composites reinforced with carbon-fiber rather than glass-fiber.[25] There is no commercialized technology of this type in the automobile industry, but extensive research sponsored by DOE is conducted at Oak Ridge National Laboratory.[26]

Welding

Welding is one of the low-cost methods for joining aluminum. Auto manufacturers have welded steel auto parts together for decades, but welding aluminum does require some process modifications. As the aluminum content in automobiles has increased, alternative welding techniques have become more important in the industry. Current research focuses on the development of modified welding methods, process monitoring, and noninvasive testing of welded joints.[27] Welding techniques that enhance productivity and maintain or improve product quality could lead to greater consumption of aluminum by auto producers; two techniques, laser and advanced welding, are undergoing further development.

Laser Welding

Laser welding is a promising method for joining aluminum, although the method works on other materials such as ceramics. Aluminum is difficult to weld with traditional electric-welding techniques because, unlike steel, it is a high conductor of electricity. It is also difficult to laser-weld because it is highly reflective and tends to scatter the laser beam. Compared to several other alternative welding techniques, however, laser welding is fast, precise, and requires less heat.[28] One drawback of laser-welding equipment is its sensitivity to contaminants commonly found in the automobile-manufacturing environment. Wider application of laser welding is dependent upon a resolution to this difficulty and the

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[24]Estimates of costs savings associated with laser ablation are not available.

[25]C. David Warren, Felix L. Paulauskas, Ray G. Boeman, "Laser Ablation Assisted Adhesive Bonding of Automotive Structural Composites," project completion report, Oak Ridge National Laboratory, Feb. 4, 1997.

[26]Ibid.

[27]"Light-weight Materials, III. Findings and Recommendations," found at http://www.pmi.princeton.edu /conference /future vehicles/lightweight.html, retrieved June 12, 1997; and "Research aims at better laser welding for aluminum auto parts," press release, May 1996, found at http://www.anl.gov/opa/news96/news960509.html, retrieved Aug. 10, 1997.

[28]Compared to arc welding (electrical-current method), *PNGV Technical Accomplishments*, July 1996, n.p.

technology must be refined to so that joint strength, assembly times, and cost meet the standards and efficiencies already achieved for bonding steel components.[29] The development of process controls for laser welding to improve joint quality is conducted under the auspices of PNGV by private companies and several national laboratories. The progress of this research is marked by the development of an on-line weld monitor that can detect surface features and other measures, as the joint is formed. A patent for the technology is now pending.[30]

Advanced Welding

A manufacturing process designed to form and join preshaped aluminum and tubular steel is under development by Dana Corp., an automotive-component parts supplier (Reading, PA).[31] The project supports automakers' efforts to increase fuel efficiency by substituting lightweight materials to achieve weight reduction of the load-bearing frames of cars and light trucks. The process more precisely forms the load-bearing structures that reduces the need for filler material to join parts. Preshaped aluminum or tubular steel is formed by exposure to high pressure within very precise die cavities and then machined according to a computer-aided design (CAD) file. The method has several advantages: dissimilar metal substrates can be joined, the time required to cure the joint is minimal, and the process need not be fixed to one area of the factory floor.[32] The process makes the adoption of aluminum a viable option for U.S. auto makers and its flexibility allows manufacturers to readily respond to consumer demands. The manufacturing process is not yet commercialized, and Dana Corp. is supported by the National Institute for Standards and Technology (NIST), under Advanced Technology Program funding.[33]

Other Bonding and Joining Technologies

Diffusion Bonding

This process was originally developed by an aircraft manufacturer and an aluminum producer. Diffusion bonding is a combination of two distinct processes; first, complex shapes are formed from a single piece of material, and second, materials are joined by diffusion.[34] The process relies on superplasticity, a property in which a material can become extremely elongated without breaking. For example, aluminum alloy can be treated to take on a superplastic property that facilitates the formation of complex auto parts. The number of parts to join is reduced; for example, Big Three collaborative work on a composite pickup truck bed of 20 pieces could replace a steel bed of 200 parts.[35] After the parts are

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[29]Estimates of costs savings associated with laser welding are not available.

[30]*PNGV Technical Accomplishments*, n.p.

[31]Larson, "Quality," *Quality*, p. 32.

[32]Estimates of costs savings associated with advanced welding are not available.

[33]ATP project brief, "Advanced Welding Technology for Structural Automotive Products," found at http://www.atp.nist.gov/www/comps/briefs/95020055.html, retrieved Sept. 30, 1997.

[34]Diffusion is a joining process whereby two flat surfaces are heat treated, causing the molecules to intermingle and bond.

[35]C. David Warren, program manager, Transportation Composite Materials Research, Oakridge National Laboratory, Oakridge TN, and advisor to the Automotive Composites

(continued...)

formed, the metals are bonded by keeping the base-metal microstructure intact at the joint interface. The method works for dissimilar metals. Researchers claim that the combination of superplastic forming and diffusion bonding combines the benefits of each to form a joint of superior strength.[36] The method leads to greater freedom of design, a potential for energy-savings, and cost-effective manufacturing. However, the process takes time, which is a major drawback for its application in the auto industry. Research on diffusion bonding is underway at the Lawrence Livermore National Laboratory and is sponsored by the DOE.[37] The technology is not yet commercialized.

Microwave for Ceramics

Ceramic is an alternative material for some automobile engine components. Ceramics are lightweight and have the capacity to withstand very high temperatures; two qualities that can help auto manufacturers reduce fuel consumption. Ceramic engine parts such as piston heads and rotors allow the engine to run without a cooling system and with less fuel. Although ceramic engine parts facilitate fuel efficiency, reliable joining methods are needed. Microwave energy is one alternative to bonding ceramics by thermal heat, which requires extremely high temperatures to work successfully.[38]

Ceramics can be joined to composite materials by applying a microwave heating process. As a joining technology, the microwave process forms an interlayer of active braze alloy and successfully creates a bond between the ceramic engine parts and composite base material.[39] The heating characteristics of ceramics are favorable to the creation of a high-strength bond; the bond is formed from the inside out (the middle is heated from center and outward). The bond also forms quickly due to the fast-heating microwave.[40] Ceramics can also be joined to metals with soldering and adhesive bonding.[41] Microwave technology for joining ceramics is not yet commercialized, although continuing research on the technology is supported by the DOE and the Continuous Fiber Ceramic Composites Programs.[42] Research to expand the role of ceramics in automobiles is conducted through the Ceramic Technology Project at Oak Ridge National Laboratory.[43]

Outlook

As alternative materials continue to make inroads into the U.S. auto industry, demand will increase for new manufacturing technologies and associated joining and bonding

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[35](...continued)
Consortium, USITC staff interview, Sept. 1997.

[36]Larson, "Quality," *Quality*, p. 30.

[37]Ibid.

[38]Ahmad Iftikhar, et. al. "Microwave Joining of SiC Ceramics and Composites," proceedings of the First World Congress on Microwave Processing, Orlando, FL, Jan. 5-9, 1997.

[39]Ibid.

[40]Craig Saltiel, et. al. "Materials Processing with Microwave Energy," *Mechanical Engineering*, Aug. 1995, p. 102.

[41]"Joining Metals and Ceramics," *Machine Design*, Sept. 14, 1995, p. 81.

[42]Ifikhar.

[43]Ceramics and Energy Efficiency, found at http://www.ornl/energy_eff/transp.html, retrieved Aug. 13, 1997.

technologies. Joining technologies for lightweight materials facilitate improved productivity, lower manufacturing costs, and a more flexible manufacturing setup. Adhesives and new welding techniques are a means to ensure greater design freedom for manufacturers. More significantly, the joining technologies profiled in this article are likely to contribute to the competitive advantage enjoyed by auto manufacturers of standard passenger vehicles made largely of lightweight polymer composites or aluminum.

Several circumstances challenge the widespread adoption of lightweight materials by the auto industry despite the need for continued improvements in processing technology. Some particular circumstances are as follows:

- Material cost is the most significant barrier to the use of polymer composites and aluminum in the auto industry.[44] Carbon steel has a clear cost advantage. On a per-pound basis, carbon steel is 4 times less costly than aluminum, 3 times less costly than of glass fiber-reinforced polymer composites, and 20 times less costly than carbon fiber-reinforced polymer composites.[45]

- While it may be possible to manufacture a polymer composite frame, the technology to mass-produce load-bearing composite parts currently does not exist.[46]

- The automobile industry's lack of demand for polymer composites does not inspire suppliers to increase their production capacity.[47]

- The lack of understanding of the nature and behavior of composites and other advanced materials may delay the adoption of alternative materials in the U.S. auto industry. Detroit does not have the design experience and familiarity with advanced materials that exists in the aerospace industry.[48]

- Nondestructive testing methods are needed to test the quality and reliability of joints and bonds.

Finally, the steel industry is working with the auto industry to develop better products and reduce costs. The auto/steel partnership poses competition for composite and aluminum suppliers who are vying for new business in the auto industry. Despite innovations such as

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[44]Thomas S. Moore, General Manager, Liberty and Technical Affairs, Chrysler Corp., "Making Composites Economically Competitive for High-volume Structural Automotive Applications," read at the Advanced Composite Conference and Exposition, Nov. 9, 1995.

[45]Since less alternative material is needed on a per-pound basis, the cost relative to steel is--aluminum, 2 times; glass fiber-reinforced polymers, 1.5 times; and carbon reinforced polymers, 5 times. U.S. Congress, Office of Technology Assessment, *Advanced Automotive Technology: Visions of a Super-Efficient Family Car* (Washington, DC: GPO) OTA-ETI-638, Sept. 1995, p. 62.

[46]Ibid., p. 64.

[47]Auto makers currently do not demand a high volume of composite parts, and suppliers lack capacity to produce a high volume. The rate of production of composite vehicle parts is slow, roughly 15 minutes per part for liquid-molded composites, compared with 17 seconds to stamp a steel part. Since these conditions have remained unchanged over the past several years, it is not cost-effective to mass-produce polymer composite parts. OTA, *Advanced Automotive Technology;* and USITC staff interviews with industry contacts.

[48]Warren, USITC staff interview, June 17, 1997.

ultralight steel, no type of steel is as lightweight as polymer composites or aluminum. These alternative materials are more likely than steel to be chosen for the production of a lightweight vehicle.

Despite some hindering circumstances, alternative materials potentially offer many competitive advantages to the auto industry, including--

- The tooling cost for polymer composites is less than steel.[49] A manufacturer must sell 300,000 to 500,000 cars to recover the cost of the die for a steel frame. For polymer composites, it is less than 50,000.

- The similarity of aluminum to steel reduces the cost of retooling because aluminum parts can be processed with some of the same equipment used to stamp steel. The design of aluminum parts is also similar to that for steel, which is important in an industry where consistency is valued highly.[50]

- The prospect of reducing emissions of carbon dioxide is perhaps the most valuable result of the widespread adoption of lightweight materials by auto producers.

Effective joining and bonding technology for alternative materials is a small but important part of reducing the weight of the average vehicle. Joining and bonding methods are "enabling technologies." These enabling technologies always provide a benefit. In this case, new joining and bonding technologies allow for the wider use of lightweight materials in the manufacture of automobiles. Although not central to a material choice, without effective joining and bonding methods, material choice is limited. The benefit accrued to auto manufacturers who adopt new joining and bonding methods is not cost-related at this point, since reinforced composites and aluminum are currently more expensive than steel. However, according to one source, there is a measurable environmental benefit associated with the adoption of lightweight materials. By comparing the material content of a 1996 typical vehicle referred to in table 1 with a passenger vehicle made largely of composites, the latter would generate 400 to 500 pounds of scrap after a 15-year life span and would produce 3,000 to 4,000 pounds less of particulate matter, a source of air pollution. According to this industry official, buried composite scrap is stable and less harmful to humans and the environment than the particulate matter released by an average vehicle not reduced in weight.[51]

Many technologies profiled in this report are not yet commercialized. It is widely agreed among auto industry officials, however, that the next generation of vehicles will be made largely of aluminum and a subsequent generation will be made of polymer composites. As this material shift occurs, demand for reliable joining technologies that are adaptable to large scale auto production will increase. Continued research and development therefore, appear ensured for joining and other enabling technologies that support alternative materials in the automobile industry.

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[49]Marechaux, USITC staff interview, June 1997; and OTA, *Advanced Automotive Technology*, Sept. 1995, p. 63.

[50]Warren, USITC staff interview, June, 1997; and Field and Clark, "A Practical Road to Lightweight Cars."

[51]Warren, USITC staff interview, Sept. 1997.

Thin-Slab Casting/Flat-Rolling: New Technology to Benefit U.S. Steel Industry

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Recent efforts to further develop and expand the role of thin-slab casting in the steel industry are highlighted. This process, combined with direct hot-rolling, greatly reduces capital investment and operating costs of producing hot-rolled carbon steel sheet. This article examines factors influencing adoption and commercialization of this technology, which has encouraged so-called "minimills" to enter the flat-rolled segment of the steel industry, until recent years the province solely of integrated steel producers.

This article was originally published in the Industry, Trade, and Technology Review *of October 1996. The update in the concluding section examines recent developments in the steel industry to develop and expand the role of thin-slab casting in the production of flat-rolled steels. Companies adopting this technology have experienced different degrees of success in achieving full production capacity, but incremental improvements have advanced the technology, resulting in a second generation of thin-slab casters.*

Certain recent and cumulative changes in steel casting and rolling,[1] called thin-slab casting/flat-rolling technologies, have lowered market-entry barriers, and have allowed the production of flat-rolled steel products (plate, sheet, and strip) in significantly smaller plants but with cost and quality benefits both to producers and to consumers. By altering cost structures, this technology has led to changes in steel industry market structure, and it may improve the international competitiveness of products the U.S. flat-rolled steel industry segment produces. This large market accounts for approximately 60 million metric tons of domestic shipments, and is a potentially lucrative source of revenues and profits to the cost-efficient producer.

[1]Most steelmakers today use a form of continuous-strand casting. Molten steel (produced in the furnace shop) is poured into one end of the continuous strand casting machine and is cooled, forming a metal skin around a liquid core (i.e., the molten steel solidifies from the outer cooled surfaces inward during the casting process) and a rectangular piece of steel is withdrawn downward from the bottom of the mold. At regular intervals, sections of the cast-steel strand are cut off, forming the semifinished product. This semifinished product is the raw material input for the hot-rolling mill, the subsequent process in a steel mill.

Integrated steelmakers have dominated the flat-rolled steel market.[2] The capital costs of building a 3-million to a 6-million-ton-per-year integrated steel mill (the estimated minimum efficient scale[3]) are estimated at more than $1,000 per annual ton of production capacity, which comes to about $4 billion to $5 billion per steel mill. This cost and the investment risk preclude the construction of "greenfield" integrated steel mills in the United States (none has been built since the 1960s), although considerable modernization of existing "brownfield" facilities has taken place. In contrast, a minimill[4] that produces thin-slab/flat-rolled steel can be constructed for about $200 per annual ton of capacity (equivalent to $400 to $500 million per mill), and it incurs lower operating costs (about 10 percent) in the production of steel sheet and coiled plate.

The shift toward small-scale technology is driven in large part by significant capital cost advantages of small-scale economies for producing many steel products. Even for existing plants, the annual reinvestment requirements are lower for smaller facilities. These economies--combined with Nucor Corp. (United States) operating success after installing the world's first thin-slab caster at a greenfield minimill--convinced five other companies to adopt this technology. The cumulative capacity of these eight thin-slab/flat-rolled mills may reach 16 million metric tons by 2000, and represents a significant increase of production capacity in this market segment that will likely affect U.S. imports and other domestic producers. In addition, three integrated U.S. steelmakers have selected thin-slab casting to replace obsolete ingot-casting facilities at brownfield sites.

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[2]Steel sheet is produced in a series of batch processes in an integrated steel mill: coke (produced from hard coal in coke ovens) is combined with iron ore and other raw material inputs in a blast furnace to produce molten iron and then refined in a basic oxygen furnace to produce steel. The liquid steel is then formed in a continuous-strand casting machine or ingot-casting molds into semifinished forms (called slab). Slab is usually inventoried and allowed to cool, but must be heated in a reheat oven to the proper temperature prior to being converted into flat-rolled products on the hot-strip mill. The resulting hot-rolled sheet may be cold-rolled and coated in subsequent processes.

[3]Minimum efficient scale of a plant refers to the smallest plant, measured by output or production capacity, for which economic production can be undertaken. Cost-size relationships are important in examining industry structure because, for many industries, increases in plant size lead to decreases in average cost. The cost necessary to achieve economies of scale may pose a barrier to market entry, or limit the number of firms in the industry. Several studies that estimate scale economies in the U.S. integrated steel segment suggest the minimum optimal size of conventional mills is 6 million net tons annually. For a recent study, see Robert P. Rogers, "The Minimum Optimal Steel Plant and the Survivor Technique of Cost Estimation," *American Economic Journal*, Sept. 1993, vol. 21, No. 3, pp. 30-37.

[4]Steel is typically produced in a "minimill" by refining steel scrap in an electric arc furnace. The molten steel is poured through a continuous-strand caster to produce semifinished products (usually, blooms and billets), that are hot-rolled on bar and rod mills. The steelmaking process in a minimill bypasses the coke-making and iron-making route, and the blooms and billets that enter the hot-rolling mill are typically smaller and lighter in weight than a slab. These differences along with the smaller scale of operations account for the smaller investment required for construction of a minimill and its lower operating cost, compared with an integrated mill. Significant advances in the technologies of electric arc steelmaking, secondary refining, and continuous-strand casting have allowed such minimills to increase in average production capacity, to begin producing thin-slab and flat-rolled products that had been largely restricted to integrated producers.

Thin-Slab Casting Processes

Significant reductions in minimum-efficient scale in the steel industry have occurred, brought about by better continuous casting technology that altered production of semifinished shapes (slabs, blooms, and billets).[5] These improvements, combined with certain others and with process linkage, simplified the economic production of steel products at significantly smaller plants, thereby lessening the capital needed to generate a dollar of sales.

Thin-slab casting technology evolved from continuous-strand slab casting, a process that was commercialized in the 1950s and which now accounts for more than 90 percent of total steel production in the United States.[6] Differences between thin-slab casting and conventional continuous-strand slab casting include the shape of the casting mold, the desired thickness of the slab, and the linkage of steel casting with direct hot rolling. The conventional continuous-strand slab casting technology produces a heavy slab[7] at a minimum of 8 inches thick. The capital investment required for this equipment and for the hot strip mill to roll the slab into sheet is high--on the order of $500 million to $1.5 billion.[8] In contrast, the thin-slab casting process makes a steel slab of about 2 inches thick with a much lower investment in the caster and rolling mill--approximately $150 million to $300 million.[9] This savings of investment and fixed costs is achievable because of two facts: (1) a thinner slab eliminates the need for primary breakdown in the hot-strip mill (enabling hot-rolling in the finishing stands of a conventional hot-strip mill); and, (2) the equipment needed to continuously cast a 2-inch thick slab is far less extensive than required for a conventional 8-inch or thicker slab.
Steelmakers adopting thin-slab casting also have tended to change plant configuration to link the caster with the hot rolling mill, and the slab immediately is rolled after casting. This

[5]Slabs are rolled to produce flat-rolled products including sheet, while blooms and billets are rolled to produce long products, including bar, rod, rails, and structurals. These semifinished products differ in terms of their dimensions, weight, the type of equipment needed for their processing, and their intended applications.

[6]Technological change is both incremental and continuous. The accumulation of incremental improvements or modifications to existing capabilities appears to be accelerating, and compresses the time frame for adopting and implementing new technology. An example is provided by thin-slab casting--in less than 10 years thin-slab casting progressed from an improved concept to full commercialization, and has nearly become a standard greenfield plant configuration.

[7] Dimensions are approximate, but the heavy slab measures about 8 inches to 12 inches thick, 6 feet to 8 feet wide, and 20 feet to 35 feet long. Slab thickness in thin-slab casting is typically about 2 inches but may range up to 4 inches or 5 inches in some versions.

[8] Estimates are for modernizing a brownfield site (existing mill) and construction of these facilities at an integrated mill on a greenfield (new) site. World Steel Dynamics (PaineWebber), Core Report ZZ, Dec. 1995, p. 14. For additional cost estimates see, Fr. William T. Hogan, S.J., *Minimills and Integrated Mills: A Comparison of Steelmaking in the United States* (Lexington, MA: Lexington Books, D.C. Heath and Co., 1987), p. 115.

[9] Ibid. Also see, Richard Preston, *American Steel: Hot Metal Men and the Resurrection of the Rust Belt* (New York: Prentice Hall Press, 1991), pp. 92-102. According to one industry executive, a 1.5-million-ton-per year sheet mill (including steel melt shop with casting and rolling facilities) can be built for about $300 million ($200 per annual ton of capacity), down from as much as $500 million 5 years ago. Martin Farricker, “Stepping in Gopher Holes Teaches Thin-Slab Lessons,” *American Metal Market, Electric Furnace Steel Supplement*, Feb. 14, 1996, p. 19A.

change in configuration reduces the capital costs of slab handling equipment, and reduces the operating costs associated with reheating slab and maintaining slab inventories. However, steelmakers and consumers initially voiced concerns that steel sheet rolled from thin-slab casters would not possess desired formability and surface quality that would limit its use to less demanding applications. Another factor limiting application is posed by the maximum 60-inch width of such sheet (a maximum 80-inch wide sheet is produced by integrated mills).

There are currently six thin-slab casting versions that have been commercialized (shaded box). Although SMS Schloemann-Siemag is the dominant supplier of thin-slab casting machines, other equipment manufacturers have had success. Steelmakers and equipment manufacturers have relied on experience to create a second generation of thin-slab casters that include improved features such as electromagnetic braking, liquid-core slab reduction, and the capability to change slab thickness without downtime (termed by some as "flexible thickness" thin-slab casting). These enhancements have improved thin-slab cast sheet surface quality and, combined with further improvements in other aspects of steelmaking, allow producers of thin-slab cast sheet to move into more demanding market niches served by U.S. and foreign integrated steelmakers.

Commercialization of Thin-Slab Processes

Since the mid-1980s, foreign equipment manufacturing companies and steelmakers in the private sector have developed thin-slab casting processes. Nucor Corp. commercial success with the first thin-slab caster (CSP design) installed at a greenfield minimill in 1989, has encouraged construction of more thin-slab casting facilities in the United States (table 1) and abroad. Approximately 20 companies worldwide have adopted or plan to adopt one or a combination of thin-slab casting technologies. The majority are in the United States, but the remainder are spread in Canada, Mexico, Japan, Korea, Malaysia, Thailand, China, Turkey, Czech Republic, and Italy. Each of the U.S. greenfield plants is a scrap-based electric furnace steelmaking operation (minimill) that has an actual or planned production capacity that exceeds 1 million metric tons annually (the majority plan for an expansion of production capacity to 1.5 to 2 million metric tons). In several instances in the United States, a traditional integrated company has formed a thin-slab minimill joint venture with an existing minimill company (e.g. Dofasco and Co-Steel, and BHP and North Star). Also, several U.S. integrated firms that currently operate coke-making, iron- and steelmaking facilities have adopted thin-slab processes, replacing obsolete ingot casting technology[10] and reducing production costs (table 1).

[10]These three companies are exceptions to the majority of other integrated steelmakers that have installed conventional continuous-strand casting equipment. See discussion later regarding reasons for adopting this technology.

Commercialized Thin-Slab Casting Processes

- # ***Compact-Strip Production (CSP)*** is based on casting technology developed by SMS Schloemann-Siemag (Germany). A 50-millimeter (approximately 2 inches) thick slab is cast, which is then passed through a tunnel "equalizing furnace" and "hot-charged" into the finishing stands of a conventional hot-strip mill. CSP was the first thin-slab casting technology to be commercialized and is the most widely used process worldwide.

- # ***In-Line Strip Production (ISP)*** was developed by Arvedi (Italy) and Mannesmann Demag (Germany). The as-cast 60mm slab is "soft" reduced to 40mm thickness by a set of rolls located below the mold, then the fully solidified slab is reduced to a 15mm-thick sheet by three shaping stands. ISP was commercialized at the Arvedi plant in Cremona, Italy. A similar casting-rolling process has been developed by Danielli (Italy) which also uses liquid core reduction (in use at Nucor, Hickman, AR and Algoma Steel, Canada).

- # The ***Continuous Casting and Rolling (CONROLL)*** process was developed by Voest-Alpine (Austria). Slab thickness can be varied between 75mm to 125mm (3 to 5 inches thick); the slab is processed through a re-heating furnace (similar to the equalizing furnace) and channeled directly into the existing hot strip mill consisting of a roughing stand and six finishing stands. This was installed for use at Armco's plant in Mansfield, OH, and the existing plant was reconfigured to minimize process discontinuities between caster, reheat furnace, and rolling mill. This process does more hot-rolling (i.e., a greater amount of reduction in thickness is achieved in hot-strip mill) compared with CSP or ISP.

- # The ***SMI*** process was developed by Japanese equipment makers Sumitomo Heavy Industries and Mitsubishi Heavy Industries. Slabs will be cast to a thickness of 90 mm but reduced to 70mm using liquid core reduction techniques (similar to the ISP process), channeled through a tunnel equalizing furnace into a hot strip mill with two roughing and five finishing stands. The SMI process reportedly is being installed at Trico Steel in Decatur, AL. Like CONROLL, more hot-rolling is performed in the SMI process compared with CSP or ISP.

- # The ***Tippins-Samsung Process (TSP)***, named for the two equipment manufacturers, produces a variable thickness slab from 75mm to 150mm (3 to 6 inches) that is channeled through a reheat furnace to a two-stand reversing hot-strip mill. Reportedly, this design allows the production of plate up to 120 inches wide, good surface quality, and potential production capacity of between 1 and 2 million metric tons, at a cost of about $300 million. According to industry sources, it might be installed at Nova in Czech Republic.

- # The ***Ultra Thin Hot-Strip (UTHS)*** process is being developed by Mannesmann Demag (Germany) and Chaparral Steel (United States), reportedly is to be installed at Natsteel, Singapore. A 90mm thick (3.5-inch) slab is cast, followed by breakdown rolling and finishing rolling down to below 1 mm thick.

Source: Compiled by staff of the USITC from various industry publications.

Table 1
Thin-slab production capacity installed and announced in the United States, by company, facility location and process, capacity, and year expected to become operational

Company	Facility location/process	Capacity[1] (*Million metric tons*)	Year[2]
Greenfield minimill plant construction			
Nucor	Crawfordsville, IN/CSP	1.0 + 1.0	1989 & 1994
Nucor	Hickman, AR/CSP&ISP	1.2 + 1.0	1992 & 1994
Gallatin Steel[3]	Ghent, KY/CSP	1.2 + 0.9	1995 & mid-1997
Tuscaloosa Steel[4]	Tuscaloosa, AL/SMS	0.9	1996
IPSCO[5]	Muscatine, IA/ISP	1.3 + 0.2	1996/97
Steel Dynamics	Butler, IN/CSP	1.0 + 1.0	1996/98
Nucor	Charleston, SC/CSP	1.0 + 0.6	1997/98
Delta Steel[6]	Delta, OH/SMI	1.6 + 1.0	1997/99
TRICO[7]	Decatur, AL/SMI	2.1	1997/98
Total	9 facilities	11.3 - 17.0	
Brownfield integrated plant modification			
Geneva Steel	Provo, UT/TSP	1.9	1994/95
Armco Steel	Mansfield, OH/CONROLL	0.7/1.1	1995
Acme Steel	Riverdale, IL/CSP	0.9-1.8	1996

[1] Announced raw steel melting capacity in million metric tons; initial steel melting capacity plus planned capacity additions (phase-II additions).
[2] Start-up date(s) of initial installation and additional capacity (phase-II additions).
[3] Joint venture between Dofasco and Co-Steel, Canadian steelmakers.
[4] A stand-alone rolling mill prior to installation of electric-furnace melting and medium-slab (5 inches) casting capability in 1996 that increased capacity by 300,000 tons.
[5] Canadian producer of pipe.
[6] Joint venture between North Star Steel (a Cargill subsidiary) and BHP (Australia).
[7] Joint venture among LTV, Sumitomo (including the trading company, Sumitomo Metals, and Sumitomo Heavy Industries, the equipment manufacturer), and British Steel.

Source: Based on various industry publications and USITC staff telephone interviews with industry officials.

Factors Aiding or Hindering Adoption of Thin-Slab Casting

The reasons that companies have adopted thin-slab casting provide insights into corporate strategy and changes in industry structure. The adoption of technology often forms part of a firm's overall competitive strategy, and contributes to that strategy through its effect on financial and operating costs as well as the company's decisions regarding product mix, markets served, and pricing. Factors that influence the decision to adopt a technology and its timing may be tangible, or quantifiable, such as indicators of company financial or economic performance; and intangible, such as the risk-posture of the company's corporate culture, as summarized in table 2.

Among the performance factors spurring the adoption of thin-slab casting technology has been the lower costs of capital investment and operations that are achievable for the production of flat-rolled steel sheet and strip compared with conventional integrated

Table 2

Certain tangible and intangible factors guiding company adoption of thin-slab casting technology

Element	Argument for adoption	Argument against adoption
Tangible factors		
Financial or economic performance	May lower operating costs through increased productivity or may decrease energy consumption. May improve quality of company's products or product mix (allow the company to produce increasingly technically sophisticated and value-added products).	Existing technology may embody sunk costs; new costs may have unfavorable impact on certain capital ratios. May encounter lengthy learning curve adjustment period (possibly several years) to achieve product quality required by markets served. Capital costs may be higher than expected rate of return; amount of investment capital available to industry or company may be limited.
Technological	May embody state-of-art, yielding enhanced flexibility in using raw materials or other inputs, productivity increases, or quality enhancements.	"Best fit" usually is in a greenfield facility and retrofit may not be appropriate for scale production economies or other reasons. Existing equipment may possess lengthy remaining economic life. Effect of new technology may be lessened by subsequent technological advances.
Industry structure	May reduce minimum economic scale, and ease entry; lucrative rewards may accrue to first innovator and market entrant.	Entry costs may remain high or unbridgeable; market strategies of existing players or later entrants may negate potential returns. Company already may be in market segment. Successful commercialization may encourage copycat imitations, reducing or eliminating advantages to the first innovator.
Intangible factor		
Corporate culture	May see existing market structure or competitors as vulnerable to new entrants (risk-taking and receptive to innovation).	Approach to decision-making is risk-averse or risk-neutral; may be receptive to innovative technology, but adopts conservative wait-and-see posture.

Source: Compiled by staff of the USITC from various industry publications.

steelmaking. The capital costs of a greenfield integrated mill[11] have been illustrated earlier as significantly higher when compared with the costs of a thin-slab/flat-rolled minimill. In

[11]There are two sources of large-scale economies in an integrated steelmaking plant: these are the integration of iron-making and steelmaking operations and the hot-strip mill, which is used to roll all continuous-strand cast slab into hot-rolled band. Engineering estimates of minimum size range upwards from 5.4 million metric tons of annual raw steelmaking capacity. F.M. Scherer and David Ross, *Industrial Market Structure and Economic Performance,* 3d ed. (Boston: Houghton Mifflin Co., 1990), p. 102. The minimum efficient scale for a conventional continuous hot strip mill is estimated at 2.7 million metric tons per annum. Robert W. Crandall, *The U.S. Steel Industry in Recurrent Crisis: Policy Options in a Competitive World* (Washington, D.C.: The Brookings Institution, 1981), p. 11. In contrast, new mini-flat-rolled mills typically possess an initial capacity of about 1 million metric tons with a planned increase to about 2 million metric tons, making them on average, less complex and smaller than their integrated steel mill competitors.

addition, trade sources indicate that construction costs and interest charges that accrue over the several years needed to bring an integrated plant on-line would render the average total costs of a new plant higher than costs at existing "best practice" integrated plants. However, retrofitting an existing integrated plant is still an option. For example, Acme Steel installed a CSP thin-slab caster to replace obsolete ingot casting because of cost, quality, and productivity benefits.[12] The potential difficulties of dovetailing thin-slab casting (or other "incremental technologies") with existing processes apparently have been minimized for the three steelmakers (table 1) that have done so. For other steelmakers that possess continuous-strand casters, retrofitting may not be an appropriate option for reasons of economic performance of their existing equipment and the technical needs of their customers.

When Nucor Corp. chose to be the first producer worldwide to adopt CSP thin-slab casting (and to build the first greenfield flat-rolled mill in the United States in nearly 30 years), it reportedly resulted from a perception that thin-slab casting provided a means of market entry to exploit a market opportunity.[13] Nucor's reported success and profitability has encouraged more market entrants, although increased prices for casting equipment and falling prices for hot-rolled band (the immediate downstream product produced by rolling thin-slab on a hot-strip mill) may have deterred some companies from considering expansion into the flat-rolled segment.[14] A comparison of estimated capital and operating costs for integrated mills producing flat-rolled products with a recently built thin-slab/flat-rolled mill is in table 3.

Table 3
Estimated capital cost and operating cost for a greenfield conventional integrated mill, modernized integrated mill, and thin-slab/flat-roll minimill in the United States, by process, 1995.

(*Dollars per metric ton*[1])

Process	Greenfield conventional integrated mill		Modernized integrated mill		Thin-slab/flat-roll minimill	
	Capital cost	Operating cost	Capital cost	Operating cost	Capital cost	Operating cost
Iron-making[2]	1,160	130-140	(3)	130	(3)	(3)
Steelmaking[4]	530 -1,134	185-200	290	185-200	125-130	180-185 (5)
Slab casting[6]	275 - 435	215-225	200	220-230	60- 80	200-215
Hot strip[7]	1,000	250-260	290	260-280	200-220	225-235
Cold-finishing[8]	700	350-380	(9)	(9)	75	270-280

[12] Reportedly, total manufacturing costs will decrease by 20 percent; processing time will decrease; finished product yield (the ratio of finished product to raw steel produced) will increase from 78 percent to 91 percent; energy requirement per ton of steel will decrease by about 46 percent; and manpower requirements per ton of steel are projected to fall by more than 50 percent. "Acme Steel Introduces the Minigrated Mill," *Purchasing*, July 11, 1996, p. 46.

[13] Preston, pp. 90-100. For a discussion of the relationship between entrepreneurship and technology adoption, see Peter F. Drucker, *Innovation and Entrepreneurship: Practice and Principles* (New York: Harper & Row, 1985), pp. 66-75.

[14] For example, World Class Processing (a steel finisher with a stand-alone rolling mill) announced it had decided not to proceed further with its plans to install steel melting capacity and thin-slab casting.

Total	3,670 -5,000	(3)	680	(3)	460-505	(3)

[1] Per metric ton. Capital costs are per ton of capacity per facility within a steel plant. Operating costs are the per ton cumulative product costs at that stage of the production process, but do not include financial costs like depreciation, interest, and taxes.
[2] Includes approximately $450 per mt in capital costs for sintering (iron ore preparation) and coke-making facilities, and $720 million for a 3.6 million metric ton blast furnace.
[3] Not applicable.
[4] Steelmaking costs for the greenfield integrated mill are based on about 4.4 million metric tons capacity (about $120 per metric ton of capacity); on about 3 million metric tons capacity (about $220 per metric ton of capacity) for the modernized integrated mill; and on 2.0 million metric tons capacity ($60 per tonne of capacity) for the mini-flat-rolled mill.
[5] These costs may vary with changes in prices for raw material inputs (e.g., scrap and other iron-bearing materials). It should be noted that a greater percentage of the production costs of a minimill vary with the business cycle.
[6] Conventional slab is approximately 8 inches thick. Thin-slab is approximately 2 inches thick.
[7] Costs include reheat furnace, primary breakdown mill and finishing mill in an integrated mill; minimill costs include a tunnel furnace and hot strip mill finishing stands. Product compared is hot-band.
[8] Includes costs for a "pickle" (acid clean) line, tandem mill, annealing, and temper mill. Product compared is cold-rolled sheet, tempered, and finished.
[9] Not available, but assumed to be similar with the cost structure of a greenfield conventional integrated mill. Depending on the circumstances, may not be applicable.

Source: World Steel Dynamics (PaineWebber), *Core Report ZZ,* Dec. 1995.

Competitive Effects of Process Commercialization and Outlook

The expansion of production capacity and output by greenfield flat-rolled steel minimills has spurred increased price competition within the flat-rolled steel segment, and the new entrants have gained market share at the expense of both imports and established domestic producers. Shipments from greenfield thin-slab/flat-rolled plants in the United States are estimated to increase from about 2 million metric tons (accounting for nearly 5 percent of U.S. producer shipments of flat-rolled steel products) in 1992 to about 16 million metric tons (about 25 to 30 percent of shipments) by 2000.[15] The increased production from thin-slab/flat-rolled mills has contributed to more intense price competition as prices of hot-rolled sheet declined by 15 percent during 1994-95 and remained at relatively low levels during early 1996. The price difference between hot-rolled and cold-rolled sheet also narrowed as several thin-slab cast minimills began selling hot-rolled sheet in thinner gauges that heretofore were only achievable on an integrated steelmaker's cold-rolling mill. Reflecting these developments, U.S. imports of commercial grade hot-rolled sheet and coiled plate have declined by 24 percent between 1994 and 1995, and by 30 percent during January-May 1996, when compared with imports during the same period in 1995.

These market conditions have placed competitive pressures on several of the higher cost U.S. integrated producers either to reduce costs, to move into more sophisticated niche products, or to exit the market segment for commercial grade hot-rolled sheet. Reportedly, some steelmaking capacity will be closed by integrated steelmakers,[16] which is expected to increase the market share of thin-slab/flat-rolled mills. According to industry estimates, about two-thirds of the total flat-rolled product market in the United States (between 30

[15]Projection based on capacity estimates by industry sources as noted in table 1.
[16] One industry analyst estimates that integrated mills will close 3 million to 6 million metric tons of basic oxygen furnace-steelmaking capacity by 2000. This is in large part due to the closure of obsolete coke ovens and supply tightness in the coke market. World Steel Dynamics (Paine Webber), *Capacity Monitor*, Apr. 1996, p. 3.

million to 35 million metric tons)[17] may be within reach of thin-slab/flat-rolled mill operations, with the greatest increases in market shares accruing to hot-rolled sheet and hot-dipped galvanized sheet. Smaller market share increases are expected in other categories of coiled plate (in the thinner gauges of this product) and cold-rolled sheet. Continued improvements in surface quality and formability should allow thin-slab/flat-rolled minimills to increasingly penetrate the domestic market for sale to original equipment manufacturers (OEM) such as automotive and construction equipment, who have tended to purchase primarily from U.S. integrated steelmakers on a contract basis (usually a 1-year cycle).

[17] World Steel Dynamics (PaineWebber), *Core Report ZZ*, "Steel's Thin-Slab/Flat-Rolling Revolution: Provoking Change, A Study of Steel Dynamics, Inc.," Jan. 1996, p. 15.

Recent Developments

Startup of Thin-slab/Flat-rolled Mills Continues

Since 1996, the new facilities (listed in table 1) have begun commercial shipments. Although no final decision has been reached, two companies, Ipsco and Nucor, announced they are considering building additional facilities that would use this new slab casting technology.[18] Commercial shipments of flat-rolled steel increased by approximately 62 percent to an estimated 7.6 million tons between 1996 and 1997, with a forecast of 10.3 million tons in 1998.[19] These increases reflect higher operating levels as production expands to reach designed capacity. Steel Dynamics Inc. (SDI) and Gallatin Steel are estimated to have achieved 95 percent and 90 percent of their rated operating capacity, respectively, for example.[20] Sheet quality is considered to be good-to-high from these new mills, making their products acceptable for exposed automotive applications.[21] In addition to standard carbon steel grades, these new mills have produced a range of stainless, electrical, high-strength-low-alloy, and low, medium, and high carbon steels. The hot-rolled products of several of these mills have successfully penetrated markets that had required higher cost cold-rolled sheet.

Construction and startup of the new thin-slab/flat rolled mills have proceeded with varying degrees of success. The most successful venture, in terms of time elapsed between beginning construction and starting commercial shipments, was SDI, which came online in a record time of 14 months, and broke even on a cash flow basis in 18 months. Most of the others have begun commercial-quality shipments in about 20 to 24 months.[22] In contrast,

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[18]Scott Robertson, “Nucor May Target Plate Rivals,” *American Metal Market*, Oct. 15, 1997, p.1; see also, Rick Teaff, “Ipsco Mulls 2d Plate Mill in U.S.,” *American Metal Market*, Oct. 9, 1997, p. 1.

[19]These estimates are for shipments made by Nucor (three facilities), SDI, Gallatin, Trico, Delta, and Ipsco. PaineWebber, World Steel Dynamics, *Steel Order Track*, Oct. 22, 1997, p. 7.

[20]PaineWebber, World Steel Dynamics, *Steel Order Track*, Oct. 22, 1997, p. 3.

[21]"Moving Up With DRI and Thin-Slab Casting,” *NewSteel*, Aug. 1997, pp. 63-74. Ford Motor Co. announced its intention to purchase 7,500 metric tons per month of steel sheet from these new mills in 1998. See, “Mini-Mills Moving Up,” *33 Metal Producing*, Jan. 1998, p. 34.

[22]The length of time needed to gain operating experience (and related learning curve economies) and the complexity of the company’s product mix are important factors; there usually is a lengthy time period between commissioning a mill and its initial commercial shipments, as the equipment is tested and personnel are trained. Prior management experience in steel mill construction and thin-slab casting operations has been shown to generally reduce the amount of time needed to bring a new mill successfully on line and begin commercial shipments. Also, the investment banking community assigns a lower risk-related value to the experience of a company’s management team, lessening financial borrowing costs. SDI was founded by a group of former Nucor managers who had built Nucor’s first thin-slab-based mill at Crawfordsville, IN; the management team was able to start up a new company, the financing was completed only nine months after they left Nucor, and the new mill came on line 14 months later. PaineWebber, “Metals,” Sept. 16, 1997 and “Wall Street Diary: Stars, Wanabees and Has-Beens, Musings of a Steel Banker,” PaineWebber, Mar. 4, 1997.

design and engineering changes during construction caused Ipsco to delay its takeover of the Muscatine, IA, facility by nearly 18 months.[23]

Technology Advancement

Thin-slab casting technology continues to evolve. The first generation of thin-slab casters is generally considered to be that installed at the Nucor facility at Crawfordsville, IN, in 1988. Compared with the rate of change of earlier technological advances, the pace of improvement in thin-slab casting technology is increasing, and a second generation of thin-slab casters incorporates changes in mold design and caster operation that result in improved quality and higher productivity. Second-generation thin-slab casters incorporate such improvements as--[24]

- Adjustment mechanisms for varying the width and thickness of a continuous-cast strand (also called flexible thin-slab), allowing a slab to be cast in thicknesses ranging from 40 mm to 80 mm. This raises downstream productivity by matching caster output to specific rolling requirements. In several of the mills, such changes can be accomplished "on the fly" (i.e., without loss of production due to downtime);

- Liquid core reduction (also called soft-shell-reduction). The continuous-cast strand is compressed between two rollers that are set immediately below the caster mold. This improves slab quality by reducing or eliminating center line porosity, promotes a more refined steel grain structure, and helps to improve slab surface quality;

- Improved oscillation control within the caster.[25] Oscillation can be tailored to specific steel grades, thereby increasing casting speed and total throughput. Improved oscillation control has been optimized at several mills by combining it with electromagnetic breaking (EMB).[26] This combination results in improved steel quality.

Mills also have made changes in downstream slab processing facilities, including improved slab cooling and descaling equipment, additional rolling to improve sheet surface quality and gauge control, and the use of artificial intelligence and neural networks for enhanced processing control. To further control product quality, all of these mills are making some use of scrap substitutes like direct-reduced iron, hot-briquetted iron, and iron carbide; four of the mills have integrated backwards to the production of these furnace charge materials.

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[23] Scott Robertson, "Takeover Talks at Ipsco Mill," *American Metal Market*, Nov. 17, 1997, p. 3.

[24] "Steel Dynamics and the Second Generation of Thin-Slab Casters," *New Steel*, Sept. 1995, p. 11, citing SDI president Keith Busse; Adam Ritt, "Acme Rolls 0.030-inch Hot Band," *NewSteel*, May 1997, pp. 72-79; and, Adam Ritt, "Casting Faster with Better Surface Quality," *NewSteel*, Apr. 1997, p. 67.

[25] Oscillation prevents the steel strand from freezing to the caster mold. Most conventional oscillators are electromechanical while the newer ones are hydraulically operated.

[26] EMB minimizes the tendency of the mold powder to be drawn into the liquid steel because it significantly reduces turbulence within the mold.

Outlook

Thin-slab casting continues to evolve at an increasing pace and the operators of such equipment have continued to improve their productivity and enhance product quality. Further research and development has been stimulated by technology partnerships that have developed between mills and the equipment suppliers. One arrangement--that of SMS (the supplier of most of the compact strip type thin-slab casting equipment) and Hylsa (a Mexican steel producer) is focused on refining operating procedures for existing thin-slab casting equipment, increasing production capacity, improving product quality, and reducing capital cost in producing light-gauge product. Improvements developed at Hylsa are expected to be channeled to other users of SMS equipment.[27]

Potential entrants to this segment of the U.S. steel industry have adopted a wait-and-see attitude regarding actual results of the early adopters, while existing companies continue to evaluate the impact of new capacity on their business. Several of the new mills have added downstream coating and heat treatment lines; this added processing capability enhances product quality and enables the mill to sell higher-valued products to customers in the automobile and construction industries.[28] Several other new mills are concentrating on the efficient production of hot-rolled sheet, but their customers are building processing plants close to the mill site.[29] For example, Worthington Industries installed a hot-dipped galvanizing line in April 1997 near NorthStar BHP's mill in Delta, OH and is building a pickling, cold-rolling, and slitting line adjacent to Trico's mill in Decatur, AL, that is expected to be operational in 1998.

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[27]"SMS teams up with Hylsa and Acme to expand CSP's capabilities," *NewSteel*, May 1997, p. 61.

[28]"Newsfront," *NewSteel,* Nov. 1997, p. 29.

[29]This yields inventory and transportation costs savings.

Sol-Gel: Industry Seeks to Commercialize Energy-Saving Technology for Existing and Emerging Markets

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This article highlights a number of industry and government efforts to develop and commercialize sol-gel processing. This process is being used to create materials which possess mechanical and thermal properties that exceed the properties imparted by conventional ceramics and glass making processes. The use of products derived through sol-gel also promises significant energy savings in architectural, automotive, and commercial and residential insulation applications. This article explores key factors affecting commercialization of sol-gel, the role of certain domestic and foreign industry and government institutions involved in its research and development, and the short- and longer-term commercial prospects for this technology.

This article was originally published in the Industry, Trade, and Technology Review *of December 1995. The concluding section contains information on the latest efforts to commercialize sol-gel related products. Most projects have been assisted at some point in their development by U.S. Government funding, and firms are now beginning to scale up commercial production of material after initial pilot production of small quantities.*

Note: A glossary of technical terms (highlighted within the article by ***bold italics***) appears at the end of this article.

The application of sol-gel processing to industrial production enables specialized materials (e.g. films and coatings, powders and grains, fibers, and porous gels and membranes) to be produced from the gel state. This method enables a more precise control of composition, purity, and microstructure, often at lower processing temperatures and reduced energy costs. Sol-gel materials possess mechanical and thermal properties that exceed the properties of similar materials produced under conventional processes.[1] The use of products derived through sol-gel processes also promises significant energy savings in certain applications.

[1]Sol-gel manufacturing was first developed during the 1950s as a means to manufacture ceramics and glass with a wide range of advanced properties.

For these reasons, there is currently strong international competition to commercially develop this technology.

Although existing markets for sol-gel products tend to be lower-volume (estimated total annual U.S. sales of less than $200 million), this technology is reported to have significant commercial potential in large, international markets such as automotive and architectural glass, and thermal and acoustical insulation, where the energy-savings advantages of sol-gel products have been demonstrated. Recently, sol-gel technology has begun to be used in the commercial production of textile fibers. Other promising commercial applications and markets in which sol-gel may eventually be used include micro-optical components (in laser optical devices), electronic sensors, and vapor-separating membranes and filters (for use in environmental emission control and food processing applications). Although these markets are presently small, sol-gel manufacturers feel they have large commercial potential worldwide.

This article examines the commercial potential for sol-gel processing in various current and emerging markets, and discusses efforts of individual firms to develop this technology. Cost and performance are examined as two of the critical conditions necessary for wider industry acceptance of sol-gel products. Finally, the article describes the role U.S. and foreign governments have played in helping to develop this technology.

The Sol-Gel Process[2]

Sol-gel processing involves a chemical synthesis of ***oxides*** that undergo a transition from a ***solution*** or ***sol*** state to the ***gel*** state. In this synthesis, oxides are transformed from small-sized units in a liquid phase into rigid material of greater molecular weight through partial loss of liquid. Both the initial chemistry of the mixture and the final stage of drying are critical to successful manufacture of the five possible types of end-product forms -- thin film and coatings, fiber, powder, porous gel, or ***monolith***.[3]

During the first stage of the sol-gel process, components are mixed to form a clear, homogeneous solution that then gels to produce a highly porous oxide. The chemistry of the mixture must be carefully controlled to induce liquid solvents to form a gel. In order to remove the solvent material, the elastic gel is then either dried, under high-pressure and high-temperature conditions, in an autoclave (a type of pressured furnace) to produce an ***aerogel***, or is dried naturally to produce a xerogel. If the drying temperature is raised too high or rises too rapidly, the solvent may escape too quickly, causing cracks in the gel structure. Generally, monoliths are the hardest materials to dry without cracking while thin films and fibers dry much easier.[4]

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[2]See articles on sol-gel appearing in *Ceramics and Glasses*; Engineered Materials Handbook, Vol. IV, 1991.

[3]"Sol-Gel Process," Lisa C. Klein. Article appears in *Ceramics and Glasses*; Engineered Materials Handbook, Vol. IV, 1991, p. 209.

[4]Ibid. pp. 210-11.

Principal advantages and disadvantages of sol-gel processing as compared to competing forming processes[5] are noted in figure 1. The prospects for reducing the current disadvantages and improving the competitive potential of sol-gel processing, principally related to cost and performance factors, are examined later in this article in the section dealing with the outlook for commercial production.

Product Applications and State of Process Adoption

The end-users of products made using the sol-gel process are likely to be most attracted to the energy-savings potential of these products and by their superior performance under extreme mechanical, chemical and thermal conditions. The glass and abrasives industries are currently the largest users of sol-gel processing (table 1).

As discussed below, a number of private sector firms are currently engaged in sol-gel related production, both on a prototype and a commercial basis. Manufacturers have identified some large existing markets that may justify investments in large-scale production; such economies of scale are necessary to make sol-gel products more cost-competitive with traditional processes and products. In other cases, production is being targeted toward future markets such as micro-optical components, that are presently small but are expected to develop significant commercial potential.

Thin Films and Coatings for Optical Applications

Films and coatings are the oldest and among the most commercially common applications of the sol-gel process.[6] Most sol-gel films and coatings are applied by "dipping", in which a ***substrate*** is lowered into a vessel containing the solution.[7]

Sol-gel coating techniques are increasingly used in the manufacture of optical coatings which alter the reflecting and light-transmission qualities, or heat absorption, of a substrate, most often glass. Industry sources believe the annual market potential for ***electrochromic***

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[5]The sol-gel process principally competes in advanced materials processing, particularly in the application of thin films and coatings, with ***vapor deposition*** technology.

[6]Sol-gel has been used in the commercial production of reflective and anti-reflective glass coatings used in instrument meter faces and in large area displays for nearly two decades and has been widely used in the manufacture of advanced abrasive products since 1988.

[7]Film thickness can be increased by increasing withdrawal speeds from the vessel and by increasing the oxide content of the solution; coating thicknesses of 50 to 500 nanometers are typically produced. Sol-gel is not widely used for depositing thicker films and coatings which require repeated dipping and firing operations; such operations are costly and also increase the likelihood of contamination. Thicker films and coatings are generally deposited using vapor deposition techniques.

Figure 1
Comparison of Sol-Gel Processing with Competing Technology

Advantages	Disadvantages
! The ability to produce high purity, homogeneous ceramic products. Chemical ***precursors***, which can be distilled and filtered, are used to produce final products that are relatively free of impurities. ***Homogeneity*** is guaranteed because particles are mixed in solution on a ***nanometer*** scale, allowing precise microstructure control in a relatively short time.[1] This enables particle size distribution, ***porosity***, and ***stoichiometry*** to be carefully controlled, either in the sol or in the sintering stage, to create high-purity structures which are ideally suited for such advanced applications as high-purity electronic coatings and sensors. ! Sol-gel's low-temperature process canachieve energy cost savings when compared with conventional processes.[3] Because **colloidal** particles have very high surface energies, sol-gel processing permits sintering (bonding) to occur at temperatures well below product melting temperatures.	! Higher raw material coasts that result from the need to use expensive, high-purity precursors. ! Removal of solvents and the overall shrinkage of the solution must be carefully controlled to avoid cracking and the dissipation of large amounts of volatile materials, because colloidal gels have very small pore structures and relatively low densities. Such concerns often limit the size of components that can be produced by this process.[2]

[1] "Sol-Gel Process," Lisa C. Klein. Article appears in *Ceramics and Glasses*; Engineered Materials Handbook, Vol. IV, 1991, p. 213.

[2] The New Materials Society: Challenges and Opportunities, Volume 2, U.S. Bureau of Mines, 1990.

[3] C. Jeffrey Brinker and George W. Scherer, *Sol-Gel Science: The Physics and Chemistry of Sol-Gel Processing*, 1990, p. 840.

Table 1
Sol-gel processing: Product form, end-use industry, specific end-use, properties, present estimated market value, estimated commercial market value over 10 years

Product form	End-use industry	Specific end-use	Properties	Present estimated market value	Estimated commercial market value over 10 years[1]
Coatings	Optical glass	Large area displays, sensors, laser optics, solar cells	Glare reduction Broadband light transmission	$50-100 million	$200 million
Thin films	Architectural/ construction	Electrochromatic window glass	Thermal efficiency Control of light transmission	Minimal	$1 billion
Fibers	Aerospace/Defense	Thermal insulation for aircraft	Heat and abrasion resistance	Minimal	([2])
	Textile	Refractory braiding and fabrics	Strength, heat-resistance	Minimal	([2])
Monolithics	Optical glass	Lenses, prismatic arrays, diffractive gratings	High purity Glare reduction	Minimal	([2])
Grains and powders	Cutting tools	Grinding wheels, abrasive belts, sandpaper	Impact resistance Sharpness	$100 million	$200 million
Porous gels and membranes	Construction/ refrigeration	Thermal and acoustical insulation	Small pore size Thermal efficiency	Minimal	$2 billion
	Chemical	Membranes for filtration and separation systems	Abrasion and heat resistance, small pore size	Minimal	$10-15 million
	Environmental	Catalytic application	Small pore size	Minimal	$10-15 million
	Food and beverage and beverages	Microfiltration systems	Small pore size	Minimal	$10-15 million

[1]Estimates of potential market sizes are based on discussions with a limited number of firms currently involved in prototype or commercial production as cited elsewhere in this article and are somewhat speculative in nature.
[2]Not available.

glass alone could total more than $1 billion by 2005.[8] Critical factors that are involved with optical coating applications include precise control of coating thickness and degree of ***refraction*** and, in multilayer films, changes in the amount of refraction between films.[9] The ability to adjust these characteristics enables the manufacture of a number of products with significant energy-saving potential.

Coated electrochromic glass for "smart windows", in which light and heat to the interior of a building can be automatically controlled, is expected to become the most widely-used application for optical coatings. The exterior of coated electrochromic glass appears uniformly reflective; however, light transmission to the interior varies inversely with sun exposure, thereby minimizing heating and cooling costs. In addition to reflective coatings, oxide coatings can also be used to produce anti-reflective surfaces. Such glass is presently used in large-area displays (shop and museum windows), computer terminals, meter faces, automotive glass and rearview mirrors, and in laser-damage-resistant, anti-reflective coatings for laser optical devices.

One leading commercial U.S. producer of sol-gel optical coatings is Donnelly Corp. (Holland, MI) which uses sol-gel to produce optical barrier coatings for electrochromic displays, automotive rear view mirrors (Polychromic™), and sunroofs. Another company, Denton Vacuum Inc. (Moorestown, NJ), has used sol-gel technology for nearly 20 years to apply reflective and anti-reflective silicon dioxide and titanium dioxide optical coatings on laminated or tempered glass for use in CRT's and flat panel displays, meter faces, instrument windows, shop and museum windows, implosion panels, and architectural glass. According to Denton, the anti-reflective glass produced using sol-gel provides clearer images by reflecting less than 1 percent of all visible light transmitted, thus reducing glare by 99 percent.[10] Conventional glass may reflect as much as 8 percent of visible light transmitted, leading to noticeable glare on the surface of the glass.

Two of the promising markets for sol-gel coatings appear to be those for electrochromic glass used in architectural and automotive glazing applications. Both Donnelly Corp. and Sage Electrochromics, Inc. (Piscataway, NJ) are actively involved in projects, financed partly by the U.S. Departments of Energy and Commerce, that may eventually lead to the commercial production of optical glass coatings for these markets. Although cost figures are difficult to establish, it appears that electrochromic glass is produced, using either existing sol-gel or vapor deposition technology, at a significant cost premium ($30-35/square foot) compared with conventional ***low-emissivity*** glass ($10-12/square foot) with which they would compete.[11] However, manufacturers contend that such cost comparisons do not account for the superior thermal efficiency of electrochromic windows. According to these manufacturers, electrochromic windows will be sold as "thermal insulating packages" that will not only replace conventional low-emissivity windows during the next

[8] John P. Cronin and A. Agrawal, "Large Area Transmissive Electrochromic Devices," (Draft), 1995, p. 1.

[9] C. Jeffrey Brinker and George W. Scherer, *Sol-Gel Science: The Physics and Chemistry of Sol-Gel Processing*, 1990, p. 847.

[10] Product literature, Denton Vacuum Inc., Moorestown, NJ.

[11] John Van Dine, SAGE Electrochromics Corp., telephone interview by USITC staff, Washington, DC, Aug. 1995.

decade, but will also add considerably to the thermal efficiency of the entire structure.[12] In addition, manufacturers are confident that they are on the path to reducing the cost of sol-gel electrochromic glass to $15-25 per square foot, a level at which such glass competes directly with low-emissivity glass.

Powders and Grains for Abrasive Applications

Future demand for sol-gel powders and grains for use as advanced abrasives appears promising due to the ability of the sol-gel process to control grain size and shape, to guarantee uniform and homogeneous microstructures, and to take advantage of lower processing temperatures.[13] The principal advantage that sol-gel has over conventional abrasive production techniques[14] is the unique ability of sol-gel to produce small, submicron-sized particles; billions of submicron particles can be contained in one 60-grit abrasive grain with thousands of micron-sized cutting points in each grain. Although the abrasive grains shed micron-sized particles while grinding, new cutting edges are continually exposed. This enables less frequent sharpening or "dressing" of a cutting tool, and extended tool life. The advance in the production of longer-lasting abrasives which can operate at higher speeds provides to fabricators the capability of working on hard-to-grind materials, such as aerospace alloys and forged steels.[15]

Sol-gel alumina abrasive grains have been produced commercially by 3M Inc. and Norton Inc. since 1988.[16] Both firms use aluminum abrasive grains to produce such abrasive products as grinding wheels, coated abrasive belts, and sandpaper. Total U.S. sales of sol-gel abrasives are nearly $100 million per year. According to Norton Inc., the development of sol-gel abrasives represents a highly significant development in grinding wheel and coated abrasive applications, allowing the company to supply specialized customers such as aerospace manufacturers with abrasives tools that are lower maintenance and longer-lasting, leading to higher productivity and reduced grinding costs.[17]

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[12]According to research conducted by Donnelly Corp., electrochromic glass is capable of reducing cooling and electric lighting energy requirements for a building containing low-emissivity glass by 50-80 percent. (John P. Cronin and A. Agrawal, "Large Area Transmissive Electrochromic Devices," (Draft), 1995, p. 6).

[13]To produce an abrasive powder or grain, a gel is formed from an aluminum oxide monohydrate solution, then extruded or spread out to a convenient shape and carefully dried before being sintered and finally crushed.

[14]For example, "fused" processing, in which powders are heated in a furnace and cooled under controlled conditions to form abrasive grains.

[15]Edward J. Kubel Jr., "Development and Application of Seeded Sol-Gel Abrasives," *ASM News*, October 1989, p. 4.

[16]In processes developed by Norton Inc. (known as "Seeded Sol-Gel", or "SG") and 3M Inc. (known as "Cubitron"), alpha alumina particles, or, "seeds" are introduced to an aluminum oxide solution to yield an abrasive grain with near-theoretical density and hardness.

[17]Edward J. Kubel Jr., "Development and Application of Seeded Sol-Gel Abrasives," *ASM News*, October 1989, p. 4.

Fibers for Heat-resistant and Reinforcement Applications

Sol-gel processes can be used to prepare continuous, refractory, polycrystalline fibers[18] that display high strength, thermal resistance, stiffness, and durability. The advantage of the sol-gel process in forming fibers is that highly refractory and chemically durable fibers can be economically formed at room temperatures; these fibers are difficult to prepare using conventional high temperature processes.[19]

Sol-gel fibers are finding commercial use in the aerospace, industrial textile, and electrical industries because of their purity and their ability to resist heat and corrosive gases. Reinforcement applications for these fibers include use in fabric, tape, and cordage. Refractory textile applications include use in furnace belts, flame curtains, and high-temperature gaskets and cables. Continuous ceramic fibers can also be combined with other fibers, whiskers, or powders and formed into porous shapes for use as insulation in the aerospace/defense industries (including use as insulating tiles in the U.S. Space Shuttle program).[20]

3M Inc., the only known U.S. manufacturer of sol-gel fibers, currently produces small, commercial quantities of continuous filament ceramic fibers (Nextel™) for use in fabrics, tapes, sleevings and cordage. According to 3M, the high-temperature performance (including low shrinkage, abrasion resistance, and thermo-electric insulation properties) of Nextel 312 and 440 ceramic fibers is superior to inorganic fibers such as fiberglass, or fused or leached silica. Because of their ability to withstand high temperatures, Nextel fibers are also being considered for use in ***matrix-composite*** materials and in heat exchangers and radiant gas burner tubes in power-generating plants.

Porous Gels and Membranes for Insulation and Filtration Applications[21]

Porous gels and membranes are characterized by high surface area and small pore volume, making them ideal for applications in thermal and acoustical insulation, in filtration and separation systems, and in catalytic applications.[22] These materials are often difficult to produce using traditional ceramic processing methods. Sol-gel pore films and membranes offer a number of advantages over conventional materials:

- they can be used at high temperatures

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[18]Fibers are typically either drawn from solution or extruded from monolithic shapes that have been dried and sintered.

[19]For example, fibers for reinforcement of concrete and glass that contain more than 20 percent zirconia oxide are difficult to prepare conventionally because of high melting temperatures required. (C. Jeffrey Brinker and George W. Scherer, *Sol-Gel Science: The Physics and Chemistry of Sol-Gel Processing*, 1990, p. 862)

[20]John Mack, "Advanced Ceramics Processing; Cracking the Problem," *Materials Edge*, July/August 1990, p. 29.

[21]Porous gels are distinguished from membranes by pore size. The most common form of porous gels and membranes are aerogels, which are lightweight, nearly transparent, porous materials in which the particles and the pores between them have dimensions of less than 100 billionths of a meter.

[22]C. Jeffrey Brinker and George W. Scherer, *Sol-Gel Science: The Physics and Chemistry of Sol-Gel Processing*, 1990, p. 868.

- they do not swell or shrink in contact with liquids
- they are highly thermal- and abrasion-resistant
- pore sizes can be carefully controlled to avoid pin holes and cracks.

The principal immediate market for porous gels and membranes is likely to be thermal insulation, where much research is presently concentrated. Eventually, the use of these materials may also extend to the microfiltration of water, wine, and beverages; the ultrafiltration of milk; the separation of gases in various industrial processes; and environmental applications such as catalysts to reduce nitrogen oxide emissions in automobiles.

The NanoPore Co. (Albuquerque, NM), relying on research pioneered by Sandia National Laboratories and the University of New Mexico's Center for Micro-Engineered Ceramics in Albuquerque, has developed a sol-gel process for producing aerogel using normal pressures and temperatures rather than the high pressures and high temperatures required under older sol-gel technology.[23] NanoPore believes that its process will lead to quicker and less-costly commercialization of aerogel for use in refrigerators, water heaters, vacuum bottles, walls, and window panes.

Aerogel thermal insulation is reported to possess ten times the thermal insulating properties of ordinary glass fiber insulation. NanoPore's pilot aerogel production plant has a rated annual manufacturing capacity of 100,000 pounds and the firm anticipates that near-term markets for aerogel insulation could total $1-2 billion in annual sales within the next decade.[24] The company expects to begin commercial production of aerogel within the next two years provided certain performance difficulties are overcome which have limited their use in some insulation applications. One of the largest performance problems is poor light transmission (opacity), which has prevented the use of aerogel as a thermal barrier in window glazing, another potentially large market for aerogel.[25]

Aerogel thermal insulation is presently manufactured at a significant cost premium over conventional insulation. For example, glass fiber insulation and urethane insulation, produced commercially at a cost of 2-3 cents per board foot[26] and 6-7 cents per board foot, respectively, cost far less than aerogel insulation, which is produced at a cost of nearly 10 cents per board foot.[27] Although the cost of aerogel insulation presently exceeds conventional insulation by a factor of between two and four, it is reported that the higher thermal resistance achieved with aerogel insulation translates to significant weight and volume savings that makes aerogel insulation more cost competitive with conventional insulation.[28]

Joint Government/Industry Support of Sol-Gel Projects

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[23]Doug Smith, NanoPore Inc., telephone interview by USITC staff, Washington, DC, Aug. 1995.

[24]Ibid.

[25]"Aerogels Set to Take Off," *Chemical Engineering Progress*, June 1995, p. 14.

[26]A board foot is defined as a volume equal to 1 square foot multiplied by a thickness of one inch, or 144 cubic inches.

[27]Doug Smith, NanoPore Corp., telephone interview by USITC staff, Washington, DC, Aug. 1995.

[28]Ibid.

Both the U.S. and foreign governments have joined with private firms to assist in the development of products made using the sol-gel process. Support by the U.S. Government of promising technological projects, which often have difficulty attracting private capital, may have important commercial benefits for industry, contributing toward achieving higher levels of energy efficiency for the entire economy. The financial and technical assistance provided by such partnerships allows smaller firms, which tend to be less well capitalized than larger firms, to raise the large sums required to develop these expensive technologies. Access to government resources offers smaller firms a means of leveraging costs, thus neutralizing many of the financial advantages of some larger firms. In some cases, participation in a joint project has allowed participants to share research information and to pool scientific talent with Government agencies and with other organizations doing similar research, such as national laboratories and universities. Sharing research has resulted in certain technical breakthroughs for some firms that potentially shortens the lead time required to bring products to market.[29] Finally, industry representatives believe that continued backing by national governments of sol-gel projects lends credibility to the commercial products developed and serves to remove much of the uncertainty associated with adoption of new designs that incorporate these products. This is particularly true of sol-gel electrochromic coatings for architectural windows where the conservative nature of architects has reportedly proved an obstacle to the broader application of sol-gel products in construction markets.[30]

The U.S. Federal Government contributes to sol-gel development by funding various industrial efforts to commercially produce components using sol-gel. These efforts are made through a variety of federal agencies and programs, including the Advanced Technology Program (ATP) of the U.S. Department of Commerce's National Institute of Standards and Technology (NIST), the U.S. Department of Energy, and the Advanced Research Projects Agency (ARPA) of the U.S. Department of Defense (table 2). Barring an immediate termination of funding, the present period of anticipated reductions in federal expenditures for research and development projects is not expected to affect the funding of projects already underway. However, because these anticipated reductions will affect the funding of projects in the future, some agency officials feel they may dampen the enthusiasm of many in industry to present project proposals.[31]

Although detailed specific information on sol-gel related research and development funding by foreign private firms and governments is often not available, it appears that there has been a major commitment by leading industrial nations to develop advanced materials technology as a means of stimulating economic growth and competitiveness. Financing of sol-gel research and development in Europe is being done through private and public

[29] John Van Dine, SAGE Electrochromics Corp., telephone interview by USITC staff, Washington, DC, Aug. 1995.

[30] Dr. Niall Lynam, Donnelly Corp., telephone interview by USITC staff, Washington, DC, Aug. 1995.

[31] John Gudas, U.S. Department of Commerce, National Institute of Standards and Technology (NIST), Aug. 1995.

Table 2
Some current sol-gel related projects financed partially with Federal funds: Participants, U.S. government agency, product, and end-use

Participants	U.S. government agency	Product	End-use
Geltech Inc.	Department of Commerce (NIST)	Silica glass	Optical components
SAGE/3M/Rutgers	Department of Commerce (NIST)	Electrochromic glass	Architectural glass
3M	Department of Defense (ARPA)	Fiber	Aerospace and other structural applications
Aerojet/ Livermore National Labs/ Lawrence Berkeley National Labs	Department of Energy	Aerogel	Thermal and acoustical insulation products
Donnelly Corp.	Department of Energy	Electrochromic Glass	Architectural and automotive glass

institutions (both individual EU governments and through EU agencies). In Japan, there also appears to be considerable government involvement in sol-gel research and development. Support by the Japanese Government for sol-gel technology is channeled through its Ministry of International Trade and Industry (MITI) and is included with other technology assistance in a number of specific materials research projects. Such projects include: High-Performance Ceramics; High-Performance Materials for Severe Environments; Advanced Material and Machining System; and Advanced Chemical Processing Technology. Germany provides support for sol-gel projects principally through the Federal Research Ministry (BMFT),[32] which supports activities dedicated to the following sectors: Physical and Chemical Technologies; Ceramics and Glass; and Composite Systems.

Domestic Sol-Gel Activity

Following is a discussion of some projects financed, in part, by the U.S. Government. Many of these projects are still in the prototype stage but all are expected to result in commercial production within 3-5 years.

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[32]In 1994, the total ministry budget was DM 450 million.

U.S. Department of Commerce (Advanced Technology Program--ATP)

Geltech Inc. (Alachua, FL) received a $1.3 million grant under the ATP in 1994 to further develop its patented sol-gel process for the molding of high-purity silica glass for monolithic micro-optical components to be used as lenses, diffractive and refractive optical devices, and ***diffractive gratings***. These high-quality silica glass products are reported to have excellent broadband (ultraviolet to near-infrared) light transmitting properties[33] enabling their use in electronic sensors and in laser systems where they are used as diffractive gratings and micro-lens ***arrays*** to split incoming laser beam energy into many equal intensity beams. Traditional molding and finishing techniques often cannot be used to process silica glass for such high-performance optical applications because the high temperatures required in using these techniques are cost-prohibitive. Moreover, conventional grinding and polishing processes are limited in their ability to manufacture small and complex micro-optical components.[34] Geltech hopes to use its sol-gel process to cast ***net-shape*** silica glass micro-optical components at room temperature, resulting in products that are extremely pure and homogeneous, and are also lower in cost than products produced using conventional techniques. Thus far, Geltech has been manufacturing dense silica glass for optical products using sol-gel technology on a prototype basis, and expects to shortly begin commercial production.[35] Geltech has also begun commercial production of porous glass for electronic sensor applications as a direct result of its sol-gel work under the ATP grant.[36]

SAGE Electrochromics, Inc., in cooperation with 3M Inc. and the Rutgers University Center for Ceramic Research, was awarded an ATP grant of nearly $3.5 million in 1992 to facilitate the manufacture of electrochromic glass for use primarily in architectural windows (SAGEGLASS™). In this process, sol-gel technology is used to deposit several layers of thin films on a transparent glass base. The momentary flow of electric current to the glass base then alters the transparency of the glass from clear to heavily shaded. The largest potential application is in "smart windows," electronically controlled windows that conserve energy by automatically lightening or darkening, depending on the amount of sunlight, the time of day, the season, or the preference of the user. The amount of incoming sunlight could be regulated through simple operation of a switch or a remote control to allow buildings to be shaded on warm days and opened to sunlight on cloudy or winter days. Success in this application could eventually allow the process to be used to produce similar electrochromic coatings in sensors, superconductors, and optoelectronic circuits. SAGE is presently producing demonstration prototypes of its electrochromic glazing product and anticipates commercial production by 1997.[37]

U.S. Department of Energy

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[33] Jean-Luc Nogues, R. Layne Howell, "Fabrication of Pure Silica Micro-Optics by Sol-Gel Processing," July 1992, pp. 1-6.

[34] Jean-Luc Nogues, Geltech Inc., telephone interview by USITC staff, Washington, DC, Aug. 1995.

[35] Ibid.

[36] William Moreshead, Geltech Inc., telephone interview by USITC staff, Washington, DC, Aug. 1995.

[37] John Van Dine, SAGE Electrochromic Corp., telephone interview by USITC staff, Washington, DC, Aug. 1995.

Donnelly Corp. is currently in the first year of a three-year, $800,000 joint project with the U.S. Department of Energy to produce electrochromic glass for the architectural and automotive industries using the sol-gel process.[38] Donnelly anticipates that commercial production of its electrochromic glass will begin in the third year of this project.[39] The firm anticipates some resistance to its product in the marketplace due to its higher initial cost and the reluctance of some architects to depart from the practice of specifying familiar building materials with well-established properties. Similarly, automotive designers are also reluctant to introduce new design concepts to replace materials with proven acceptance in the marketplace. However, Donnelly Corp. is confident that once the advantages of electrochromic glass are demonstrated and the cost is reduced to more competitive levels, it will be able to effectively compete in these huge markets.[40] According to the company, the expected sales of electrochromic glass could exceed $1 billion within the next 5 to 10 years.[41]

Donnelly is confident that it will eventually lower the cost of its electrochromic glass from the present $30-35 per square foot to $15-25 per square foot as it continues to make technical innovations in product technology. At this lower cost level, electrochromic glass would begin to compete effectively with conventional low-emissivity glass produced at $10-12 per square foot. Donnelly is now focusing its research efforts on finding cost-effective means to produce electrochromic coatings.[42]

Aerojet Corp. (Sacramento, CA) has begun production and testing of organic aerogels as part of a 15-month, $2.6 million Cooperative Research and Development Agreement with Lawrence Livermore and Lawrence Berkeley National Laboratories. Commercial manufacture of these aerogels is expected to begin following the expiration of the agreement in 1996. Potential aerogel identified by Aerojet include refrigeration systems, automotive door panels, ceilings, catalytic converters, and a number of aerospace applications.[43]

U.S. Department of Defense (Advanced Research Projects Agency--ARPA)

3M Inc. is currently working with ARPA to develop Nextel 610, a new generation 99.5 percent aluminum oxide fiber to improve the strength and thickness of reinforced metal-matrix and ceramic-matrix composites. Thus far, 3M has supplied a limited quantity of Nextel 610 fibers from its pilot plant to ceramic composite manufacturers for experimental use in aircraft engines. 3M also anticipates selling Nextel 610 fibers to reinforce metals such as aluminum or titanium for use in aerospace applications such as missile fins, and for strong, lightweight parts for aircraft, bicycle frames, or automobiles. The company

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[38] Dr. Niall Lynam, Donnelly Corp., telephone interview by USITC staff, Washington, DC, July 1995.

[39] Eugenie Uhlmann, Donnelly Corp., telephone interview by USITC staff, Washington, DC, July 1995.

[40] Dr. Niall Lynam, Donnelly Corp., telephone interview by USITC staff, Washington, DC, July 1995.

[41] John P. Cronin and A. Agrawal, “Large Area Transmissive Electrochromic Devices,” (Draft), 1995, p. 1.

[42] Anoop Agrawal, Donnelly Corp., telephone interview by USITC staff, Washington, DC, Sept. 1995.

[43] "Aerogels Set to Take Off", *Chemical Engineering Progress*, June 1995, p. 16.

anticipates a ten-year time horizon before large-scale production and commercialization of Nextel 610 begins.[44]

Foreign Sol-Gel Activity

The following is a brief discussion of some of the known sol-gel activities by foreign competitors.

Schotte Glaswerke (Germany) is the world's leading volume producer of optical coatings using sol-gel technology, producing reflective and anti-reflective products used in computer monitors, meter faces, and large-area display glass. Asahi Glass and Hitachi of Japan are also seeking to establish commercial production of sol-gel optical coatings for use in similar applications. There is no known foreign commercial production of electrochromic glass; however, Pilkington Ltd. (United Kingdom), New Materials Technology Corp. (Germany), Saint-Gobain (France), and Toyota and Nikon in Japan are seeking to commercially develop this technology. Pilkington and New Materials Technology will reportedly begin commercial production of electrochromic glass by late 1996 or early 1997.[45] In addition to its production and research facilities in the United States, Donnelly Corp. also has facilities in Ireland, France, and Germany from which it intends to eventually supply the European market with sol-gel coated materials.[46] Although there is yet no known foreign commercial production of aerogel, a number of foreign firms are producing aerogel on a prototype basis with commercial production expected soon. Both BASF and Hoechst of Germany are producing aerogel in pilot plants with commercial production reported to be imminent. BASF reportedly has annual aerogel production capacity of 100,000 square meters in its plant and will soon begin selling aerogel for use as a translucent (semi-transparent) thermal insulating barrier in window glazing.[47] Hoechst is manufacturing aerogel under technology licensed by NanoPore Inc. (United States). The manufacture of aerogel for use in the refrigerator and hot-water heater markets is being encouraged by tighter environmental legislation in Germany.[48] Despite its higher initial cost, aerogel use is being encouraged in Germany because it is easier for refrigerator manufacturers to handle, process, recycle, and reuse aerogel than conventional insulation.[49] Airglass (Sweden) is preparing for commercial production of aerogel in a plant capable of producing nearly 100,000 pounds of aerogels annually, comparable to the rated capacity of NanoPore’s pilot plant.

Outlook for Commercial Production

[44] Robert Carlton, 3M Corporation, telephone interview by USITC staff, Washington, DC, Aug. 1995.

[45] Dr. Helmut Schmidt, New Materials Technology Corp., telephone interview by USITC staff, Washington, DC, Nov. 1995.

[46] Eugenie Uhlmann, Donnelly Corp., telephone interview by USITC staff, Washington, DC, Nov. 1995.

[47] Dr. Helmut Schmidt, New Materials Technology Corp., telephone interview by USITC staff, Washington, DC, Nov. 1995.

[48] "Aerogels Set to Take Off," *Chemical Engineering Progress*, June 1995, pp. 17-18.

[49] Ibid.

The principal obstacles to wider use of the sol-gel process in manufacturing are the related problems of cost and performance. Because sol-gel is still a relatively expensive production process, its use presently can only be justified, on a cost basis, for high-performance applications which tend to be low-volume. Manufacturers of sol-gel components believe the cost of such components eventually will substantially decline. This is expected to occur through a combination of increased demand sufficient to allow average production costs to decline, and further technical breakthroughs aimed at reducing manufacturing costs of sol-gel products to costs of competing products. Another obstacle is the requirement to develop manufacturing processes that guarantee consistent high-volume production of quality components. Because of existing low production levels for many sol-gel products, process technology has not advanced sufficiently to produce components of a consistent level of quality. Further advances and refinements in processing technology are needed to guarantee consistent levels of quality before large production runs can begin.[50]

Existing large-volume markets which sol-gel manufacturers expect to enter include markets for architectural and automotive glass, and for thermal and acoustical insulation. Within the next 5 to 10 years, the expected sales of electrochromic glass used in architectural and automotive applications could exceed $1 billion.[51] Manufacturers are seeking to demonstrate the ability to produce consistent, high-quality material in the dimensions required for architectural and automotive glass at a competitive cost.[52] Entry into these markets would allow manufacturers to produce in sufficient quantities to demonstrate consistent high quality and also to realize economies of scale, thereby reducing costs further.

Similarly, the market potential for aerogel use in thermal and acoustical insulation is also potentially large; estimates of potential U.S. annual sales of aerogel products over the next decade approach $2 billion.[53] Commercial prospects for aerogel depend on the ability of manufacturers to resolve technical problems such as opacity and to reduce costs to levels that would make aerogel insulation competitive with conventional insulation. Industry officials believe that further reductions in the cost of producing aerogel, combined with aerogel's superior thermal qualities, will eventually unlock this large potential market.

Many of the advanced technology markets for sol-gel products do not presently exist in volumes large enough to justify increased volume production of sol-gel components. However, this situation is likely to change as such devices as optical lasers, optical waveguides, solar cells, and optical fibers find increasing applications in the 21st century.

[50]Doug Smith, NanoPore Inc., telephone interview by USITC staff, Washington, DC, Aug. 1995.

[51]John P. Cronin and A. Agrawal, "Large Area Transmissive Electrochromic Devices," (Draft), 1995, p. 1. This market estimate is based on gaining just a small market penetration of the more than 35 million new cars and trucks produced annually worldwide, and a modest penetration of the market for low-emissivity windows, which now command 40 percent of the residential window market and nearly 30 percent of the commercial window market.

[52]Dr. Niall Lynam, Donnelly Corp., telephone interview by USITC staff, Washington, DC, July 1995.

[53]Doug Smith, NanoPore Inc., telephone interview by USITC staff, Washington, DC, Aug. 1995.

The U.S. Government has played an important role in facilitating the financial investment and innovative research efforts required to bring this technology to market and to match research and development efforts of foreign governments. A variety of jointly funded U.S. programs have committed significant resources to developing the commercial viability of this technology. Continuation of joint efforts is viewed by some industry officials and end-users as an important component in ensuring the domestic commercial success of this promising technology, and global competitiveness in this new technology field.

Recent Developments

Although commercial application of sol-gel technology continues to be concentrated in sol-gel abrasives, its use in the manufacture of films, coatings, powders and grains, fibers, and porous gels and membranes for other end-use industries has grown rapidly in recent years. Total U.S. sales of sol-gel produced products rose from less than $200 million in 1995 to nearly $300 million in 1997, of which approximately $200 million is sales of sol-gel abrasives. For nonabrasive end-uses, the use of sol-gel to produce silica glass for optical products was largely being done on a prototype basis in 1995. Today, the sol-gel process is being used to commercially produce silica lenses for the electro-optics industry. Although the grant to Geltech Inc. (Orlando, FL) for prototype production of high-purity silica glass for monolithic micro-optical components under the ATP (Advanced Technology Program) expired in 1997, the sol-gel technology developed through the ATP allowed the firm to begin commercial production of porous glass for use in electronic sensors designed for home monitoring systems. The company currently produces more than 100 million units of such glass annually. Geltech's development work in sol-gel also was instrumental in the firm's selection for a U.S. Department of the Army contract for $500,000 to build prototype windows molded in silica. The windows will be mechanically hard, transparent to visible and infrared light, resistant to laser radiation, and possess the necessary optical quality for military and commercial applications. Eventual applications include night-vision optics, imaging systems for tank periscopes, surveillance camera systems, and power-limiting devices for commercial systems.[54]

The manufacture of porous gels and membranes for thermal insulation is still largely in the product development stage but is nearing commercial availability. Some joint commercial production of aerogel by Allied Signal Corp. and the NanoPore Corp. (Albuquerque, NM) is used by the semiconductor industry. NanoPore, in combination with Sandia National Laboratories, the University of New Mexico, and the U.S. Department of Energy has also developed a sol-gel process for producing aerogels which has reduced product cost from as high as $45/kg to as low as $7/kg, a price at which it begins to compete with conventional glass-fiber insulation.[55] NanoPore is currently producing aerogel at its pilot plant in Illinois and soon expects to begin commercial production of more than a million pounds of aerogel annually, dedicated largely for the building construction market.[56] According to NanoPore officials, aerogel thermal insulation possesses 10 times the thermal insulating properties of

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[54]William Moreshead, Senior Scientist, Geltech Inc., telephone interview by USITC staff, Washington, DC, Nov. 1997 and product information supplied by Geltech.

[55]"Low-Cost Method for Aerogels," *R&D Magazine*, Sept. 1996, p. 51.

[56]Doug Smith, President, NanoPore Inc., telephone interview by USITC staff, Washington, DC, Nov. 1997.

ordinary glass fiber insulation; the total market for aerogel insulation could reach $1 to 2 billion by 2005.[57]

The market for sol-gel coatings for use in electrochromic glass used in the manufacture of "smart windows", continues to advance. Donnelly Corp. (Holland, MI), a commercial producer of sol-gel optical barrier coatings for electrochromic displays, has been involved in a project, financed partly by the U.S. Department of Energy, to produce optical glass coatings using sol-gel processing for the architectural market. As a result of technology developed during this project, Donnelly has decided to build a pilot plant to produce 5,000 to 10,000 square feet of electrochromic glass in 1998. The cost of the glass produced is likely to be in the range of $30 to $35/square foot, compared with conventional low-emissivity glass, which is produced at $10 to $12/square foot. Donnelly remains confident that as production is scaled up, average cost will fall to $15 to $25 per square foot, a level at which such glass competes directly with conventional low-emissivity glass. Annual market potential for electrochromic coatings has been estimated at $1 to $2 billion by 2005.[58]

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[57]Ibid.

[58]Officials of Donnelly Corp., telephone interview by USITC staff, Washington, DC, Nov. 1997.

Glossary of Terms

Aerogel	The most common form of porous gels and membranes, which are lightweight, nearly transparent, porous materials in which the particles and the pores between them have dimensions of less than 100 billionths of a meter.
Arrays	An arrangement of micro-lenses of equal diameter and curvature which are assembled into compact units. Micro-lens arrays are typically used in semiconductor laser devices.
Colloid	A state in which small particles of solid, liquid, or gas are distributed in a gas, liquid or solid. The dispersed particles are so small that they do not form an obviously separate phase, but they are not so small that they can be said to be in true solution.
Diffractive grating	An optical device, used in laser systems, to produce discrete beams of energy by diffracting various incoming wavelengths of electromagnetic energy.
Electrochromic glass	Glass or layers of glass upon which several layers of thin, transparent, and conductive coatings of materials such as tungsten oxide are deposited. By varying the amount of electrical energy supplied to the glass, the transparency of the coatings can be altered to vary the amount of light or heat penetrating the glass.
Gel	A colloid in which a liquid contains a solid arranged in a fine network extending throughout the system to produce a viscous, jelly-like product.
Low-Emissivity	A surface coating for glass that permits the passage of most shortwave electromagnetic radiation (especially light), but reflects most longer-wave radiation (heat).
Matrix-composites	Advanced materials in which discrete or continuous reinforcing fibers are embedded in a matrix, often of metal or ceramic. Composites have very high strength and stiffness in the direction of the fibers.
Monoliths	Bulk gels that are cast to complex shapes. Monolithic gels are often formed at room temperature and consolidated into final shapes at lower temperatures.
Nanometer	A unit measuring thickness in billionths of a meter.
Net-shape	A processing method which is used to produce a semi-manufactured part which is close to the final manufactured part.

Eliminates the need for extensive and more costly finishing operations.

Oxide A binary compound of oxygen with another element. Most oxides are prepared by reacting an element with oxygen at an appropriate temperature.

Porosity The state of a material which allows the passage of gas or liquid through pores in the material. Porosity varies with the particle size of the material.

Precursor An intermediate compound used in the formation of specific final materials.

Refraction The change of direction in the propagation of a light wave as it passes through a medium such as glass.

Sintering The bonding of adjacent surfaces in a mass of particles by molecular or atomic attraction. Sintered materials are heated at temperatures below the melting temperature of any component part in the material.

Sol Sometimes known as a colloidal solution. A liquid colloidal dispersion.

Solution A uniformly dispersed mixture, at the molecular or ionic level, of one or more substances (the solute) in one or more substances (the solvent). These two parts of a solution are called phases.

Stoichiometry The branch of chemistry that deals with the quantities of substances that enter into and are produced by chemical reactions.

Substrate Any solid surface on which a coating or layer of a material is deposited.

Vapor Deposition A process used to apply a thin coating with a desired set of properties to an inexpensive substrate. The most popular vapor deposition methods used by industry include Chemical Vapor (CVD) and Physical Vapor Deposition (PVD).

Direct Ironmaking: A Case Study in Government and Industry Cooperation to Commercialize Manufacturing Processes for Materials

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This article examines a U.S. government-industry project to develop and commercialize direct ironmaking. This process eliminates the traditional and increasingly expensive coke processing element of steelmaking, which is considered important to improving the competitiveness of the U.S. steel industry. This article explores key factors affecting commercialization of direct ironmaking, the role of industry and government institutions involved in its research and development, the status of competing processes abroad, and the result of the joint project.

Since this article was first published in the <u>Industry, Trade, and Technology Review</u> *of May 1995, the joint U.S. industry-Government effort to develop an alternative ironmaking process was concluded, but additional commercialization funding has not been provided. However, several other technologies developed abroad have moved closer to commercialization. Beyond the already widely used Corex process, it appears that the Russian Romelt process will be the next smelting process to be commercialized. Competing with the smelting technologies are several other processes that use the direct reduction method to produce direct reduced iron (DRI). Midrex and Hylsa are already widely used; several others are near commercialization. Given budgetary constraints, it is unlikely that the U.S. Government will fund further work in developing an alternative ironmaking process. The concluding section of this article elaborates on recent developments.*

Note: A glossary of technical terms and abbreviations (highlighted within the article by ***bold italics***) appears at the end of this article.

Increasing competition abroad and rising costs at home have spurred efforts by the U.S. steel industry to develop and commercialize new technologies that will increase efficiency and productivity, lower production costs, and improve material characteristics. A recently concluded 5-year pilot project funded by the U.S. Department of Energy (DOE) and the American Iron and Steel Institute (AISI) explored the technical and economic viability of direct ironmaking,[1] pursuing a process based on bath ***smelting***.[2] The consensus of the domestic and international steel industry is that bath smelting is the prime technology of the future of high quality iron production for steelmaking.[3] The joint project to develop direct ironmaking in the United States is one of several efforts underway worldwide to incorporate the smelting technology into the steelmaking process.

The purpose of the AISI-DOE direct ironmaking project was to develop a cost-effective, efficient, and environmentally safe technology that will reduce costs and, in the long run, increase the productivity of steel producers. For the ***integrated*** steelmaker, the blast furnace is the primary vehicle for producing molten iron, of which ***coke*** is a major input. As ***metallurgical coal*** reserves in the United States declined and the costs associated with cokemaking rose, steelmakers began to pursue the direct use of coal in ironmaking, including pulverized coal injection (PCI) in blast furnaces. These methods can partially reduce the amount of ***metallurgical coke*** needed to produce iron (known as the coke rate), whereas cokeless bath smelting technology would replace coke altogether.

There are several reasons the direct ironmaking project was initiated. The American steel industry is facing potential capital investment costs, running into billions of dollars, as a large portion of its cokemaking capacity nears the end of its design life. Increasingly stringent environmental regulations[4] have raised both the capital and operating costs of coke oven batteries, generating the need to explore technologies that would eliminate this step from the integrated steelmaking process. A description of the past, current, and anticipated future processing methods of steelmaking are outlined in figure 1.

Foreign steel industries, facing similar challenges, have also pursued research in the area of direct ironmaking technology, and two have been identified as front-runners in the race to commercialize the technology: Corex, which has already been commercialized by Austria's Voest-Alpine Industrieanlagenbau (VAI), and DIOS of Japan. The status of these technologies is discussed later.

The challenge for these new processes, however, is that adoption by the industry depends not only on the technical proficiency of the new technology, but also on proven, significant potential for economic advantage over the traditional coke oven or ***blast furnace*** method.

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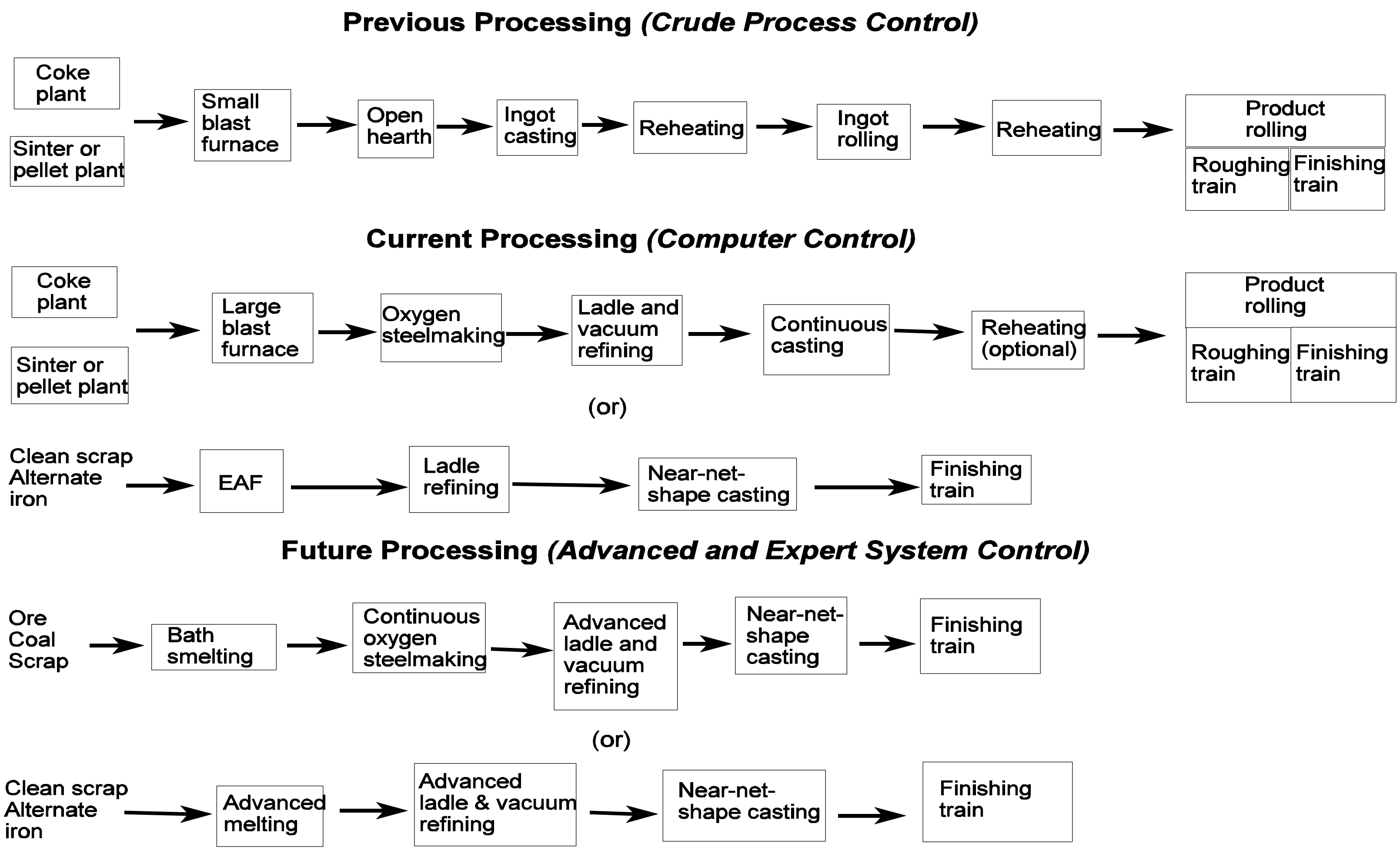
[1]The phrase "direct steelmaking" is often used interchangeably with the term "direct ironmaking." Because products resulting from this process are expected to be high carbon iron, not steel, this article will refer to the process as "direct ironmaking."

[2]In bath smelting, oxygen, prereduced ***iron ore pellets***, coal and ***flux*** are charged into a molten ***slag*** bath containing a high percentage of carbon. Slag is an accumulation of the impurities released from the ore that collect on the surface of the bath during smelting. The carbon removes oxygen from the iron ore and generates carbon monoxide and liquid iron. Oxygen is then injected to burn some of the carbon monoxide gas before it leaves the smelting vessel (***post combustion***). The heat from the burning gas then generates a portion of the energy used in the reduction of the ore in the bath. The partially combusted gas is used to preheat and prereduce the ore, which means removing a portion of the oxygen content before the ore is injected into the bath. American Iron and Steel Institute, *Direct Steelmaking Program*, AISI, p. 4.

[3]Paul Millbank. "Direct Route To Iron Gathers Momentum," *Metal Bulletin Monthly Supplement*, Apr. 1995, p. 24.

[4]The 1990 amendments to the Clean Air Act tightened regulations on coke oven emissions.

Figure 1
Past, current, and anticipated steelmaking processing methods



Source: Based on Fruehan, R.J., "Challenges and Opportunities in the Steel Industry," *Iron and Steelmaker*, Mar. 3, 1993, p. 59.

Confirming that these two criteria were achievable through the direct ironmaking process was the goal of the AISI-DOE pilot project.

DOE's involvement in this project was made possible through legislation known as the Steel Initiative of 1986.[5] This legislation was a result of proposals by the President's Council on Industrial Competitiveness to support joint research efforts by the industry and national laboratories. The substance of the bill was developed by a DOE-AISI joint task force, and mandates that costs of research and development of new technology be shared toward achieving the purpose of saving energy, increasing competitiveness, and generating benefits for the entire industry.

The DOE-AISI collaboration is an example of government involvement to enhance the competitiveness of U.S. industries through cooperative technology development. The effort to develop the direct ironmaking process for commercial use demonstrates a convergence of interests, and is unique in light of multiple company-industry-government cooperation and the role of environmental regulation driving new process adoption. The mixed results of the joint AISI-DOE direct ironmaking program may have implications for future government-industry cooperative initiatives.

DOE-AISI Pilot Project Background

In 1987, AISI assembled a task force to select the process most likely to improve competitiveness of the U.S. steel industry and to outline a program of research and development to facilitate rapid implementation of the technology. After an extensive review of cokeless iron and steelmaking technologies that were already under development worldwide, the task force concluded that future steelmaking should be based on a coke-free, coal-based bath smelting process for the production of the hot metal that is subsequently refined to steel.[6] However, the task force determined that foreign technologies under development did not adequately meet certain requirements of the North American steel producer,[7] including a coal-based operation that utilized pelletized iron ore feed,[8] a process that maintained the flexibility to melt ***scrap*** as well as the ability to generate excess energy for other uses, and a process that resulted in substantial reductions in capital and

[5]The Metals Initiative Program of 1988, which was established by the Steel and Aluminum Energy Conservation and Technology Competitiveness Act of 1988, augments the Steel Initiative by expanding its mandate to encompass a wider variety of metals. Its purpose is twofold: (1) to "increase the energy efficiency and enhance the competitiveness of American steel, aluminum and copper industries...; and (2) to continue steel research and development efforts begun under the Department of Energy (DOE) program known as the Steel Initiative." *Steel and Aluminum Energy Conservation and Technology Competitiveness Act of 1988 Annual Report* (Washington, DC: U.S. Department of Energy, Feb. 1990).

[6]Egil Aukrust, *AISI Direct Steelmaking Program Final Technical Report*, U.S. Department of Commerce, Technology Administration, National Technical Information Service, Springfield, VA, Aug. 1994, p. 2.

[7]J.M. Farley and P.J. Koros, *AISI-DOE Direct Steelmaking Program*, AISI, Jan. 30, 1992, p. 1.

[8]There is a large, modern installed capacity for production and transport of pellets in North America. According to statistics compiled by *Skillings Mining Review* (July 30, 1994), total U.S. and Canadian iron ore pellet plant production in 1993 was 73.7 million metric tons, with an estimated 9 percent increase in 1994 to 80.3 million metric tons. Total annual capacity is 87.1 million metric tons.

operating costs. As a result, the task force recommended that AISI propose a research and development program for joint funding by the industry and DOE. Two years of proposal development and assessment were involved before work on the DOE-AISI program actually began in November 1988. The chronology of project development is outlined in table 1.

Table 1
Chronology of project development

Apr. 1987	DOE issues Steel Initiative Management Plan, which provides a framework for implementation of research programs, and follows with a research plan identifying a number of key areas where the steel industry could benefit from advanced technology, including direct ironmaking.
Aug. 1987	AISI assembles a task force to explore existing domestic and foreign technologies that could be further developed to enhance the U.S. steel industry's competitiveness.
July 1988	AISI submits a research proposal to the DOE for development of a direct ironmaking process.
Nov. 1988	Work begins on the AISI-DOE direct ironmaking project.
Dec. 1988	On recommendation from the House Committee on Science, Space and Technology, Congress enacts an amendment to the Steel Initiative, which substantially increased funding of the direct ironmaking project.
May 1989	The AISI-DOE Cooperative Agreement for the direct ironmaking project is approved by the DOE.

Source: AISI.

Management and Funding

The projected budget of the joint AISI-DOE project was $30 million for 3 years. Subsequent amendments extended the project to March 31, 1994, a total of 5 1/2 years, with a total cost of $60.3 million. DOE provided $46.3 million (77 percent), while AISI provided the remaining $13.9 million (23 percent).

Cooperating organizations provided services, personnel, equipment, and technical expertise to the project. Research encompassed three coordinated efforts: university research[9] on pellet-slag-coal reactions; industrial research[10] on prereduction, BOF postcombustion, and heat transfer; and research conducted at the pilot plant to experiment at the 15 ton scale with process performance. No national laboratories were involved in this project.[11]

A Technical Advisory Committee consisting of senior professional personnel from the steel industry was created to oversee technical issues and to provide individual project

[9]Research related to the program was conducted at Carnegie Mellon University (CMU), Massachusetts Institute of Technology (MIT), University of British Columbia (UBC), McGill University (McG), McMaster University (MU), and at the U.S. Steel (USS) and the Union Carbide Industrial Gases Technical Centers. Farley and Koros, *AISI-DOE Direct Steelmaking Program*, pp. 2-3.

[10]Involved organizations included International Business Machines (IBM), North American Refractories Co. (NARCO), Linde Industrial Gases, EG&G, U.S. Steel, and Dofasco Steel, Inc., among others.

[11]Egil Aukrust, AISI, conversation with USITC staff, Mar. 13, 1995.

managers.[12] The pilot plant was located at a donated U.S. Steel site in Universal, Pennsylvania, under the management of the AISI through a board of directors composed primarily of industry experts from the various AISI member companies. DOE maintained a significant involvement in the project through its membership on the board, its review of all technical activities, and its joint effort with AISI in developing detailed progress reports on the project. The relationships are depicted in figure 2.

Foreign Government Support of Competing Technologies

There are several competing cokeless ironmaking processes that are in various stages of development around the world. A brief comparison of these processes and of their current status provides a useful perspective on which to gauge the progress and objectives of the AISI-DOE research initiative. The principal competing foreign technologies include the Corex process, DIOS (direct iron ore smelting), HIsmelt, and Jupiter. The development of these direct ironmaking processes have benefitted from foreign government involvement to varying degrees.

Corex

The Corex process[13] was developed when gas prices increased significantly at the end of the 1970s. As a result, interest in natural gas-based iron ore reduction processes waned, and interest in coal-based processes increased. Development of Corex started in 1981 and is currently the only proven, commercialized direct liquid ironmaking technology. The Austrian and German Governments reportedly funded the pilot plant in full, but the terms are unclear.[14]

Corex has been in commercial use since December 1989[15] when ISCOR, the South African steel producer, brought a 300,000 million ton per year (tpy) facility on line. Pohang Iron and Steel Company (POSCO) of South Korea subsequently began construction of a Corex plant in late 1992 (startup scheduled for late 1995) with an annual capacity of 700,000 million metric tonnes per year (mmtpy), effectively moving the Corex process into higher

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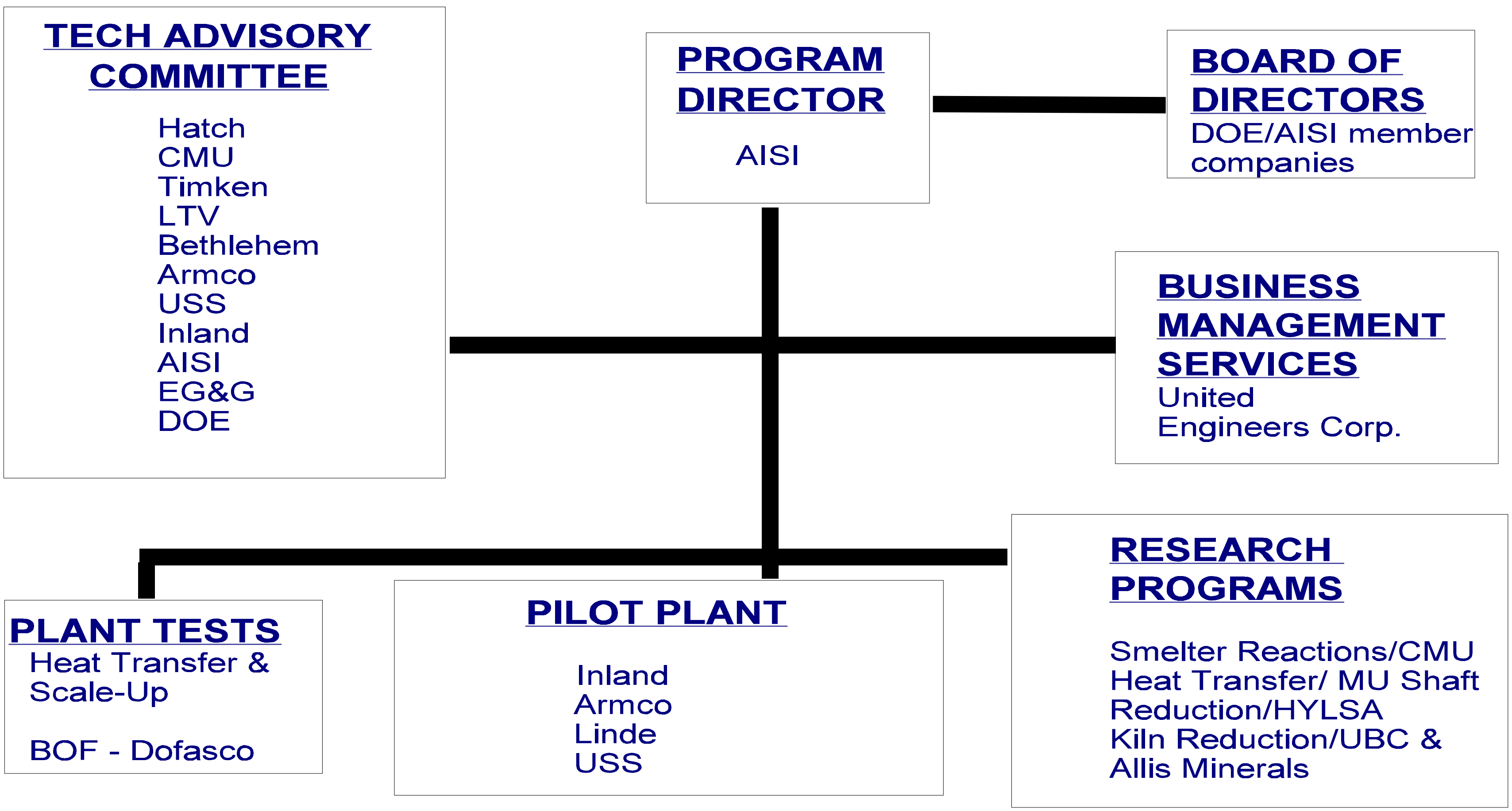
[12]Farley and Koros, p. 3.

[13]Corex utilizes a dual chamber operation where solid iron ore is reduced in the upper chamber and them melted in the lower chamber where coal and oxygen are generating heat and reducing gases. Because the reactions are compartmentalized, coke is no longer needed to provide burden support. In addition, lower grade coals and ores, which are more readily available worldwide, can be utilized.

[14]Former Korf official, interviewed by USITC staff, Apr. 28, 1995.

[15]Official of the Robert Westman Co., U.S. licensee for Corex, phone interview with USITC staff, Mar. 22, 1995.

Figure 2
Framework of Program Management for DOE-AISI Direct Ironmaking Project



Source: Farley and Koros, p. 8.

volume iron production. At present, Voest-Alpine has received new orders from Turkey, India, and Korea[16] for plants with production capacity up to 600,000 tpy, and there is reported significant interest by the former Communist countries.[17]

The Corex process in the United States may get financial support from the DOE. Airproducts and Chemicals Inc., Centerior Energy Corp., and Geneva Steel Co. plan to jointly invest money in a Corex ironmaking plant to be built at Geneva's Vineyard, Utah mill, which will produce 3,000-3,200 tons per day (tpd) of hot metal and generate 250 megawatts of electricity from byproduct gases. The Department of Energy, through its Clean Coal Technology program, had originally approved partial funding for a Corex installation at another steelmaker's facility. The Geneva plan envisions the DOE contributing $150 million of the project's $825 million total cost. The partners must obtain DOE approval to relocate[18] the project to Utah, however, and negotiate the Department's cooperative role. Negotiations, presently underway, are expected to conclude in July, 1995. A 1999 operational start-up date is expected.[19]

DIOS

The DIOS process[20] has been the subject of cooperative research between the Japan Iron and Steel Federation (JISF), Japan's eight integrated steelmakers, and the Center for Coal Utilization in Japan. According to the Japan Iron and Steel Federation, the research project has been supported since 1988 with subsidies and aid by the Ministry of International Trade and Industry (MITI).[21] The 7-year project was budgeted at 13 billion yen (approximately $100 million), two-thirds of which was provided by MITI.[22] In developing the DIOS process, JISF has been holding technology exchange meetings with counterparts of various countries in an attempt to foster international cooperation in the technology development process.[23]

Operations at the 500 tpd pilot plant at NKK Keihan's works began in December 1993 and

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[16]India's Jindal Group placed an order in July 1996 for a 640,000 tpy Corex plant to be built in Karataka state to serve a new hot rolled steel plant, and a letter of intent has been signed for a second unit. The first is expected to be in operation by late 1997. A month after the Jindal order, South Korea's Hanbo Steel and General Construction ordered two 750,000 tpy Corex plants; startup is expected in mid-1997.

[17]"The Impact of Changes in the Iron and Steel Industry on Coal-tar Production from Coke Ovens," *Steel Times*, May 1994, p. 175.

[18]DOE had originally approved funding to help install a Corex reactor at LTV Steel Company's Cleveland (OH) Works. However, LTV's plans were tabled in 1994 reportedly because earnings projections on electricity were not satisfactory. "Geneva, At Last, May Get Corex," *33 Metalproducing*, Nov. 1994, p. 9.

[19]Dr. Lowell Miller, Associate Deputy Assistant Secretary, Clean Coal Technology Program, phone interview with USITC staff, May 17, 1995.

[20]The DIOS process uses pressure to retard gas velocity, cut coal consumption, and promote carbon monoxide combustion. Ore pellets are fed into a fluidized bed reduction furnace at the same time that coal is injected through the bottom. Partially reduced ore and tar then move into a smelting furnace that is fed coal and oxygen simultaneously.

[21]"Research On A Next-Generation Ironmaking Process," *Steel Today and Tomorrow*, July-Sept. 1994, p. 7.

[22]Representative of the Japan Steel Information Center, interviewed by USITC staff, Mar. 21, 1995.

[23]"Research On A Next-Generation Ironmaking Process," *Steel Today and Tomorrow*, p. 8.

will run through 1995, at which time a formal assessment will be made by the participating companies as to the success of the project. According to JISF, the DIOS process is expected to reduce costs by about 10 percent and to cut carbon dioxide emissions 5 to 10 percent compared with blast furnace ironmaking. Other anticipated benefits include the direct use of nonmetallurgical coal for greater flexibility in selecting resources (Japan has no metallurgical coal reserves) and facility and energy cost reductions because of the elimination of the iron ore ***sintering*** and cokemaking processes. Full commercialization of DIOS is expected by the year 2000.

HIsmelt

The Australian company CRA Ltd. and Midrex Corporation of North Carolina formed a 50-50 joint venture in 1989 to develop a direct smelting process, known as HIsmelt.[24] These partners have spent approximately $200 million developing the process, including the construction of a 150,000 tpy demonstration plant at the HIsmelt Research and Development in Kwinana, Western Australia. HIsmelt has been entirely financed by the two partners, without any government support.[25] HIsmelt is ideal for Australian steel producers because it is suited to Australia's Pilbara iron ores, and for iron production using low-cost iron ores and nonmetallurgical coals.

Jupiter

The European program, Jupiter,[26] was the result of an initiative started in 1989 by the French steelmaker Usinor-Sacilor looking for a smelting reduction process to supply virgin metal to electric steelmaking plants. The development of the Jupiter concept was supported by research work by IRSID (Usinor-Sacilor Process Research Center). Jupiter received partial funding from the European Coal and Steel Community (ECSC), a predecessor to the European Union.[27] The remainder of the financial support was generated by the three European companies: Usinor, Lurgi, and Thyssen Stahl. Although demonstration of the feasibility of the reduction process on a pilot plant scale was under discussion, the Jupiter program was apparently abandoned last year.

Research Goals and Results

[24]HIsmelt uses a circulating fluid bed reactor for preheating and prereduction. Hot blast air is used for the initial combustion of the coal because the nitrogen in the air is believed to promote heat transfer and to control postcombustion temperatures. Smelting begins with the bottom injection of coal which is dissolved in the bath. The dissolved carbon is used to reduce the iron ore, releasing carbon monoxide which is post-combusted by injecting oxygen in the bath.

[25]Official of Midrex Corp., interviewed by USITC staff, Mar. 21, 1995.

[26]The Jupiter process is unique in that coal gasification occurs in the reduction process (the others are based on the gasification of coal in the smelting reaction and on the direct use of the resulting gas in the reduction, both reactors being physically and metallurgically linked), and, therefore, secures the reducing gas and energy requirements. In this first step, it delivers a mixture of directly reduced iron and char, which is used in a melting process using both fossil fuel (residual char) and electric energy. The resulting gas from melting is thus not used for reduction.

[27]Funds for ECSC research grants are drawn from monies collected from producers via a tonnage-based production levy.

AISI directed its research efforts in the direct ironmaking project to address perceived deficiencies in the other technologies being developed abroad. For example, the AISI task force had determined that the most advanced process, Corex, which was operating on a demonstration basis in South Africa at the time, was inadequate since it did not employ the post-combustion process needed to ensure thermal balance. In addition, the economic viability of the Corex process, largely based on the significant byproduct production of low-BTU gas, was questioned by the task force.[28]

The AISI-DOE project sought to develop optimum designs and operating techniques for the smelter and associated equipment as well as to solve engineering problems involved in making the process work economically on a commercial scale.[29] AISI initially expected that its process would have reduced direct operating costs by $10 to $25 per ton of steel produced, compared to the present coke oven-blast furnace-basic oxygen furnace (***BOF***) technology. The energy cost savings are estimated at about 20 percent.[30]

In addition, AISI believed that its research had potential for application by minimill (***non-integrated***) producers using the electric arc furnace (***EAF***), which account for almost 40 percent of the steel produced in the United States today and 31 percent of steel produced worldwide.[31] AISI's direct ironmaking process was intended to enable the iron to be cast into "***pigs***" that could compete economically as input in EAF production with high-quality scrap, which is becoming more scarce worldwide.

The joint AISI-DOE direct ironmaking project ended in March, 1994, revealing a gap between the actual results obtained at the pilot plant and the established goals for productivity and fuel rate. This gap, which affects both capital and operating costs, is estimated to be approximately 40 percent in the case of ***high volatile coals***. Nevertheless, AISI expressed optimism that the gap can be closed by addressing the deficient aspects of the process.[32] These include improved distribution of oxygen through the application of side-blown tuyeres,[33] better distribution of raw materials in the reaction vessel, the use of newly developed sensors to measure foam height and to observe char distribution and behavior within the pressurized vessel, and cooperative information exchanges with other smelting programs.

According to AISI's final technical report, the pilot plant project indicates that the process fundamentals, on which the joint program was initiated, are valid. Further, it notes that despite the shortfalls, several steel companies view the results to be sufficiently encouraging to consider building a demonstration plant.[34] Comparative savings in the capital and operating costs for the coke oven-blast furnace and AISI processes of ironmaking are

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[28]AISI, *Direct Steelmaking Program*, p. 4.

[29]Ibid.

[30]Ibid, p. 2.

[31]International Iron and Steel Institute, *Steel Statistical Yearbook 1994*, Committee on Statistics, Brussels, 1994, pp. 12-13.

[32]American Iron and Steel Institute, "AISI Direct Steelmaking Findings Encouraging, Lead to New Research on Waste Oxide Recycling," press release, AISI, Washington, DC, May 18, 1994, p. 1.

[33]The nozzles through which the hot blast of air is directed into the smelting vessel.

[34]Aukrust, *AISI Direct Steelmaking Program Final Technical Report*, p. 8.

projected to be in excess of ten percent.[35] A cost comparison is reflected in table 2.

Table 2
Projected cost advantages of AISI's direct ironmaking process v. existing coke oven/blast furnace[1]

Basis	Coke oven/ blast furnace	AISI process
	Dollars per annual metric ton	
Capital costs	243	160
	Metric tons per day per cubic meter	
Production intensity	1.0	4.6
	Dollars per metric ton	
Operating costs	131	120

[1] Costs are per annual metric ton of hot metal based on plants with hot metal capacity of one million metric tons per year.

Source: Aukrust, AISI Direct Steelmaking Program, pp. 139-40.

The reported significant cost advantage of the AISI process derives in part from its much greater process intensity. These data reflect the much smaller size of the AISI smelter compared with other units of similar production capacity, which substantially reduces construction costs. Finally, with regard to the variable operating cost estimates for the two processes, certain cost factors could further decrease the AISI cost by up to $5 per metric ton through scaleup or maturation.[36]

Based on the findings of the direct ironmaking pilot project, AISI and DOE launched another cooperative pilot project, the Steel Plant Waste Oxide Recycling and Resource Recovery by Smelting Program in April, 1994, to determine the feasibility of converting steel plant waste to pig iron for use in steelmaking or foundry industries. According to AISI, the steel industry currently generates three million tons of blast furnace and basic oxygen furnace dusts and one half-million tons of rolling mill sludge each year. The Waste Oxide project is aimed at recovering these wastes, most of which are currently disposed of in landfills, a process that is growing increasingly expensive. Further, it is estimated that

[35] Ibid, p. 1.

[36] The estimated costs include stirring the bath with nitrogen. It is expected that nitrogen will eventually be replaced with air, at a savings of $1.40 per metric ton. Other items, including better hot metal desulfurization and the substitution of fluxes, could result in additional savings, according to AISI.

widespread recycling of steel plant wastes could save 10 trillion BTU of energy per year.[37]

The Waste Oxide project further broadens and enhances the basic smelting technology developed by the direct ironmaking project. It is directed by the same AISI team and uses the same pilot plant built for the direct iron smelting project. DOE is providing 70 percent of the project's $7 million cost,[38] and AISI members are responsible for the remaining 30 percent. AISI's portion is funded on an elective basis by 13 of its member companies.[39]

In January, 1995, AISI announced that the waste oxide pilot project had been successfully completed, laying the groundwork for a possible commercial demonstration project. Project directors determined in December that no further trials were required, ending the project 2 months ahead of schedule. The engineering firm of Mannesman DeMag was commissioned to work with AISI on conducting a feasibility study of the economic returns of a full-scale demonstration project for the waste oxide technology.[40] If the feasibility study shows that the process is expected to be viable commercially, AISI will proceed with a proposal to fund the demonstration plant.

Conclusions

Confirming the potential for the direct ironmaking process examined by AISI-DOE to clearly achieve economic advantages and technical proficiency over existing production methods--the two primary goals of the pilot project--was not sufficiently demonstrated to justify commercialization without further research. However, significant knowledge was gained from laboratory and pilot testing[41] to enable researchers to learn how to optimize the direct ironmaking process and to provide the foundation for future research.[42] Major obstacles stand in the way of the commercialization and the subsequent adoption of the DOE-AISI, or of any other, direct ironmaking process in the United States, including the level of capital investment that would be required. Given the capital intensity of the modern steel industry, new technologies must ensure a net reduction in cost over the existing process. This has not been proven definitively by the DOE-AISI pilot project.

Although the direct ironmaking project has not proven the economic feasibility of the

[37]American Iron and Steel Institute, "Waste Oxide Recycling Demonstration Weighed as Pilot Project Successfully Concluded," press release, Jan. 30, 1995.

[38]Like the direct ironmaking project, the DOE's contribution of the waste oxide project is funded by the Metals Initiative.

[39]They include Acme Metals, Cleveland-Cliffs, Geneva Steel, Georgetown Industries, HARSCO, Inland Steel, LTV Steel, Lukens, National Steel, Rouge Steel, Stelco, USS Kobe, and USX. Additional financial assistance will be provided by principal subcontractors and suppliers, including Mannesmann Demag, Hatch Associates, and NARCO Research.

[40]The feasibility study will quantify the potential economic return on a smelter at the Lake Erie Works plant of Stelco and should provide the information necessary for proceeding with a proposal for a demonstration plant by the spring of 1995, according to AISI. The smelter would be designed to process about 600,000 tpy of waste oxides and to produce about 250,000 tons of hot metal per year.

[41]Researchers have learned how to optimize the direct ironmaking process by understanding better such issues as the dissolution of materials, reduction mechanisms and rates, slag foaming and control, the behavior of sulfur, dust generation, and the entire question of energy efficiency--including postcombustion and the role of coal volatile matter.

[42]Aukrust, *AISI Direct Steelmaking Program Final Technical Report*, p. 9.

technology in terms of commercialization, it launched a new step in developing bath smelting for ferrous products, which, as it turns out, will be viable in a wider range of applications, as exemplified by the waste oxide project. The success of the joint AISI-DOE Steel Plant Waste Oxide Recycling and Resource Recovery by Smelting Program, which was spawned by the direct ironmaking project, indicates the value of the basic research which facilitated the development of bath smelting technology to a stage where it could serve as a foundation to launch the new project. It is possible the new information learned during the research trials conducted at the waste oxide pilot plant could further the development of the direct ironmaking process if the project is revisited at a future time. AISI has not announced any specific time frame, however, on this score.

According to government and industry officials the administrative partnership between the government and the industry worked well. The industry was able to proceed with research important to its future and leveraged its investment almost three-fold. The joint project lends support to the concept that government-industry cooperation can contribute positively to the drive for technology innovation in the domestic steel industry.

Recent Developments

Over the last 2 years, efforts to develop alternative ironmaking processes have intensified throughout the world, but no new processes have been commercialized. New DRI plants based on proven technologies, including Corex, Hylsa, and Midrex, have mushroomed, while other technologies are just getting off the ground, including the process developed by the U.S. steel industry. However, the lack of U.S. Government funding has now caused the industry to seek alternative routes towards commercialization.

The Steel Plant Waste Oxide Recycling and Resource Recovery by Smelting project, which evolved from the Direct Ironmaking Project, yielded promising results. The project demonstrated the complete conversion of all forms of steel plant waste oxides, including those high in zinc, to useful products: molten pig iron, slag for roadbed or cement production, clean off-gas as fuel, and a zinc-rich raw material for the nonferrous industry. The pilot plant trials established that energy savings up to 25 percent in the blast furnace and coke oven processes are achievable in this process.[43] The recycling project concluded in 1996. The Department of Energy (DOE) provided $5.6 million (67 percent) and the industry cost-share (provided by AISI and Mannesmann Demag) was $2.6 million.[44] An AISI proposal for a commercial demonstration plant to convert 500,000 metric tons per year (tpy) of waste oxides to 250,000 metric tpy of hot metal was submitted to the DOE, but Government funding was not available. However, the AISI is reportedly still interested in

[43]Department of Energy, Office of Industrial Processes, "Executive Summary: Steel Projects," found at http://www.oit.doe.gov/IOF/steel/exsum.html, retrieved on Nov. 19, 1997.

[44]Telephone conversation with Bob Trimberger, Department of Energy, Office of Energy Efficiency and Renewable Energy, Nov. 19, 1997.

pursuing the technology and is in the process of seeking partnerships outside the United States for further development.[45]

Despite the lack of government funding, developing an ironmaking technology continues to be a priority for the U.S. industry as well as the U.S. Government. Indeed, steel is among seven energy- and waste-intensive industries that are participating in DOE Office of Industrial Technologies new collaborative R&D strategy called "Industries of the Future" which is intended to result in the demonstration, evaluation, and acceleration of new technologies and scientific insights named as priorities by the industries.[46] To achieve this goal, AISI has created a tactical agenda, or a "Technology Roadmap," which identifies the critical technical advances that the steel industry believes are necessary for steel to remain "the material of choice" into the next century.[47] A major goal is to develop and commercialize an alternative ironmaking process. The industry predicts that in the next 15 to 20 years there will be a shift away from the traditional blast furnace method of iron production technologies; utilization of these new technologies will be key to future international competitiveness. Advances in both iron smelting and direct reduction technologies are discussed below.

Developments in Iron Smelting Technology

Among the iron smelting technologies, the Corex process, which uses coal directly to produce liquid hot metal, is the only process commercially available. Corex plants are in operation in South Africa, India, and Korea. Posco's (Korea) Corex facility has produced more than 1 million metric tons of hot metal since its startup in November 1995.[48] Posco is the second Corex plant to become operational, after Iscor (South Africa) which was commissioned in 1989. Plans by Geneva Steel, Air Products, and Centerior Energy to work with DOE in developing a combined ironmaking and energy generating facility using the Corex technology has been on hold pending final DOE approval, which Geneva officials say they do not anticipate any time soon.[49]

The Romelt process, developed by the Moscow Institute of Steel and Alloys, is reportedly ready for commercialization, with worldwide development rights split between ICF Kaiser International and Nippon Steel.[50] Romelt is a bath smelting process for converting iron oxides (virgin ores or waste materials) into blast furnace grade pig iron using noncoking coals. During the testing of AISI's Waste Oxide Recycling Program, which uses similar technology, the team consulted with Romelt's team and sent material to their pilot plant for

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[45]Ibid.

[46]Department of Energy, Office of Industrial Processes, "Steel: Industry of the Future -- Fall/Winter 1996 Update," found at http://www.oit.doe.gov/IOF/steel/, retrieved on Nov. 19, 1997.

[47]As part of this initiative, the steel industry published "Steel: A National Resource for the Future," in May 1995, which is known as the "Steel Industry's Vision Report." This report laid the ground work for its Technology Roadmap. AISI listed three overriding priorities in its Technology Roadmap: product efficiency, recycling, and environmental engineering. AISI, *Steel Technology Roadmap*, found at http://www.intervisage.com/AISI/MandT, retrieved Oct. 10, 1997.

[48]*New Steel*, "Posco's Corex Plant Passes the Million-Ton Mark," Nov. 1997, p. 14.

[49]John Schrieffer, "Increasing R&D's Productivity," *New Steel*, June 1996, p. 75.

[50]Robert Brooks and George W. Hess, "Searching for Tips on Mill Waste Recycling," *33 Metalproducing*, Aug. 1996, p. 54.

testing.[51] As for the other smelting technologies under development, pilot plants have been built but no dates have been set for commercialization.[52] Table 3 presents descriptions of the various iron-smelting technologies under development or in use.

Table 3: Main iron smelting technologies, feed material used, and changes in status since original article.

Process	Feed	Changes in Status
AISI	Coal/pellets or waste oxides	Smelter tests complete; AISI looking for partner to further develop technology after loss of U.S. Government funding.
Ausmelt	Fine and lump coal and any iron source (wide range of suitable feed materials)	Being developed in Australia by Ausmelt Pty; a pilot plant in Victoria has been proven at 1-5 t/d. A new 1-3 t/h (2t ore/hr) pilot plant is now planned.
Cyclone Converter Furnace (CCF)	Coal/fine ore	Cyclone furnace tested (not linked to smelter).
CleanSmelt	Coal/fine ore	Cyclone and smelter tested in combination.
Corex	Coal/pellets or lump ore	3 plants operating, several others planned.
DIOS	Coal/fine ore	Pilot plant closed in 1996.
Hismelt	Coal/fine ore	Pilot facility operating.
Romelt	Coal/ore or waste oxides	Semi-commercial plant built, worldwide development rights split between ICF Kaiser International and Nippon Steel.

Source: Compiled from various industry sources.

Developments in Direct Reduction Technology

Midrex and the Hylsa processes, both gas-based direct reduction technologies, are the oldest and most widely used technologies, producing over 90 percent of direct reduced iron worldwide. The Midrex process dominates, generating more than 60 percent of total DRI production (table 4).

A description of the direct reduction technologies currently in use or under development are presented in table 5. Midrex and the Hylsa technologies will likely dominate into the new century, given the number of new plants planned or under construction throughout the world.

Table 4: World DRI Production by process in 1995 and 1996, in million metric tons

[51] Telephone conversation with Bob Trimberger, Department of Energy, Office of Energy Efficiency and Renewable Energy, Nov. 19, 1997.

[52] AISI Steel Technology Roadmap.

Process	1995	1996
Midrex	19.86	21.00
HYL III	5.76	6.31
HYL I	2.39	2.81
SL/RN	1.02	1.08
Others	1.64	2.08
TOTAL	**30.67**	**33.28**

Source: Midrex Direct Reduction Corp.

Outlook

Development and implementation of these technologies will increase into the new century, and although government collaboration may continue to be pursued, the industry will likely seek other avenues to support R&D and commercialization efforts. Indeed, although the U.S. industry continues to pursue joint efforts to develop an ironmaking process in a collective fashion, a number of U.S. firms are moving independently to develop and implement certain existing technologies in their own production processes. They are also pairing up with other domestic and foreign firms, partly in an effort to minimize the costs involved. For example, LTV recently formed a joint venture with Cleveland-Cliffs and Lurgi (Germany) to build the first commercial-scale Circored plant in Trinidad. LTV researchers helped evaluate the technology and will assist in implementation as the project progresses.[53] Meanwhile, Nucor has joined efforts with U.S. Steel and Praxair (U.S.) to develop a new steelmaking process using iron carbide. The process would use oxygen and iron carbide to make steel in a self-contained vessel, which would eliminate the need for a blast furnace, coke, or electricity. However, before building a pilot plant, Nucor needs to determine if it can produce quality iron carbide economically at its Trinidad plant.[54]

[53]John Schrieffer, “Increasing R&D’s Productivity,” *New Steel*, June 1996, p. 78.
[54]Ibid.

Table 5: Main direct reduction technologies, and current status.

Process	Status
Gas-Based	
Midrex	Commercially available since 1971. Plants operational in Argentina, Canada, Egypt, Germany, India, Iran, Libya, Malaysia, Nigeria, Qatar, Russia, Saudi Arabia, Trinidad and Tobago, the United States, and Venezuela. Additional plants planned or under construction in Egypt, Korea, Mexico, South Africa, the United States, and Venezuela.
HYL I and HYL III	Commercially available since 1976. Plants operational in Brazil, Indonesia, Iran, Malaysia, Mexico, and Venezuela. Additional plants planned or under construction in Iran, Mexico, Russia, and Saudi Arabia.
Finmet	Developed by VAI to improve on the Fior process (Venezuela). Finmet plants are being built in Venezuela and Australia.
Spirex	Being developed by Midrex Direct Reduction Corp. and Kobe Steel. Construction of a 30,000 tpy demonstration plant was slated to begin in late 1997 in Puerto Odaz, Venezuela, at Kobe's Opco site.
Iron Carbide	Developed by Gordon Geiger, this process produces a variant of DRI called iron carbide. Nucor plant operating in Trinidad; Qualitech's plant is under construction and due to start up in 1998.
Circored	Developed by Lurgi, uses circulating fluidized-bed (CFB) reactor. The first commercial plant will start up in mid-1998 in Trinidad and Tobago to supply HBI to the U.S. market. A joint venture with iron ore miner Cleveland Cliffs Inc. (46.5%), steelmaker LTV (46.5%), and plantmaker Lurgi (7%).
Coal-Based	
SL/RN (Stelco, Lurgi, Republic Steel Co., Nation Lead Corp.)	Currently operating plants in India, Peru, and South Africa; two more are planned for India.
Inmetco	Developed by Inco of Canada; installing a 400,000 tpy unit at Nakornthai Strip Mill Public Co. in Thailand.
Fastmet	Developed by Midrex and parent company Kobe Steel; is currently being developed and demonstrated at a 3 t/h unit at Kobe's Kakogawa work in Japan. A plant is planned for Thailand.
Comet	Developed by the Belgian steel research organization CRM and following extensive laboratory tests a demonstration plant is now under construction at Sidmar's plant near Gent.
Circofer	Developed by Lurgi; Circored's sister technology. Still in testing stages.

Source: Compiled from various industry sources.

Glossary of Terms[55]

BOF	Basic Oxygen Furnace. The chief method of producing steel. The furnace is charged with molten iron from a blast furnace and steel scrap. Oxygen is blown into the furnace at high velocity to speed combustion and refine the iron and scrap.
Blast furnace	Cylindrical steel vessel, lined with heat-resistance brick, which, once charged with coke, iron ore, and limestone and heated, produces molten iron for further refining in a steelmaking furnace.
Coke	A lumpy, porous form of carbon produced by the baking of coal to drive off its volatile elements so that the fixed carbon and the ash are fused together.
EAF	Electric Arc Furnace. A furnace in which iron and steel scrap, limestone, and other additives are melted and converted to steel. Heat supplied by an electric arc melts and refines the charge.
Flux	In chemistry and metallurgy, a substance that promotes the fusing of minerals or metals or prevents the formation of oxides.
Iron ore pellet	A blast furnace raw material made by the beneficiation (concentration) of low grade ores. Pellets are marble-sized and increasingly contain flux as well as iron ore and a binder.
Integrated	Method of steelmaking, typically with BOF, that makes steel from the virgin material of iron ore, coal, and limestone.
Non-integrated	Steelmaking methods that make new steel, usually in an electric arc furnace, from scrap steel.
High-volatile coals	Coals containing over 32 percent of volatile matter.
Metallurgical coal	Certain coals possessing characteristics that make them suitable for producing metallurgical coke.
Metallurgical coke	A coke with very high compressive strength at elevated temperatures, used in metallurgical furnaces, not only as a fuel but also as a support for the weight of the charge.
Pig iron	High-carbon iron made by the reduction of iron ore in the blast furnace.
Postcombustion	In smelting, the injection of oxygen to burn off some of the carbon

[55]Definitions are drawn primarily from U.S. Department of the Interior, Bureau of Mines, *A Dictionary of Mining, Mineral and Related Terms*, Washington, DC, 1968, and from American Iron and Steel Institute, *Steelmaking Flowlines*, Washington, DC, 1982.

monoxide gas before it leaves the smelting vessel.

Scrap The principal metallic charge to electric furnaces. Scrap is also typically used as part of the charge in BOFs. It is classified as "home scrap" (croppings originating in steel mills), "prompt industrial scrap" (trimmings returned by steel users) and "dormant, or obsolete, scrap" (the materials collected and processed by dealers).

Sintering Process that uses the fine, iron-bearing materials recovered from ore handling, iron and steel operations, and environmental control equipment and partially fuses these fine particles into 1/4-inch material to be used in ironmaking.

Slag In the smelting process, an accumulation of impurities released from the iron ore that collects on the surface of the molten iron.

Smelting The chemical reduction of a metal from its ore by a process usually involving fusion, so that the earthy and other impurities, separating as lighter and more fusible slags, can readily be removed from the reduced metal.

PART II

OTHER MATERIALS TECHNOLOGY RESEARCH

Thermoplastic Elastomers in the Auto Industry: Increasing Use and the Potential Implications

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Thermoplastic[1] elastomers[2] (TPEs) are a group of specialty rubbers that combine the elasticity of thermoset[3] rubbers with the processing advantages of plastic materials. TPEs have continued to enjoy growth in a wide range of applications during the 1990s. The automobile industry, which is currently the largest consumer of TPEs, is expected to increase its use of these materials by more than 7 percent annually between 1995 and 2000, to reach 1.1 billion pounds.[4] During the same period (1995-2000), consumption of thermoset rubber for all industries is estimated by industry sources to increase to 38.2 billion pounds, an average annual growth rate of 2.7 percent. By comparison, total TPE consumption is expected to increase from 1.9 to 2.5 billion pounds, an average annual increase of 5.6 percent.[5] The disparity in growth rates is indicative of a growing trend in certain sectors, such as the auto industry, toward replacing thermoset rubbers and rigid thermoplastics (e.g., polyvinyl chloride) with thermoplastic elastomers. In addition, auto producers are developing new products specifically designed to use the unique characteristics of TPEs. This article provides an overview of the advantages that TPE materials offer manufacturers, examines use of TPEs in the auto industry, and briefly looks at the role of TPEs in other sectors.

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Thermoplastic elastomers (TPEs) are a rapidly growing class of specialty rubber materials that demonstrate a unique combination of performance and processing characteristics, blending both thermoplastic (or plastic) and rubber properties. Compared with rubbers, plastics are generally easier to process because they can be reshaped with heat and do not

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[1]Thermoplastic materials are those that can be reshaped with the application of heat.

[2]Materials that ". . . can be stretched to at least double their length at room temperature and, on the removal of the tension, quickly return to their original length." K.F. Heinisch, *Dictionary of Rubber* (New York: Halstead Press Book, 1966), p. 189. The term elastomer is essentially synonymous with rubber; the two words will be used interchangeably throughout this article.

[3]Thermoset materials are those that cannot be reshaped through the application of heat because of the existence of chemical bonds that cannot be broken through changes in temperature.

[4]Marc S. Reisch, "Thermoplastic Elastomers Target Rubber and Plastics Markets," *Chemical and Engineering News (C&EN),* vol. 74, No. 32 (August 5, 1996), p. 11.

[5]Reisch, "Thermoplastic Elastomers," p. 10.

have the temperature restrictions of thermosets. For these reasons, manufacturers typically prefer to work with plastic materials if possible. For some purposes, however, the elastic properties of thermoset rubbers are favored over the comparable rigidity of plastics.[6] By offering a combination of the easy processing of a thermoplastic component and the elasticity of a rubber, TPEs have become desirable for many applications, particularly in the auto industry.[7]

World consumption of both natural and synthetic thermosetting rubber has been relatively stable in recent years, while TPEs have experienced steady growth[8] (figure 1), estimated at 11 percent over the 3-year period of 1995-97. Total worldwide consumption in 1996 for synthetic and natural rubber, totaling 21.2 billion pounds and 13.2 billion pounds, respectively, far exceeded the 2.0 billion pounds of TPE consumed in the same year.[9] The automobile industry reportedly consumes 31 percent of all TPE produced.[10]

Materials classified as TPEs generally fall into five groupings, as outlined in the shaded text box.[11] Styrene block copolymers (SBCs) are the most commonly used TPE (figure 2), accounting for about 50 percent of consumption. However, it has been projected that thermoplastic olefins (TPOs), used extensively in the North American auto industry, will have an average annual growth of almost 10 percent for model years 1995-2005, increasing from 165.0 million pounds to 425.0 million pounds (table 1).[12] The majority of the TPOs currently are used in the exterior[13] of vehicles, although the most substantial growth will come from increased use for interior applications, such as airbag covers.[14] Annual growth

[6]Most elastomers owe their elasticity to crosslinking, by which molecular bonds are formed across polymer chains, allowing the material to sustain significant deformation and still return to its original shape once deforming stress has been eliminated. By comparison, thermoplastic materials, which lack the crosslinks that allow for elasticity, are typically more rigid than thermosets. However, they do not take a permanent shape through initial processing; with minimal effect on performance and processing, plastics can be reshaped by applying heat. P.W. Allen, *Natural Rubber and the Synthetics* (London: Crosby Lockwood, 1972), pp. 14-15.

[7]A TPE comprises at least two intertwined polymer systems, where one is a rigid thermoplastic material and the other is a soft elastomeric material. The TPE is intended to be used between the softening temperature of the two polymers. When temperatures fall below the softening point of the rigid phase, it acts as a backbone to restrict movement of the soft phase polymer. However, when heated above the softening temperature of the hard phase, the TPE loses its shape and becomes a viscous liquid. The hard phase resolidifies upon cooling, allowing for reshaping of the material. For thermoset rubbers, modifying shape to a significant degree involves the cleavage of chemical bonds. Charles A. Rader, "Thermoplastic Elastomers: Non-tire Market Share Up to 11% as Production Reaches 420,000 Tonnes," *Modern Plastics*, vol. 72, No. 12 (Mid-November 1995), p. B-56.

[8]Reisch, "Thermoplastic Elastomers," p. 11.

[9]Information obtained from the International Institute of Synthetic Rubber Producers' website (http://www.iisrp.com/) on Sept. 4, 1997.

[10]Kerri Walsh, "Automotive End Uses Drive Demand," *Chemical Week*, vol. 159, No. 25 (June 25, 1997), p. 36.

[11]There is no consensus on the exact types of TPEs, but the five classes used here are reasonably common.

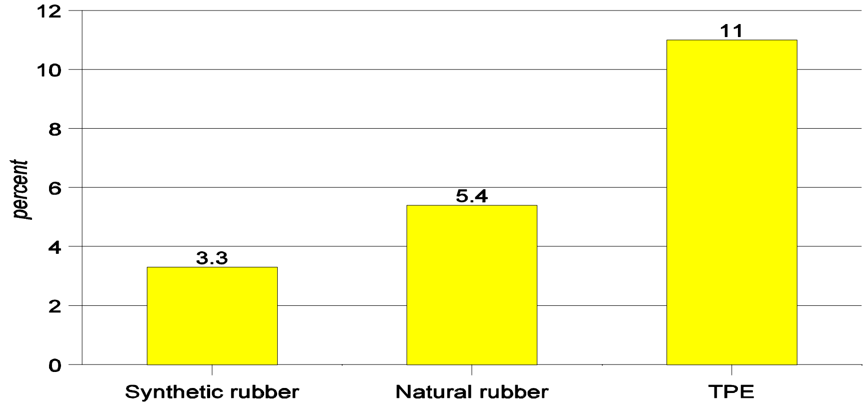
[12]Bernie Miller, "TPO Takes the Fast Lane to Big-Time Applications," *Plastics World,* vol. 53, No. 10 (October 1995), p. 43.

[13]Exterior automotive parts include bumpers, cladding and side trim, wheel flares, and front grilles.

[14]Other interior applications include skins to cover dashboards and door panels, improving their tactile properties.

rates during 1995-2005 for TPOs in the auto industry are estimated at more than 9 percent for exterior parts compared with 34 percent for interior parts.[15]

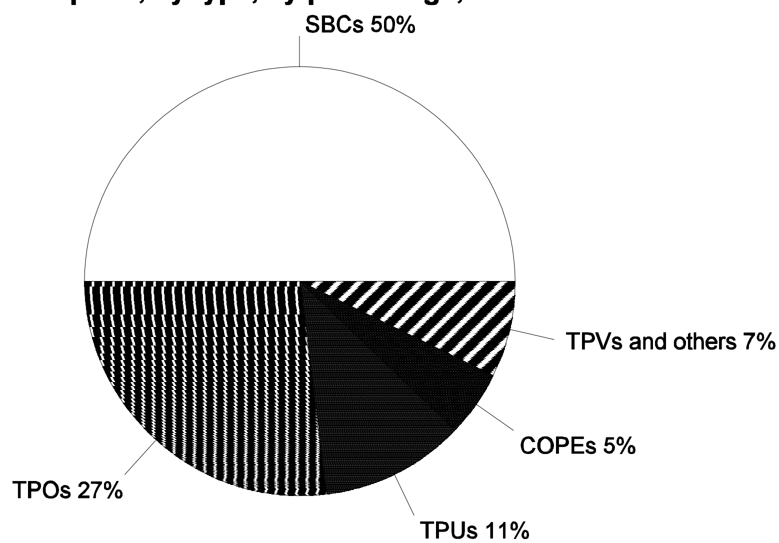
Figure 1
Growth in world rubber consumption during 1995-97, by type, in percent



Source: Compiled by USITC staff from data obtained from the IISRP website (http://www.iisrp.com/) on Sept. 10, 1997.

Figure 2

Share of TPE consumption, by type, by percentage, 1995



Source: Marc Reisch, "Thermoplastic Elastomers Target Rubber and Plastics Markets," *C&EN,* vol. 74, No. 32 (August 5, 1996), p. 14.

[15]Although use of TPOs in underhood body parts, including air intakes, boots and bellows, and splash shields, exceeded that of interior parts for 1995, it is anticipated that by 2005 interior parts will use 34.1 million pounds, while underhood parts will use 28.6 million pounds. Miller, "TPO Takes Fast Lane," p. 43.

Major Types of Thermoplastic Elastomers

- ***Styrene block copolymers (SBCs)*** are the least expensive ($0.70-$2.50 per pound) and most commercially successful category of TPEs. SBCs include three main subcategories: styrene-butadiene-styrene (SBS), styrene-isoprene-styrene (SIS), and styrene-ethylene-butylene-styrene (SEBS). SBS is frequently used in footwear, consumer products, asphalt, and polymer modification. Its most significant shortcoming is poor resistance to oil and high temperatures. SIS is frequently used in the adhesives industry because of its softness and ease of combining with resins, oils, and solvents. The most recent innovation, SEBS, was designed to be resistant to oxidation and weather; it is well-suited to applications such as automotive weatherstripping and cable coatings.

- ***Thermoplastic olefinics (TPOs)*** are composed of a thermoplastic, such as polypropylene, that has been blended with an unvulcanized rubber. TPOs can be relatively rigid materials, with hardness ranging from 60 Shore A to 60 Shore D at room temperature. For this reason, they are used in applications such as automobile bumpers and fascias, where impact resistance is critical. While TPOs have fair resistance to some chemicals, their resistance to chlorinated hydrocarbon solvents is low. TPOs generally fall within the price range of $0.75-$1.00 per pound.

- ***Thermoplastic urethanes (TPUs)*** have soft segments of either a polyester or polyether macroglycol paired with hard segments that are the product of the reaction between low-molecular-weight glycol and diisocyanate. TPUs are noted for high UV resistance, excellent tear strength, and good abrasion resistance, which make them a good alternative to traditional rubbers. TPUs are attractive to the auto industry because they do not need a primer before being painted. Significant weaknesses include poor resistance to strong acids and steam. TPUs are typically priced at $2.50 or more per pound.

- ***Thermoplastic copolyester elastomers (COPEs)*** have alternating hard segments, usually an ester, and soft segments, usually an ether, which give them a unique set of performance characteristics. COPEs are relatively easy to process, are resistant to oil and many chemicals, and have good flex resistance across a broad range of temperatures. Their high cost ($2.40-$3.60 per pound) prohibits use in many applications, although they are suited for use in selected blow-molded auto underbody parts.

- ***Thermoplastic vulcanizates (TPVs)*** have two phases, a finely dispersed thermoset rubber phase and a polyolefin continuous phase. The vulcanized rubber phase improves compression set, chemical resistance, and thermal stability. Because of the superior processing characteristics of TPVs, they are seen as a reasonable replacement for thermoset rubbers even though the cost of raw materials for TPVs is higher. TPVs generally cost between $1.40 and $2.00 per pound and are used in automotive boots and bellows, hose and tubing, and other applications.

Source: Compiled by USITC staff from “Elastomers and Rubbers: Thermoplastic Elastomers,” *Machine Design*, vol. 68 , No. 3 (Feb. 8, 1996), p. 82; Malcolm Thompson, “TPEs Open the Door to Better Designs,” *Machine Design*, vol. 65, No. 15 (July 23, 1993), pp. 47-49; Charles A. Rader “Thermoplastic Elastomers: Non-tire Market Share Up to 11% as Production Reaches 420,000 Tonnes,” *Modern Plastics*, vol. 72, No. 12 (Mid-November 1995), p. B-57.

Table 1
North American TPO usage in cars and light trucks for 1995, and projected usage for 2000 and 2005, in million pounds; annual growth rate, 1995-2005

Application	1995	2000	2005	Annual growth rate, 1995-2005 (*Percent*)
Type of part:				
Exterior:				
Bumper systems (incl. fascia, trim, strips)	100.0	220.0	280.0	10.8
Cladding, side trim	20.0	35.0	35.0	5.8
Wheel flares	6.0	6.5	6.8	1.2
Front grilles	3.0	8.0	12.0	14.9
Other trim	18.5	22.6	28.5	4.4
Subtotal, exterior parts	147.5	292.1	362.3	9.4
Interior:				
Airbag cover	1.8	6.3	8.1	16.3
PVC skin replacement	0	10.0	20.0	([1])
Other interior	0	4.0	6.0	([1])
Subtotal, interior parts	1.8	20.3	34.1	34.2
Underhood, Body:				
Air intake (blow mold)	13.4	18.3	22.0	5.1
Boot, bellows (blow mold)	0.2	0.4	0.6	11.6
Splash shields	2.0	4.0	6.0	11.6
Subtotal, underhood/body parts	15.6	22.7	28.6	6.2
Total	**164.9**	**335.1**	**425.0**	**9.9**
Comparative measures:				
Vehicles produced (*million*)	13.0	13.3	13.5	0.4
Pounds/vehicle	12.7	25.2	31.5	9.5

[1] Not applicable because the quantity is zero for the initial year under consideration.

Source: Bernie Miller, "TPO Takes Fast Lane to Big-time Applications," *Plastics World,* vol. 53, No. 10 (October 1995), pp. 42-48.

Processing Advantages of TPEs

The major advantages of TPEs over thermoset rubbers relate to processing, particularly the option of processing TPEs on equipment that is used for plastic extrusion[16] or injection molding.[17] By comparison, traditional rubbers require slow batch processing using capital-intensive machinery.[18] TPEs also can be made in specific grades because they are produced in continuous processes, whereas it is much more difficult to achieve consistent specifications for the materials produced in batch processing because of slight variations in the conditions for each batch.[19]

[16]Extrusion, a common plastics processing technique, involves heating the material in a cylinder and then forcing it through a die with a rotating screw. Sheets, rods, bars, and tubes can be made by extrusion. Douglas M. Considine, ed., *Chemical and Process Technology Encyclopedia* (New York: McGraw-Hill Book Company, 1974), p. 884.

[17]Injection molding is a process in which granulated thermoplastic materials are heated and then forced into a mold of the desired item. Usually the molds are standardized, which limits the part sizes and shapes that can be made. Considine, ed., *Chemical and Process Technology Encyclopedia*, p. 883.

[18]Reisch, "Thermoplastic Elastomers," p. 11.

[19]Peter Mapleston, "New Grades and Processes Expand TPE Capabilities," *Modern Plastics*, vol. 73, No. 5 (May 1996), pp. 64-65.

Thermoset rubber is limited in its processing methods, in part because of low temperature constraints required to prevent premature vulcanization.[20] By comparison, a number of more specialized processing techniques are possible with certain TPEs. For example, film and sheet extrusion and thermoforming[21] processes are being developed to use TPOs in "soft-skin" applications in car interiors. After extrusion, the TPO is then thermoformed to a more rigid material, thereby improving the feel of the end product.[22] Although the thermoplastic polyvinyl chloride (PVC), which has excellent tactile characteristics, is currently the most common material used for thermoformed products, TPO use in mid-priced cars is growing in popularity because of its superior UV resistance, better color stability, and lower weight.[23] Low-pressure injection molding is also opening TPOs to new soft-feel applications. In this process, a composite of TPO skin and polyolefin[24] foam is placed in a mold, and polypropylene[25] is then injected under low-pressure conditions. In one step, the producer generates a finished part with no adhesive materials required.[26]

Blow molding,[27] which is not an option for thermoset article manufacturers, also has been pursued by TPE producers. Because of easier processing and the ability to generate extremely thin parts, blow-molded TPEs reportedly offer significant cost savings[28] over injection-molded hollow parts made of thermoset rubbers.[29] For this reason, TPEs are becoming a popular material choice for hollow products, such as bottles, convoluted boots, and bellows.[30]

Innovations in TPE processing techniques, especially molding, are likely to produce an increase in part consolidation, meaning that one single large part takes the place of several smaller parts.[31] Parts consolidation is attractive to the auto industry because it reduces assembly and disassembly cost and leads to improved energy efficiency.[32] For example, a new design for an intermediate steering shaft[33] that incorporated TPE components reduced the number of parts from 13 to 3; this lowered the cost of the product by about 20 percent.[34]

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[20] Vulcanization is the industrial process in which raw rubber is heated with sulphur and certain other chemicals to achieve the crosslinks that "set" thermoset rubbers. Heinisch, *Dictionary of Rubber*, p. 189.

[21] Thermoforming is a process in which a sheet of material is heated and then pulled (by vacuum, pressure, or a mechanism) onto a form or mold. This process is effective for low-cost parts with large surface areas; the costs of tooling are low and there are no restrictions on part size. Considine, ed., *Chemical and Process Technology Encyclopedia*, p. 884.

[22] Sherman, "New Applications Breed New Ways to Process TPOs," p. 16.

[23] Miller, "TPO Takes Fast Lane," p. 43.

[24] A polymer based on any of the olefins, which are carbon-based molecules with the basic formula of C_nH_{2n}.

[25] A thermoplastic polymer of propylene.

[26] Sherman, "New Applications Breed New Ways to Process TPOs," p. 16.

[27] In blow molding, a thin cylinder, called a parison, is extruded and then inserted in a split mold; the parison is then pneumatically pressed into the mold to produce a thin, hollow part. Considine, ed., *Chemical and Process Technology Encyclopedia*, p. 884.

[28] Estimates of cost savings associated with TPE processing are not available.

[29] Rader, "Thermoplastic Elastomers," p. B-58.

[30] Ibid.

[31] Eller, "Interiors," p. 52.

[32] Eller, "Interiors," p. 49.

[33] An automobile part that connects the steering shaft to the steering gear and serves to isolate the driver (via the steering wheel) from imperfections in the driving surface.

[34] "A New Feel for the Road," *Automotive Production*, vol. 108, No. 7 (July 1996), p. 22.

TPEs, like all thermoplastic materials, are recyclable. Because of the efforts by industry to minimize processing waste, the ease of recycling TPEs provides a considerable advantage over thermoset rubbers. In processing TPEs, scrap can be returned to the manufacturing lines after simple drying and regrinding steps. Individual finished products can be recycled as well, although the process is slightly more involved than for scrap.[35] This is attractive to the auto industry[36] since many of the rubber components of a car are discrete parts, and it is therefore possible to remove an individual component and use its material in the production of another item.[37] The average car, exclusive of tires, contains about 26 pounds of rubber, offering a substantial incentive for automakers to use TPEs in place of thermosets.[38]

For parts processors currently producing thermoset rubber articles, there are some disadvantages to switching to TPE materials. First, the type of equipment used for TPE parts is very different than that which is used for thermosets, requiring a significant additional investment in new equipment to convert to TPE materials. Even though the upfront cost of thermoplastic processing equipment is less than that for thermosets, the additional investment and time required to learn a new processing technique may be considered prohibitive by a thermoset rubber producer.[39] Additionally, raw materials for TPEs are generally more expensive than materials for thermoset rubber production, although lower production costs[40] reportedly offset this additional expense in many instances.[41]

The most significant disincentives to using TPEs in place of thermoset rubbers are based on performance characteristics. High-grade thermoset rubbers offer superior blends of abrasion resistance, flexural strength, deformation resistance, and, most notably, heat resistance when compared with TPEs. In applications that require strong performance in these areas, the processing advantages of TPEs are insufficient to justify their use. For example, because TPEs are affected by heat, they are not used in place of thermoset rubbers in automobile tires, currently the largest single application for rubbers.[42]

Applications in the Auto Industry

Experimentation with new materials is fairly common in the automobile industry, and the combination of properties of TPEs has attracted automobile and auto parts producers for original equipment (OE) as well as the replacement markets. Initially, TPEs were used primarily for applications that had been dominated by thermoset rubbers, but the scope of

[35]Rader, "Thermoplastic Elastomers," p. B-58.

[36]For more information on the recycling of post-industrial and post-consumer TPOs to produce resins for use in automobiles, please see the following journal article: Lindsay Brooke, "Like a Virgin," *Automotive Industries*, vol. 177, No. 4 (April 1997), pp. 105-109.

[37]Mapleston, "New Grades and Processes," p. 65.

[38]Ibid.

[39]Rader, "Thermoplastic Elastomers," p. B-56.

[40]Estimates of cost savings associated with TPE processing are not available.

[41]Rader, "Thermoplastic Elastomers," p. B-58.

[42]Reisch, "Thermoplastic Elastomers," p. 11.

uses for TPEs is expanding. Increasingly, applications requiring the characteristics of thermoplastic materials such as PVC have begun switching to TPEs. TPEs can reportedly offer considerable savings to automakers over thermosets on the basis of processing costs,[43] and TPE parts can be 15 to 30 percent less expensive than comparable goods of other thermoplastics.[44] Additionally, auto producers' concern with minimizing vehicle weight, which has been buffered by claims that gas consumption could be lowered by 750,000 barrels per day if carmakers were to reduce automobile weight by 25 percent during this decade,[45] has led to increasing use of plastic materials in place of metals.[46]

Current Applications

Early, less sophisticated thermoplastics elastomers were chosen mainly for their low cost, low-temperature impact resistance, and potential for recycling. The auto industry found use for these materials, generally TPOs and SBCs, in applications with low-performance requirements, such as bumper guards, air dams, wheel well liners, rubstrips, dashboard trim, grommets, and step pads. Recent technical developments have strengthened the performance of TPOs for use in higher stress automotive products, including bumper fascia, cladding, and side trim. Producers reportedly are able to reduce the wall thicknesses of these parts by using TPEs, resulting in cost savings[47] and shorter processing times, with superior performance over other plastic materials.[48]

The application of TPOs in the auto industry has expanded to significant interior and underhood parts as well. The replacement of PVC skins in several key uses, including skins for instrument panels, door trim panels, and consoles, is a boon for TPO producers. The thermoplastic elastomers perform better in several areas, including long-term property retention and simplified recycling, when compared with PVC; however, TPEs are not typically used for soft skins in high-end automobiles because their tactile qualities are considered to be inferior to those of PVC.[49]

Several types of TPEs are high in cost,[50] which has limited their use in the auto industry. However, there are cases in which other factors somewhat offset the importance of cost in choosing a material. For example, glass fiber-reinforced TPUs have been introduced as a lighter substitute for steel in vehicle body panels. In addition to offering energy efficiency through lower vehicle weight, TPUs have excellent structural integrity, low warpage, dimensional stability, and high paintability (with no primer required).[51] High-priced COPEs are generally used only in high-performance parts, such as the constant velocity boot,

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[43] Ibid.

[44] Miller, "TPO Takes Fast Lane," p. 43.

[45] Jim Callari, "Playing the Resin Game," *Plastics World*, vol. 53, No. 9 (September 1995), p. 115.

[46] John Couretas, "Material Assets: Suppliers of Metals, Plastics Battle for a Bigger Share of Vehicle Content," *Automotive News*, No. 5701 (February 24, 1997), p. 32i.

[47] Estimates of cost savings associated with TPE processing are not available.

[48] Miller, "TPO Takes Fast Lane," pp. 42-43.

[49] Ibid., p.47.

[50] As indicated in the text box, there is a broad range of TPEs, which vary significantly in price.

[51] Martin O'Neill, "High-Performance Markets Drive TPU Innovation, Growth," *Modern Plastics*, vol. 74, No. 3 (March 1997), p. 71.

"where functional integration enables them to replace traditional materials."[52] COPEs also are favored over thermosets for these types of parts because the products made from these thermoplastic elastomers typically do not need to be replaced during the lifetime of the vehicle.[53]

As the development of TPVs has flourished (detailed below), automakers have found increasing use for these materials, such as in the corner sections of window seals. Formerly an application for thermoset rubber, use of TPVs allows producers to avoid finishing steps, including trimming and bonding, and expedites the overall production process from approximately 3 minutes to a matter of seconds.[54]

In most of the aforementioned parts, a TPE has been used as a replacement for thermoset rubber or another plastic material. However, TPEs are not limited to serving as replacements for other materials in existing applications. There are some products that have been developed with TPEs as the primary materials employed from the outset. For example, airbag designers have used a variety of thermoplastic elastomers in their effort to create an effective yet inexpensive product. There is still considerable design experimentation to be done on these parts, especially in light of recently released information on potential hazards related to their use.[55] However, the TPE combination of firm yet flexible properties seems particularly well-suited for these products. Given the expected magnitude of the market for airbags, this reportedly bodes well for TPE producers.[56]

Developments and Future Applications

TPE producers have been active in developing highly specialized materials intended for specific end uses. There also has been significant research and development of new processing techniques to maximize performance characteristics, while minimizing the quantity of material and time required for production of each article. Some significant innovations in the auto industry are outlined below.

Considerable progress has been made in the area of TPVs. For example, one recent development is a TPV grade that can be foamed in a water-based extrusion process; the material is then used in the production of the hoodseals of a Japanese recreational vehicle.[57] In another innovative extrusion process, TPVs are coextruded with another thermoplastic (e.g., polypropylene) to produce a single component with distinct rigid and soft sections. The dual nature of these materials makes them particularly useful for producing seals: the rigid segments anchor the seal in place while the soft segments perform the sealing function. Given the wide variety of automotive seals, each with particular requirements depending on the section of the vehicle involved, there is likely to be considerable material and process development in this area. Industry experts have predicted that auto seal producers will

[52]Mapleston, "New Grades and Processes," p. 65.

[53]Ibid.

[54]Ibid.

[55]Information obtained from the Airbag Options website (http://www.airbag.net/) on January 8, 1998.

[56]Mapleston, "New Grades and Process," pp. 66, 68.

[57]Robert D. Leaversuch, "TPEs Address Emergent Needs in Molded Automotive Interior Parts," *Modern Plastics*, vol. 73, No. 4 (April 1996), p. 93.

continue to pursue easily processed, low-priced replacements for the thermoset rubbers currently in use.[58]

TPUs are often considered to be too expensive for use in most auto parts, especially compared with lower priced TPOs and TPVs. However, there has been substantial research on the possibility of alloying TPUs with any of several lower grade materials. The price reduction could be significant enough to warrant such combinations, in spite of the compromise on performance.[59]

A new processing technique that looks promising for the production of a variety of auto parts employs robotic[60] extrusion technology to cover hard materials with a soft TPE profile. The innovation was first used in Europe to produce an automotive belly pan,[61] and auto parts manufacturers are anticipating a wide range of new applications, including engine encapsulation parts, sunroof profiles, and edged protection for metal parts.[62] Using this technique, the TPE is extruded through a flexible, heated hose; robots shape the profile to the rigid substrate, which can be made of any material that can withstand the heat and mechanical constraints of the process. With minor modifications to the robot's program, part specifications can be altered to meet a wide variety of needs. By comparison with the injection molding methods (see footnote 17) that are used in similar applications, robotic extrusion reportedly lowers tooling costs,[63] gives flexibility to adjust to production of different parts, produces tight tolerances, and allows for a variety of hollow shapes.[64]

Outlook for TPE Producers

The growing popularity of TPEs is not limited to the auto industry. Several other sectors also are expected to demonstrate high average annual growth rates for TPE use during 1995-2000 (table 2), even surpassing growth in the auto industry. Although the auto industry is likely to continue as the leading consumer of TPEs, medical products will be a particularly strong area of growth, followed by consumer products and construction.[65] TPEs offer the medical industry considerable benefits over thermoset rubbers on toxicological grounds; certain unhealthful chemical additives required for the vulcanization process, such as heavy metals (e.g., tellurium and selenium) and aromatic hydrocarbons (e.g., dibenzoyl-p-quinone dioxime), are unnecessary in production of TPEs.[66]

[58]Robert D. Leaversuch, "New Applications Extend End-Use Penetration," *Modern Plastics*, vol. 74, No. 1 (January 1997), p. 75.

[59]Patrick Toensmeier, "TPE Formulations Show New Versatility," *Modern Plastics*, vol. 72, No. 5 (May 1995), p. 75.

[60]The name of this processing technique reflects the role of robots in shaping the extruded material.

[61]According to an auto industry expert, an automotive belly pan is used to cover the bottom of an automobile, thereby smoothing airflow under the vehicle and reducing noise.

[62]"TPE Robotic Extrusion," *Machine Design*, vol. 69, No. 2 (Jan. 30, 1997), p. 108.

[63]Estimates of cost savings associated with TPE processing are not available.

[64]"Robotic Extrusion Molds Soft Materials over Rigid Substrates," *Machine Design*, vol. 69, No. 11 (June 5, 1997), p. 96.

[65]Reisch, "Thermoplastic Elastomers," p. 13.

[66]Rader, "Thermoplastic Elastomers," p. B-58.

Table 2
Estimated world growth for thermoplastic elastomers, by industry, 1995-2000

Industry sector	1995	2000	Average annual growth
	----*(Million pounds)*-----		(*Percent*)
Motor vehicles	798	1,133	7.3
Footwear	503	593	3.3
Industrial machinery and equipment	463	653	7.1
Consumer products	236	346	8.0
Wire and cable	130	165	4.9
Medical products	99	174	11.9
Construction	62	90	7.7
Other	44	64	7.8
Total	2,335	3,218	6.6

Source: Marc S. Reisch, “Thermoplastic Elastomers Target Rubber and Plastics Markets,” *Chemical and Engineering News,* vol. 74, No. 32 (August 5, 1996), p. 13.

Regional Consumption

North America is currently the leading regional consumer of TPEs in the world (table 3), which is consistent with its position as the leading consumer of rubbers. According to the International Institute of Synthetic Rubber Producers, North American consumption of TPEs was expected to grow at a high rate during 1995-97, especially in comparison with that of the second largest consumer, Western Europe. The tepid projected growth in consumption for Western Europe has been attributed to the region’s sluggish economy. Latin America, the Commonwealth of Independent States, and the Middle East and Africa all showed gradual growth during 1995-97.[67] Data on Asian TPE consumption are not available; however, as indicated by recent business developments (see following section), growth in Asian markets would seem likely.[68] China in particular has been a significant consumer of TPEs for use in its footwear industry.[69]

[67]The IISRP website (http://www.iisrp.com/) on September 4, 1997.

[68]However, it should be noted that these developments arose prior to the recent economic problems in Asia, and at this time there is no firm indication as to how TPE consumption will be affected.

[69]The Economist Intelligence Unit, “World Rubber Trends and Outlook,” ch. in *Rubber Trends: The Worldwide Rubber Industry, 1st quarter 1997* (London: The Economist Intelligence Unit, 1997), p. 21.

Table 3
TPE consumption, by region, in million pounds, 1995-97

Region	1995	1996[1]	1997[2]	Average annual growth, 1995-97 *(percent)*
North America	831.0	913.6	976.4	8.4
Western Europe	694.3	694.3	722.9	2.0
Latin America	26.7	30.9	33.1	11.3
Commonwealth of Independent States	19.8	22.0	22.0	5.4
Middle East and Africa	13.2	13.9	14.8	5.9
World	1,924.1	2,027.7	2,135.7	5.4

[1] 1996 figures are based on partial year data.
[2] 1997 figures are forecasts by IISRP.

Source: Compiled by USITC staff from data obtained from the International Institute of Synthetic Rubber Producers' website (http://www.iisrp.com/) on Sept. 4, 1997.

Business Developments for TPE

Business activity involving TPE has thrived recently. While the following is not an exhaustive list of business developments in TPEs, the information cited is indicative of the growth anticipated by the chemical industry.

In North America, expansion of TPE capacity is ongoing. An earlier indication that thermoplastic elastomers were becoming serious competitors with rubber and plastics was the emergence of a joint venture by two large chemical companies. In January of 1991, Monsanto Chemical Co. and Exxon Chemical Co. joined forces to form Advanced Elastomer Systems (AES), a company intended to draw on the parent companies' strengths to develop innovative thermoplastic elastomers.[70] Similarly, on April 1, 1996, DuPont Dow Elastomers was created as a joint venture between DuPont Chemical Co. and Dow Chemical Co., with a focus on the creation of specialized elastomer materials.[71]

Other developments followed. Bergmann Kunststoffwerk of Germany, a part of the M.A. Hanna Group of Ohio, has invested in a new production facility in Spain. The site will increase the company's TPE production by 25 percent.[72] Additionally, an Asian company, Taiwan Synthetic Rubber (TSR), purchased a 30 percent stake in a U.S. TPE producer, J-Von. TSR plans to use the investment as an opportunity to expand its TPE technical capabilities as well as its U.S. marketing experience. Conversely, J-Von expects the arrangement to help gain entry to the Asian market, for both sales and investment.[73] Another Asian company, Kuraray (Japan), has pursued the possibility of building a TPE plant in Texas, given the significant demand for its products in the United States and Europe. After 3 years of marketing in the American and European markets, Kuraray is interested in building a production facility to supplement its 10,000 metric ton (about 22 million pounds) plant in Japan, ideally with a geographical advantage for the U.S. market.[74] With the stated goal of capturing 20 percent of the world TPE market, DSM (Netherlands)

[70]"AES, an Instant Giant, Says It Will Catalyze Big Expansion of TPE Field," *Modern Plastics*, vol. 68, No. 3 (March 1991), p. 16.

[71]Information obtained from the DuPont Dow website (http://www.dupont-dow.com/) on Sept. 16, 1997.

[72]"Business Briefs," *Modern Plastics*, vol. 73, No. 3 (March 1996), p. 19.

[73]"TSR Invests in China, Thailand, U.S." *Chemical Week*, vol. 158, No. 10 (March 13, 1996), p. 21.

[74]"Kuraray May Build Texas Plant," *Chemical Week*, vol. 159, No. 14 (April 9, 1997), p. 12.

recently invested in increased production capacity at its plant in Belgium; the new capacity triples the previous level to 15,000 metric tons (about 33 million pounds) annually.[75]

In March 1996, it was reported that the Taiwanese TPO and TPU producer Polystar Engineering Plastics Co. was acquired by two other Taiwanese companies: Tong Yang Industry Co., an auto parts producer, and Integral Chemistry. Reportedly, Tong Yang sought a local source of TPOs for its annual production of 600,000 bumpers, the majority of which are exported to the United States, and 120,000 instrument panels. Prior to this acquisition, Tong Yang was importing about 13.2 million pounds of TPOs annually.[76] In Iwakuni, Japan, the Toyobo Co. built a plant designed for production of 7.7 million pounds of copolyester elastomer annually. Without the new facility, Toyobo was already producing 5.5 million pounds of TPEs per year, most of which were sold to Southeast Asian auto parts producers.[77] Additionally, Dow Elastomers established its Asian headquarters in Singapore in 1996 to begin marketing TPE in the region. About 15 percent of the company's sales are to the Asia-Pacific region, and there is an expectation for this percentage to rise to 25 to 30 percent by 2001, as significant growth is anticipated in consumption of wire and cable, automobiles, and footwear. DuPont Dow has long-term plans to set up production facilities in the region.[78]

Conclusions

The prospects for TPEs in the auto industry seem promising. As cars continue to become lighter in weight and more energy efficient, automakers and parts producers are expected to continue to experiment with new and innovative materials. Research and development to find more efficient, faster, and more effective processing methods is also likely to persist as an integral facet of design for the auto industry. Moreover, as parts consolidation and recycling of parts (and materials) become increasingly important objectives, the auto industry will continue to experiment with alternative materials. Because of the ease of processing, potential for recycling, and performance characteristics of thermoplastic elastomers, the auto industry can be expected to find increasing use for these materials in the future. Average annual growth of TPE use in the motor vehicle sector between 1995 and 2000 is estimated at 7.3 percent, projected to reach 1.1 billion pounds in 2000 (table 2). In North America, TPOs specifically are expected to increase from 165 million pounds in 1995 to 335 million pounds in 2000 and 425 million pounds in 2005 (table 1).

In spite of the optimistic growth rates anticipated for TPE, it should be noted that TPEs remain a fairly small portion of total elastomer (including natural and synthetic thermoset rubber) consumption. Although use of TPEs will continue to grow from a broader scope of applications, certain performance constraints, particularly the lack of heat resistance, will curtail their application in specific areas. As noted earlier, the largest end use for rubber is tires, an application for which TPEs are considered unacceptable.

[75] "DSM Starts Up Rubber TPEs," *Chemical Week*, vol. 159, No. 14 (April 9, 1997), p. 30.

[76] "TPE Supplier Acquired by Taiwan Companies," *Modern Plastics*, vol. 73, No. 3 (March 1996), p. 23.

[77] "Business Briefs," *Modern Plastics*, vol. 73, No. 3 (March 1996), p. 23.

[78] " DuPont Dow Slates Singapore for Base," *Modern Plastics*, vol. 73, No. 6 (June 1996), p. 25.

World production of TPEs is increasing to keep up with demand, and growth is expected to continue at a high rate. Because TPE producers and the auto industry, the largest current user of TPEs and frequent driving force for material development, have an established relationship, it does not seem likely the auto industry will encounter a shortage of materials as a result of the rise in TPE use in other sectors, such as the medical industry. Many possibilities remain for the auto industry to improve the performance, appearance, and efficiency of its products, and there seems to be a commitment from TPE producers to play a significant role in this process.

U.S. Bicycle Industry Creates Innovative Products Using Metal Matrix Composites

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Competitive cycling has pushed bicycle manufacturers toward the leading edge of technological innovation. Bicycle companies are increasingly turning to advanced materials, such as metal matrix composites (MMCs) in an effort to lighten frames while improving strength and stiffness.

Since this article was first published in the Industry, Trade, and Technology Review *of May 1994, the bicycle industry has not significantly expanded the usage of MMCs in their products. The concluding section of this article updates recent developments.*

The U.S. bicycle industry's attempts to improve the performance of bicycle frames and components have led to the aggressive pursuit of alternate materials since the early 1980s. Bicycle frame and component[1] design is an engineering compromise between cost and physical properties (including weight, strength, stiffness, energy absorption, and ease of manufacture). These considerations depend on the material used, the configuration of the material (i.e., dimensions such as tube diameter and wall thickness), and the configuration of the frame and components. In the 1970s, in virtually all the better quality bicycles,[2] steel alloys were used in the frame and aluminum alloys were used in components. Since then, many new materials have been adopted for use in bicycles, but steel and aluminum alloys remain the standards for comparison.

Metal matrix composites (MMCs) are one of the most recent innovative materials to be considered for use in bicycles.[3] U.S. produced, MMC-containing bicycles have been available in the U.S. and foreign markets for several years. These bicycles are priced at the upper end of the better quality market and will likely stay expensive. However, this commercialization is an important initial step in gaining acceptance of the material by the bicycle industry and consumers, and building a base for further adoption. This article examines innovation and materials use by the U.S. bicycle industry, the U.S. bicycle market and industry structure, and the bicycle MMC infrastructure. It concludes with a discussion of the outlook for more widespread adoption of MMCs.

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[1]The frame is the most important part in determining the ride characteristics of a bicycle and draws primary interest when considering alternate materials. Components are all nonframe parts of a bicycle.

[2]Better quality bicycles are sold mostly through independent dealers and are a distinct market segment from the lower quality bicycles that are typically sold by mass merchants such as toy and department stores.

[3]MMCs are composed of a metal or metal alloy base (called the matrix) and a reinforcing material (usually ceramic) dispersed within the matrix. For a more detailed description of MMCs, see U.S. International Trade Commission, "Metal Matrix Composites May be Key to More Efficient Automobiles," *Industry, Trade, and Technology Review*, May 1993, p. 1.

Design and Material Innovation by the Bicycle Industry

Since the beginning of the 1980s, the U.S. bicycle industry has generated a large number of innovative products, using a wide variety of materials and designs. The mountain bicycle was one of the most notable innovations,[4] creating a new sport (i.e., off-road bicycling) and a new design configuration that is extremely popular with consumers; this type of bicycle now accounts for roughly two-thirds of all U.S. better quality bicycle sales.

One recent design innovation is the bicycle with a suspension system. It gives a smoother ride and better handling on difficult terrain, but adds a significant amount of material to a bicycle. Strong, light-weight parts are essential in designing a viable suspension bicycle with a reasonable overall weight.

This high degree of technical innovation has been accompanied by an intense focus on the adoption of alternate materials. New materials, such as aluminum alloys (for frame applications), metal matrix and carbon fiber composites, aluminum-lithium alloys, titanium alloys, and beryllium alloys, have been developed for use in bicycles. During the 1984 Summer Olympics in Los Angeles, U.S. bicycle team members used aluminum-alloy frame bicycles, which helped to validate these types of frames, and generated broad interest in other alternative materials for frames.[5] The success of Greg LeMond, the first U.S. racer to win the Tour de France and a strong proponent of innovation, also furthered interest in alternate materials in the United States. During 1985-86, bonding technology improved dramatically, allowing engineers greater flexibility in joining dissimilar materials (a critical technology for making carbon fiber composite frames).

Material Alternatives

Steel-alloy frame bicycles still dominate the sales of better quality bicycles, accounting for about 85 to 90 percent by quantity of the U.S. market.[6] Steel's strength, stiffness, and low cost makes it an attractive material, but its relative weight is a significant performance deterrent.[7] The aluminum-alloy frame bicycle is the most popular nonsteel type. With the

[4]The mountain bicycle was actually invented during the mid-1970s, although serious commercialization did not start until the 1980s. In this article, the term mountain bicycle refers to a style of bicycle rather than bicycle use. Compared with a road bicycle, this bicycle has a sturdier frame, wider tires, an upright riding position, and more gears.

[5]According to an industry source, the use of aluminum-alloy frames originated from research at the Massachusetts Institute of Technology, where it was found that aluminum's lower degree of stiffness compared with steel could be offset by using larger diameter frame tubes. The first company to produce bicycles with aluminum-alloy frames was founded in the United States in 1978.

[6]Published figures on the composition by frame material of the U.S. better quality bicycle market are not available. Figures used in this article represent rough estimates made by representatives of two U.S. bicycle producers.

[7]Steel-alloy tubes can be produced with extremely thin walls, and a frame with these tubes can be nearly as light as any alternative material frame. However, these tubes are also relatively expensive to produce. Designing a bicycle involves tradeoffs between material and fabrication

(continued...)

development of oversize tubing to compensate for aluminum's lower degree of stiffness, these bicycles have become the most popular alternative to steel-alloy frame types, accounting for approximately 9 to 11 percent of the U.S. market.

Another popular alternative for bicycle frames and components is carbon fiber composite material, which may be the best material to minimize weight. The material has been developed extensively for road bicycles. Bicycles with carbon fiber composite frames account for from 1 to 2 percent of the U.S. market. However, durability, a significant design consideration, has limited the use of carbon fiber composites for mountain bicycle frames; relatively large lugs (usually made of aluminum) must be used where the tubes intersect to give the frame sufficient strength, which tends to diminish the overall weight savings.[8] Recently, mountain bicycle producers have developed new manufacturing processes to avoid the heavy-lug problem. One company has developed a carbon fiber composite lug and another company has developed a process to make a one-piece carbon fiber composite frame. However, these bicycles are at the high end of the carbon fiber composite bicycle price range.

Recently, titanium has received considerable promotion in the bicycle industry for use in the production of both frames and components. High cost has been a major deterrent to its use in the past, but exports from Russia have greatly increased the supply of titanium on world markets and its price has decreased considerably in the last few years. Titanium-alloy frame bicycles account for less than 1 percent of the U.S. market.

MMCs are relatively new to the bicycle industry. First used commercially in a mountain bicycle frame in 1991, MMC-frame bicycles currently account for less than 1 percent of the U.S. market. Three companies supply MMCs to the bicycle industry for frame applications--Duralcan (subsidiary of the Canadian aluminum company ALCAN), DWA Composites (owned by British Petroleum), and Alyn Corp. (a U.S. ceramics and composites company). The MMCs made by these companies have a matrix of aluminum and, respectively, a reinforcing material of aluminum oxide, silicon carbide, and boron carbide particles. Aluminum MMCs can be used as substitutes for conventional steel alloys to achieve a significant weight reduction, and as substitutes for aluminum alloys (without using oversize tubing) to significantly improve strength and stiffness. Other important advantages of these MMCs, compared with aluminum alloys, include better fatigue resistance, superior energy absorption, and improved friction performance.

Table 1 shows a relative ranking of several important properties of these materials. Bicycle frame and component design involves tradeoffs in properties when selecting materials. For example, one of the tradeoffs in steel alloys is low cost versus a high specific weight.

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[7](...continued)
costs.

[8]In contrast, most frames made of metal and MMCs do not need lugs; the frame tubes are simply welded to each other.

Table 1
Relative ranking of bicycle frame materials[1]

Material	Typical composition(s)	Material properties: Cost[2]	Specific weight[3]	Strength	Specific stiffness[4]	Process-ability[5]
Steel alloys	0.80-1.15% Cr 0.35-0.60% Mn 0.15-0.35% Si 0.15-0.25% Mo 0.27-0.34% C Balance Fe	1	7	1	5	1
Aluminum alloys	0.25-6.1% Zn 0.8-2.9% Mg 0.1-2.0% Cu 0.35-0.8% Si 0.4-0.7% Fe 0.15-0.7% Mn 0.04-0.35% Cr 0.01-0.2% Ti Balance Al	2	2	5	7	2
Carbon fiber composites	Carbon fibers in resin epoxy	6	1	3	1	7
Titanium alloys	3.0% Al 2.5% V	7	6	2	6	3
Duralcan MMC	85% Al 15% Al oxide	3	4	5	4	4
DWA MMC	80% Al 20% Si carbide	5	5	4	3	5
Alyn MMC	88% Al 12% B carbide	4	3	4	2	6

[1] The lower number indicates an advantage, i.e., lower cost, lower specific weight, higher strength, higher specific stiffness, or better processability.
[2] Includes the cost of materials and fabrication.
[3] Weight divided by volume.
[4] Stiffness divided by density.
[5] Processability refers to ease of shaping and joining the material.

Note.--Cr is chromium, Mn is manganese, Si is silicon, Mo is molybdenum, C is carbon, Fe is iron, Al is aluminum, Zn is zinc, Mg is magnesium, Cu is copper, Ti is titanium, V is vanadium, and B is boron.

Source: *Mountain Bike*, Jan. 1994; compiled by staff of U.S. International Trade Commission.

U.S. Bicycle Market and Industry Structure

Bicycles with frames of alternate materials are significantly more expensive than steel-alloy frame bicycles. Good quality steel-alloy frame bicycles retail in the United States for $300 to $400, compared with $600 for aluminum-alloy frame bicycles, $800 for carbon fiber composite-frame bicycles, $900 for MMC-frame bicycles, and $1,600 for titanium-alloy frame bicycles.[9]

Annual sales in the United States of better quality bicycles are estimated at slightly more than 3 million units, sold primarily through independent bicycle dealers.[10] The breakdown of sales for 1992 by retail price category is as follows:

Retail price range	*Units sold*
Less than $400	2,000,000
$400 - $750	750,000
$750 - $1,000	300,000
$1,000 - $1,200	75,000
Greater than $1,200	50,000
Total	3,175,000

The total better quality bicycle market in the United States, including sales of bicycles, components, and services, is approximately $2 billion.[11]

The lowest cost MMC-frame bicycle falls into the upper end of the $750-$1,000 price segment. Other models currently available cost over $1,000. Therefore, at current prices, it appears that MMC bicycles are competitive in only a relatively small segment of the better quality market.

The structure of the world bicycle industry is strongly influenced by the labor-intensive nature of producing better quality bicycles. Many bicycle producers use foreign assembly operations, especially in Taiwan and more recently in China, to take advantage of less expensive labor. Although the U.S. bicycle industry is a world leader in bicycle innovations, few better quality bicycles are actually produced in the United States. Imports supply most of the better quality U.S. bicycle market, but many of these imports are U.S. designed and engineered bicycles sold under U.S. company labels. Figures for U.S. production of better quality bicycles are not available, but industry sources estimate such production accounts

[9] A range of prices applies to all types of bicycles, depending on the configuration of the frame material and the quality of components. Thus, a steel-frame bicycle with a suspension system and high-quality components can easily cost more than $1,500, a high-end carbon fiber composite-frame bicycle more than $2,000, and a titanium-alloy frame bicycle more than $5,000. Price data from "Super Spec '94," *Bicycling*, Mar. 1994, pp. 105-120; Performance Bicycle Shop sales brochure; and Stephen C. Levin, "Composites and Bicycles: Market Diversification in Action," Proceedings of the 38th International Symposium of the Society for the Advancement of Materials and Process Engineering, May 1993, p. 4.

[10] An additional 10 million bicycles composed the total 1993 U.S. market, but these are the lower quality, low-cost types.

[11] Levin, "Composite Bicycles," and the National Bicycles Dealers Association.

for only 10 to 15 percent (about 300,000 to 450,000 units) of the U.S. market for these bicycles, and is concentrated in bicycles priced above $800.

U.S. exports of larger bicycles (those with both wheels over 25 inches in diameter, which includes most of the popular styles of bicycles) have averaged over 200,000 units per year during 1991-93.[12] The principal markets were Western Europe and Canada, which together accounted for about three-quarters of such exports in 1993. The relative portion by quality of these exports is not available.

Japanese companies dominate production of components for better quality bicycles, including components that are part of the original equipment of bicycles, and components that are sold to replace original equipment. Japanese component producers also have foreign assembly operations in some Southeast Asian countries to take advantage of less expensive labor. Most better quality bicycles have Japanese components, whether made in the United States or in foreign countries (for U.S. or foreign companies).

The Bicycle MMC Infrastructure

There are a number of companies in the United States and Canada that are involved in the bicycle MMC infrastructure, including MMC production, frame fabrication, component production, and assembly operations. In contrast to most of the better quality bicycles sold in the U.S. market, MMC-frame bicycles are produced in the United States.

Duralcan has a plant in Canada that produces aluminum MMCs, using a relatively straightforward technique of mixing the reinforcement material in molten aluminum and casting semifabricated shapes. The Duralcan material has the simplest and least expensive production process, but its properties are not as significant an improvement over the aluminum matrix material as the other MMCs. The DWA MMC is produced by mixing powders of the two constituents together and sintering the material.[13] The Alyn Corp. material, called boralyn, is produced using a proprietary method of mixing the metal and ceramic material and hot isostatically pressing the mixture into a semifabricated form.[14] These MMCs are then extruded to form tubes or other shapes.

The Duralcan material is the most extensively developed MMC and is the most widely used. A company in California, Specialized Bicycle Components (SBC), uses this MMC in mountain bicycle frames, which are built by another U.S. company, Technical Dynamics, according to SBC design specifications. SBC assembles the frames into finished bicycles. Current production of the MMC bicycle is about 20,000-25,000 units per year, of which approximately 35 percent are exported to Western Europe (mostly Germany, United Kingdom, and Italy). The least expensive MMC-frame bicycle produced by SBC retails for approximately $900.

[12]Export figures are official statistics of the U.S. Department of Commerce. Some industry representatives believe that most U.S. exports classified as "other" bicycles were larger bicycles. Exports of such bicycles averaged 317,000 units annually during 1991-93, and Canada and Western Europe combined accounted for about one-third of these exports in 1993.

[13]Sintering is a process of densifying and bonding the constituent powders by applying heat.

[14]In hot isostatic pressing, interparticle bonding and densification of a material is achieved by applying high pressure and high temperatures.

SBC has been developing its MMC bicycles for 7 years. The goal was to produce a mountain bicycle that mirrors the performance of a racing mountain bicycle, but with a reasonable retail price. The company considered a number of alternate materials for their mountain bicycle frames, including aluminum-lithium alloys, specially treated aluminum, and other MMCs before deciding to pursue the Duralcan material. Company officials believe the Duralcan material appeared the best suited for mountain bicycle frames because of the fatigue resistance, stiffness, and energy absorption effect of the material.[15] The company continues to produce a wide range of mountain bicycles with steel frames and also has a model with a carbon fiber composite frame (using a lugged design). SBC is also examining the possibility of making certain components, such as seat posts and fork braces, out of the Duralcan MMC.

The boralyn material is currently used in two bicycle models produced by Univega in the United States that retail for over $1,400. Sales levels are believed by industry representatives to be small. The Alyn Corp. sells boralyn tubes to Univega, which has another company weld the tubes into frames. Several other companies are testing boralyn but have not developed any commercial products.

Currently the DWA material is not used commercially in any bicycle. DWA Composites is developing its MMC in the United States, and is working with several bicycle companies to develop frames. It expects that bicycles with its MMC will soon be available. Industry sources expect bicycles with DWA MMC frames to retail for approximately $1,000.[16]

Lanxide Corp., a U.S. advanced materials company, also produces an MMC and is developing MMC bicycle components through a joint venture company called Lanxide Sports International (LSI). The MMC is composed of aluminum reinforced with silicon carbide and is produced using Lanxide's proprietary liquid metal infiltration process.[17] The MMC is available in castable ingot form and can be used to manufacture parts using conventional casting methods. The infiltration process allows for a relatively high percentage of reinforcement material (above 30 percent) compared with the Duralcan MMC (which is limited to 20 percent reinforcement content) and the company claims its MMC has better properties as a result. LSI has developed prototype components in cooperation with casting companies. Suspension parts, pedal crank arms, chain rings, and brake system parts have been developed and some of these parts reportedly will be commercially available within one year. LSI plans to sell components to domestic and foreign bicycle and component companies for original and replacement equipment. LSI is also trying to develop frame applications for its MMC.[18]

Several other companies are developing MMCs in the United States for bicycle applications. One company that makes aluminum-alloy bicycle frames is developing MMC frames using the Duralcan MMC. Dia-Compe, MC-21 Incorporated, Sun Metal Products, Odyssey Co., Innovative Bicycle Components, and others are developing bicycle components that use MMCs. Dia-Compe, a U.S. producer of aluminum components, is currently trying to

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[15]Specialized Bicycle Components representative, telephone interview by USITC staff, Washington, DC, Jan. 12, 1994.

[16]DWA Composites representative, telephone interview by USITC staff, Washington, DC, Jan. 13, 1994.

[17]In this process, silicon carbide powders are molded into a preform and molten aluminum is allowed to infiltrate into the pores of the preform, forming the MMC.

[18]LSI representative, telephone interview by USITC staff, Washington, DC, Apr. 20, 1994.

develop markets for MMC components. It purchases parts from MC-21 Incorporated, a company that manufactures parts using the Duralcan MMC. Dia-Compe believes the MMC material is particularly well suited for components, such as wheel hubs on bicycles with suspensions (these bicycles need stronger hubs to accommodate the suspension parts) and rims, because the MMC is an excellent braking surface. Although Dia-Compe is still in the initial stages of developing markets for such components, it has already sold a small number of test hubs in Europe. Sun Metal Products is close to commercializing wheel rims made out of the Duralcan MMC. Innovative Bicycle Components is using the Duralcan MMC in developing wheel hubs and brake parts.

Odyssey Co., a U.S. manufacturer of bicycle components, is also attempting to develop MMC parts. This company is developing a cog set (i.e., the rear chain sprockets) for mountain bicycles made of the DWA MMC and expects to have a commercial product by mid-1994. The company intends the product for replacement sales (i.e., not as original equipment) to the high-priced end of the market. The company plans to distribute the cog set in the United States and foreign markets using its existing distribution network.

Many foreign companies are also developing MMC bicycles and components using the Duralcan MMC. One major Japanese bicycle company has developed an MMC-frame bicycle prototype and may soon produce it commercially. Another Japanese company and a Taiwanese company are developing an MMC bicycle frame. At least four European bicycle companies are developing MMC applications.

Outlook

The current production of bicycles and components containing MMCs is small, but the technical merits of the MMC material are attracting interest among bicycle and component producers. Technical experience with MMCs in bicycle applications is only beginning, and MMCs lag behind more established alternative materials, such as aluminum and, to a lesser extent, carbon fiber composites. A considerable amount of development is still needed to find the optimum applications, designs, and MMC com- position. For example, MMC frame design parameters, such as tube diameter, wall thicknesses, and tube configuration, which have been researched extensively for steel and aluminum alloy frames, have not been adequately developed. Component design is just beginning to fully consider the potential of MMCs. Additionally, other MMC compositions (some of which may simply change the amount of reinforcement material in existing MMCs) may prove to be more practical than the compositions currently used.

However, there are many more companies producing or evaluating the use of aluminum and carbon fiber composites or doing both than are dealing with MMCs. Some large bicycle companies are not even seriously considering use of MMCs. This hesitation is partly due to the many material choices available as well as the prospect of making further improvements in the materials already being used.

Further development of MMCs for bicycle applications appears likely. Although MMC bicycle production is small compared with the total U.S. market of better quality bicycles, it appears that the market is being successfully developed. Current production is a modest 5 to 10 percent of U.S. production of the better quality types of bicycles. MMC bicycles also account for a small but significant portion of U.S. exports of bicycles. This initial commercialization has demonstrated that U.S. and foreign markets are receptive to MMCs, and more producers will likely be attracted to these markets. Component production should also increase because MMC properties seem especially advantageous in such applications as rims. Lately the development of new markets for MMCs has been spurred by the decline in U.S. defense spending. Companies that developed MMCs for military use are turning to such alternative markets as the bicycle industry to make up for lost sales.

Bicycles containing MMCs are costly, and cost forms a significant barrier to wider use. However, production process improvements and design innovations could effectively lower the cost of MMC usage. According to industry sources, there is a strong possibility that MMC extrusion methods could be improved substantially, which would lower production costs. Further, MMCs could be used in less expensive bicycles by designing frames that combine MMC tubes in high-stress areas and tubes of cheaper materials in the less stressed areas. MMC components could also be selectively used on less expensive bicycles in only the areas of highest stress or wear.

If MMC bicycles and components do become more widespread, U.S. companies are well positioned to increase their market share in U.S. and foreign markets. The innovative U.S. industry appears to have a substantial head start over foreign companies. However, intense competition is likely from other materials, such as carbon fiber composites and titanium.

Recent Developments

Specialized Bicycle Components continues to sell a mountain bicycle frame made of Duralcan's MMC and has also recently developed a road racing bicycle made of the same material. The bicycle industry remains a minor consumer of MMCs. However, MMC consumption in the automobile industry appears poised to increase substantially. For more information, see “Metal Matrix Composites May be Key to More Efficient Automobiles” later in this report.

Aluminum Product Development and the Automotive Industry

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The automotive sector offers excellent potential for increased aluminum consumption. Automakers are expanding their use of aluminum to increase fuel economy and reduce emissions, but price, supply, manufacturing cost, and recyclability pose concerns. Research and development continues, aided by experience. Aluminum competes with steel; steelmakers have significantly improved sheet quality, also through collaborative efforts with automakers.

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As a single market, the automotive sector probably has the best potential for increases in aluminum consumption during the 1990s. Although consumption of aluminum per car currently is relatively low, automakers worldwide are expanding the use of aluminum, driven by concerns about performance, fuel economy, emissions, and materials recyclability. Aluminum companies are striving to capitalize on aluminum's physical and mechanical properties. These properties favor aluminum substitution for other metals and materials in automobile bumper systems, engines and drive trains, heat exchangers, frames, and exterior panels. Specific initiatives include joint research, development, and marketing efforts with automakers. As a result of these efforts, industry analysts predict consumption of aluminum in automobiles will double between 1992 and 2000, to 2.8 billion pounds. This article examines aluminum's increasing importance in automobile construction, auto industry efforts to increase its use, and projections for future aluminum use in the auto industry.

Aluminum Use in the Auto Industry

Automakers lightened average car weights by about 25 percent, to about 3,000 pounds during 1978-80, doubling fuel economy and improving performance. Currently there is limited market-driven impetus to achieve even higher fuel economy in the United States[1] because gasoline is considered relatively inexpensive and because most automakers are meeting Federal Corporate Average Fuel Economy (CAFE) standards of 27.5 miles per gallon (mpg). Some industry analysts think that the average automobile will have to be lightened further, by 500 to 700 pounds (16 to 22 percent), to meet upcoming fuel

[1] Weight savings and fuel economy have been cited as reasons for operators of fleet vehicles such as trailers, delivery vans (e.g., U.S. Postal Service fleet), and railroad cars to specify more aluminum in their vehicles.

efficiency and emissions requirements.[2] Moreover, automakers estimate that existing vehicles have achieved near optimum light-weighing with the choices of materials and manufacturing methods currently employed. Further gains are expected to rely on enhanced processing of traditional materials or developing new processes and material forms to increase cost-competitiveness, and expand use of existing lightweight materials in midsize sedans.

The corrosion resistance, strength, light weight, and ease of fabrication of aluminum have steadily increased its use by automakers. Aluminum producers are poised to compete with current steel monocoque designs[3] with aluminum spaceframes[4] or body-in-white.[5] Spaceframes represent potentially the largest single automotive application, requiring approximately 80 kilos (176 pounds) of aluminum; an aluminum body-in-white would require approximately 120 kilos (264 pounds) of aluminum.[6] Both designs would be augmented by aluminum sheet for floor pans and exterior panels. As emissions standards become increasingly tighter,[7] other alternatives, such as electric cars, may be necessary. Some industry experts indicate that lightweight aluminum spaceframes are the only viable structure currently available for electric car production.

Aluminum use per car ranged from 174 to 191 pounds in 1992.[8] During 1980-93, aluminum consumption grew 35 percent while its share increased from 3 to 6 percent of the total weight of U.S.-built cars over the same period (figure 1). Automakers reduced average car weights and used much less of conventional steels and iron. However, the total weight of

[2]Enhanced fuel-efficient cars (to achieve 85 to 100 mpg by 2010, for example) is one long-term goal mentioned by some automakers and the U.S. Government. Materials research and development is proceeding under the Lightweight Materials for Transportation Program Plan, coordinated by the U.S. Department of Energy. See U.S. Department of Energy, *Lightweight Materials for Transportation: Program Plan*, Mar. 1993.

[3]The outer skin of the vehicle takes on structural characteristics and body panels are welded to a stamped/welded frame.

[4]The aluminum spaceframe is a vehicle platform. For example, Alcoa-Audi design uses fewer than 100 aluminum extrusions and interconnecting diecast nodes robotically welded to form the spaceframe, versus the 300 or so welds used on a steel monocoque frame. According to a spokesman for Alcoa, an aluminum spaceframe weighs 40 percent less than a steel monocoque design, and has greater rigidity (leading to improved handling) and higher crash resistance. Although the spaceframe currently costs approximately two and one-half times more than a monocoque, industry executives believe cost-parity is achievable through redesign. The manufacturing process is reportedly flexible in volume and design requirements.

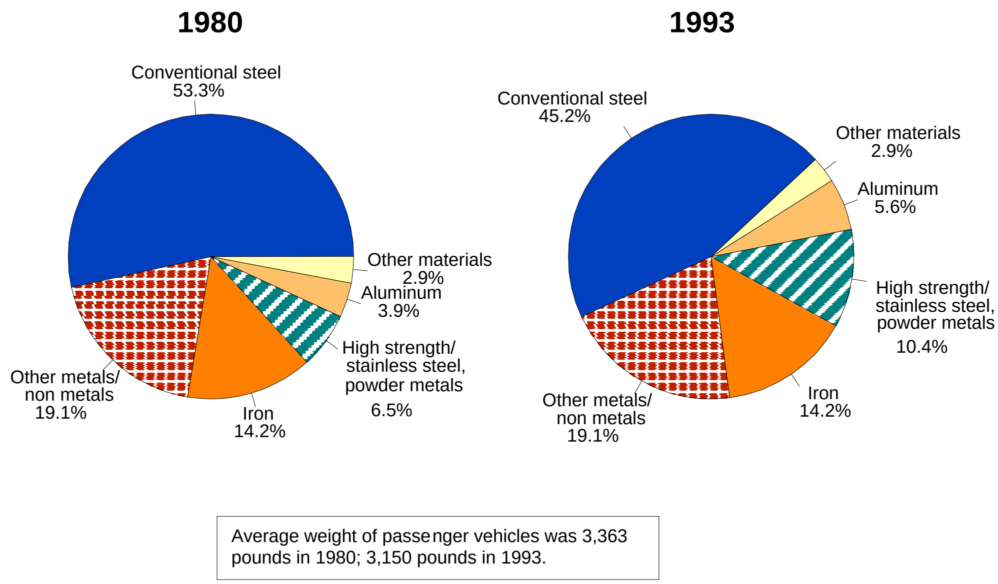
[5]Alcan's body-in-white is reportedly similar to a steel monocoque, namely a stamped frame that is welded together to form a "unibody."

[6]"Everybody's Doing It: Chasing After a Chunk of the Automotive Market," *Metals Week*, Nov. 1992, p. 8. For a list of automakers using aluminum engine blocks and heads, see Stephen E. Plumb, "Aluminum Is Taking a Star Role," *Ward's Auto World*, Sept. 1993, pp. 30-31.

[7]California has mandated zero emissions for 2 percent of cars sold in that State after 1998.

[8]The American Automobile Manufacturers Association reports per car aluminum use of 173.5 pounds in 1992; a study undertaken on behalf of the Aluminum Association estimated per car use to be slightly higher, 191 pounds in 1992.

Figure 1
Material usage per passenger car built in the United States, 1980 and 1993



Source: Compiled from data presented in AAMA Motor Vehicle Facts and Figures, 1993.

steel and iron dropped only moderately, as automakers increased the use of more specialized steels and powder metals.[9]

Aluminum shipments to the automobile industry are increasingly important to the aluminum industry, rising by 60 percent between 1980 and 1992 to 1.4 billion pounds and accounting for nearly 10 percent of total net shipments of aluminum in 1992.[10] The automotive industry represents the fastest growing end-use segment, and aluminum producers reportedly have targeted the automotive industry for direct sales, bypassing distributors and service centers that accounted for about 36 percent of aluminum shipments in 1992. Currently, more than 100 auto parts are made from aluminum. These components include bumper systems, wheels, brakes, air-conditioning compressors, heat exchangers and radiators, engine cylinder heads, rocker arms, pistons, and engine blocks, steering and suspension systems, shock absorbers, transmissions, and drive train parts.

Aluminum body structures are currently used in several sports cars. GM's Chevrolet Corvette uses an extruded and welded aluminum rear subframe. Jaguar's top sportscar is almost entirely aluminum, including the engine, an adhesively bonded aluminum chassis, and outer panels. Audi and Alcoa produced the Audi A8 model in 1994, featuring an

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[9]Calculated from data of The American Automobile Manufacturers Association, *AAMA Motor Vehicle Facts & Figures '93*, p. 50.

[10]Calculated from data presented in The Aluminum Association, *Aluminum Statistical Review for 1992*, pp. 6 and 19, and AAMA Motor Vehicle, *Facts & Figures '93*, p. 3. This was due partly to greater automobile production (12-percent increase between 1982 and 1992) and partly to greater per car use of aluminum.

aluminum space frame, floor pan, body panels, and a cast-aluminum engine.[11] And Honda's Acura NSX model has used aluminum extensively, including as a spaceframe, since the 1990 model year. Reynolds has worked with Ford to produce a prototype aluminum spaceframe for the Contour and Synthesis concept cars; Ford reportedly is building 20 all-aluminum Mercury Sables for field testing.[12] With respect to electric cars, GM's Impact uses a welded/bonded aluminum spaceframe,[13] and Kaiser Aluminum has manufactured an aluminum spaceframe for CalStart's electric vehicle.[14]

Auto Industry Efforts to Increase Use of Aluminum

Certain factors have limited the increased use of aluminum in automobiles. Steelmakers have made considerable progress in reducing automobile weight through improved designs (for example, laser-welded tailored blanks)[15] that reduce the number of parts and lower weight, tooling and fabrication costs; more-over, automakers are making more efficient use of a new generation of lighter gauge medium-strength steels, high-strength/low alloy steels, and bake-hardenable steels.[16] These new automotive steels, which industry spokesmen point out did not exist 5-years ago, have enabled automakers to increase steel use for added safety and structural features, currently designed in steel, such as antilock brake systems, door-intrusion beams, roof structures, and undercarriage reinforcements.[17] Cost and design factors may also hinder more substantial adoption of aluminum. Aluminum is more expensive than steel, about 4 times the cost on a pound-for-pound basis;[18] requires more energy to weld; and is susceptible to fatigue cracking.[19] Automakers have expressed concern about the suitability of aluminum for exposed surfaces.

Aluminum producers have attempted to encourage the use of their product in autos by helping to stabilize prices, improving performance and cost-reduction efforts, emphasizing

[11]Alcoa is reportedly working with 11 other carmakers on spaceframe development. Drew Winter, "Aluminum is Hot, Hot, Hot," *WARD'S Auto World*, Sept. 1993, p. 49. Also see Alex Broad, "Cars lighten up as partners get together," *Metal Bulletin Monthly*, Feb. 1994, p. 60.

[12]Also, Ford's Lincoln Mark VIII uses nearly 500 pounds of aluminum in its frame, body panels, engine and other components. Use of aluminum in hoods and roofs is expanding as well, and is currently being used on Ford's Grand Marquis/Crown Victoria and Lincoln Town Car lines, Toyota's Supra, and GM's upcoming Aurora. Winter, *WARD'S*, p. 49.

[13]Reportedly the Impact is a 2910-pound (including an 1100-pound battery pack) 2-seater electric car with a 168-piece aluminum alloy spaceframe that is the lightest and stiffest aluminum vehicle structure developed to date. It was developed to meet California's zero emissions standards in 1998. Cliff Gromer, "New Age of the Electric Car," *Popular Mechanics*, Feb. 1994, p. 40.

[14]"Everybody's," *Metals Week*, p. 8.

[15]Tailored blanks are patchworks of different types of sheet steel ready to be stamped into specific body parts. They may include combinations of sheet steel of different thicknessses, strengths, or coatings.

[16]Wallace D. Huskonen, "Steel Finds a Way to Lighten Up Cars," *33 Metal Producing*, Oct. 1993, p. 53.

[17]Stephen E. Plumb, "Aluminum," *Ward's Auto World*, Sept. 1993, pp. 30-31.

[18]Recently automotive sheet steel cost about 36 cents per pound while aluminum sheet cost $1.35 per pound. This means about $675 of steel would be used on the frame for Ford's Sable versus about $1,350 of aluminum for the equivalent frame. Julie Edelson Halpert, "Aluminum Is Put To the Test by Ford," *New York Times*, Apr. 3, 1994, section 3 (Business), p. 7.

[19]Many spaceframe designs use adhesive bonding with welding to mitigate fatigue cracking.

safety and recycling benefits (tabulation below), and through widespread involvement in joint ventures and strategic partnerships.

Aluminum adoption factors:

Light-weight	--Aluminum intensive vehicles weigh 25 to 45 percent less than steel cars, achieving retention of vehicle size and passenger comfort, and improving fuel economy, vehicle performance (acceleration, braking distance, reaction time) and handling. Lightweighing of primary components allows secondary economies through weight reduction of engine and drive train components, brakes and suspension system. Light- weighing appears to be more readily achievable than development of innovative engine technologies.
Formability	--Aluminum may be alloyed relatively easily, and may be formed, fabricated, and joined by existing methods. A wide range of properties can be engineered for automotive applications through choice of alloy, hardness and strength, and fabrication process. Light weight, heavier gauge, and strength characteristics stiffen the frame to improve car ride, handling, and safety. Process costs may be lower than those of steel, and design flexibility is high. Corrosion resistance allows use where methanol-based fuels corrode steel.
Safety	--Aluminum gauge (thickness) is usually 50 percent greater than steel in equivalent frame and absorbs crash energy more effectively. Weld-bonded aluminum structures generally perform at an equivalent level in frontal, rollover, and side intrusion crashes. Spaceframe's crash- worthiness is 20 percent greater than a stamped aluminum frame.
Cost/price	--Aluminum's cost, by weight, is several times greater than most steels, although the total value of frame is small relative to total value of auto. Price premium is declining as newer steels cost more and automakers gain experience designing with aluminum; spaceframe cost is estimated at 150 to 250 percent greater than equivalent steel frame although parity may be achieved. Price stability may be enhanced through use of hedge and options purchases, and risk sharing arrangements.
Recyclability	--Both steel and aluminum are currently recycled (i.e., possess an infrastructure for recycling) and are market driven. The three major automakers established their Vehicle Recycling Partnership consortium in November 1991, and are changing designs and materials-sourcing patterns to enhance vehicle recycling.

With respect to price volatility, aluminum is traded on several international commodity markets and shares a reputation for speculator-enhanced price volatility with other futures commodities. Aluminum producers have made efforts to emphasize the price stability aspects of hedging, options, and risk-sharing arrangements. Aluminum's relatively higher cost relative to steel has limited its use to specialty automobiles or to relatively small production runs; to selective replacement with aluminum to achieve lighter weight and attendant fuel savings; or to avoid slipping into a higher CAFE weight class and incurring government penalties. Increased CAFE standards (currently 27.5 mpg, expected by industry sources to increase to 32 to 35 mpg by 2003) may encourage greater use of aluminum. Changes in government policy with respect to recycling also affect aluminum use. European competition currently is being affected by German legislation dealing with automobile recycling, for example.[20] Aluminum compares favorably with steel, and it is superior to plastics. It may be more or less readily reused (unlike plastics), and aluminum recycling is market based.[21]

Automotive-Aluminum Industry Joint Ventures

Joint ventures and strategic partnerships between the aluminum companies and automobile producers are particularly important for increasing market penetration.[22] As is evident from selected joint ventures and strategic partnerships (figure 2), research and development partnerships targeting the automotive industry are widespread, and multinational aluminum companies are expanding into emerging capitalist and developing economies. Every major aluminum company is working with auto companies to develop either a spaceframe, as in the case of U.S.-aluminum producers Alcoa, Reynolds, and Kaiser, or a body-in-white, as in the case of Alcan (Canada).

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[20]Drew Winter, "Ship Ahoy! Automakers Sail Into Recycling," *WARD'S Auto World*, Sept. 1993, p. 66.

[21]Relatively high prices of scrap aluminum also provide an incentive for recyclers to locate, dismantle, and sort differing aluminum components. According to industry estimates, more than 85 percent of aluminum automotive scrap is reclaimed and recycled, and more than 60 percent of the aluminum used in automobiles is scrap based. This latter percentage is expected to rise to 90 percent by 2010. *WARD'S Auto World, Winter*, p. 67.

[22]These joint ventures and partnerships involve competitive technologies. These differ from precompetitive research and development consortia such as the United States Automotive Materials Partnership and the United States Council for Automotive Research, which are participating in government-sponsored research.

Figure 2
Selected joint ventures, strategic partnerships, and cooperative research and development in aluminum products by region and country, companies, and enduses

Region/country	*Companies involved*	*Product or industry/enduse*
North America	Reynolds Aluminum --Ford Motor Co. --Chrysler --General Motors	 Spaceframe development for Contour and Synthesis cars; all-aluminum Mercury Sable being field-tested in 1994. Chrysler Prowler is test vehicle. Reynolds supplies wheels to GM and various components to Chevrolet division.
	Alcan (Canada) --Ford Motor Co.	Joint research, begun late 1992, to develop light-alloy fenders for new Taurus line and aluminum sheet for car body applications. Main supplier for Ford Synthesis 2010, in concept stage.
	Ks Aluminum Technologie --Doehler-Jarvis (Germany)	Two German companies formed a joint venture during 1992 to produce aluminum auto parts, including transmissions, for sale to Ford Motor.
	Alcan (Canada) --General Motors	GM and Alcan formed a strategic partnership in 1992 to research weldable and bondable sheet for GM's electric car program; GM is reportedly working with other aluminum producers on extrusions for space frames and structural stampings.
	Altek Automotive Castings (Alcan Aluminum, Canada and Teksid, sub. of Fiat, Italy)	Two companies formed joint venture in 1993 to manufacture engineered aluminum castings for the automotive industry.
	Kaiser Aluminum --CalStart	Electric vehicle using aluminum frame and body panels.
European Union	Hayes Wheels International --Nova Hut AS Ostrava (Czech Republic)	Joint venture to sell fabricated aluminum wheels to BMW AG (Germany).
	Hydro Aluminium Extrusion Group (Norway) --BMW (Germany) --Pininfarina (Italy)	 Multiyear agreement signed in 1993 to perform joint research on automotive applications for extruded aluminum structures. Supplies aluminum structures for E1 and Z13 concept cars. Joint development of Ethos One and Ethos Two concept cars, built from aluminum spaceframes and thermoplastics.

Figure 2--Continued
Selected joint ventures, strategic partnerships, and cooperative research and development in aluminum products by region and country, companies, and enduses

Region/country	*Companies involved*	*Product or industry/enduse*
European Union--Continued	Alcan (Canada) --various	Joint efforts with British Leyland since early 1980s to make a body-in-white out of stamped aluminum by adhesive bonding and spot welding; it has since made several prototype bodybuilds for Italy's Bertone and Ferrari, GM, and Jaguar.
	Alcoa (U.S.) --Audi (Germany)	Spaceframe development since 1984; brought $70 million facility on line in 1993; Audi 300 model uses spaceframe, aluminum sheet components (floor pan, body panels), cast aluminum alloy engine. Alusuisse-Lonza (Switzerland) is to supply aluminum alloys.
	Pechiney Rhenalu Kaiser Aluminum (U.S.) KawasakiSteel (Japan) Furukawa Electric (Japan)	December 1993 agreement to develop aluminum body panels for French and European car manufacturers. Multiyear agreement focuses on alloy metallurgy, formability, surface preparation, and joining methods in established applications (engine blocks) and promoting its use in sheet and structural applications.
	Alcoa (U.S.) VAW Aluminum AG	Formed new company (Alcoa VAW Presswerk) to produce and market aluminum extrusions, tube,and rod for automotive and other industries.
	Hoogovens (Netherlands) Alusuisse (Switzerland)	Commercial rolling of aluminum-polypropylene-aluminum sheet (Hylite) to begin in 1994; developed for exposed sheet applications (doors, roof, and hood).
Hungary	Alcoa (U.S.) Hungalu (Hungary)	Alcoa and Hungalu formed joint venture to produce semifinished, rolled, and extruded forms of aluminum and certain processed products in Hungary in December 1992. Alcoa's and Hungalu's European subsidiaries have joint marketing and sales responsibility.
Russia	Reynolds Metals (U.S.)	Aluminum company joint venture with castings producer in St. Petersburg to produce aluminum wheels.
Japan	Hayes Wheels International Nissan Motors	Partnership formed in 1993to to export fabricated aluminum wheels.
	Reynolds Metals Co. (U.S.) Mitsubishi (Japan)	Global joint venture formed in 1992 to develope automotive extrusions.

Figure 2--Continued
Selected joint ventures, strategic partnerships, and cooperative research and development in aluminum products by region and country, companies, and enduses

Region/country	*Companies involved*	*Product or industry/enduse*
Japan--Continued	Reynolds Metals Co. (U.S.) Sumitomo Light Metal Industries Ltd. (Japan)	Partnership formalized in December 1992 to develop and market automotive sheet.
	Kaiser Aluminum (U.S.) Kawasaki Steel Furukawa Aluminum	Partnership formalized in October 1992 to develop and market automotive body and sheet, extrusions (space frames), castings and forgings.
	Alcoa (U.S.) Kobe Steel	Partnership formed to conduct joint research and development and market automotive sheet, extrusions, castings, forgings. Supplies aluminum for all-aluminum Acura NSX sports cars (contains 1,000 pounds of aluminum). Showa Denko developed cast aluminum parts for suspension used on Acura.
	Kawasaki Steel-Furukawa Aluminum Nippon Steel-Sky Aluminum NKK-Mitsubishi Aluminum Nippon Steel-Showa Aluminum-Nippon Light Metal; Sumitomo Metal Industries-Sumitomo Light Metal Industries.	Joint aluminum research and development, production and automotive sales between Japanese steel companies and Japanese aluminum companies.

Source: Compiled by the staff of the U.S. International Trade Commission from various articles appearing in *American Metal Market, Metal Bulletin Monthly, Journal of Commerce, Light Metal Age, HFD,* and others.

Outlook

Automotive consumption of aluminum, particularly for mass-produced autos, represents a potentially large and relatively untapped market compared with other segments of the transportation industry. Most auto industry executives believe passenger cars will weigh less and use less steel during the 1990s.[23] Consumption of aluminum in U.S. passenger cars is estimated to grow from its 1993 per unit level of approximately 174 pounds per passenger car to about 350 pounds by the year 2000.[24] Aluminum spaceframes may comprise 10 percent of body styles of cars produced in North America by 2000.[25]

Growth in aluminum consumption is foreseen in parts and components such as cast engine cylinder heads and engine blocks, pistons, and wheels. Growing use of aluminum sheet reportedly is likely within 2 to 3 years for automobile fenders, deck lids, hoods, and load floors followed by growth later in applications for doors, quarter panels, and roofs. These applications represent selective substitution by automakers where the aluminum price-premium to steel may be overcome by better performance.

Anticipated added pressure on manufacturers of large luxury sedans and sport cars to meet fuel economy regulations and emission standards suggest that such firms will likely be among the first automakers to make changes that affect aluminum consumption. Automakers are likely to use aluminum for alternative use vehicles, such as electric cars, because of performance requirements related to light weight, and because of emissions requirements mandated by State laws. Stricter CAFE standards and emissions regulations may hasten increased aluminum consumption for mass-produced autos, which may proceed more rapidly as the industry gains more design and fabrication experience.

Recent Developments

Materials Substitution Continues

The use of light-weight materials, such as aluminum, in automobiles has increased while heavy cast iron and certain other metals have accounted for a smaller share of vehicle weight.[26] Aluminum use increased by approximately 11 pounds, reaching 206 pounds per

[23]These estimates show a 10-percent reduction in passenger car unit weights and a 15-percent reduction in steel content per passenger car produced in North America in 1995 and 2000 (using CAFE standards of 27.5 mpg and 35 mpg, respectively). They indicate a 33-percent increase in aluminum use per unit. Delphi VI Survey of the University of Michigan Transportation Research Institute, reprinted in "Everybody's," *Metals Week*, p. 12.

[24]Bob Regan, "US vehicle aluminum reused," *American Metal Market*, Sept. 24, 1992, p. 6; Halpert, "Aluminum Is Put To the Test by Ford," *New York Times*, Apr. 3, 1994, section 3 (Business), p. 7 (quoting executives at GM and Ford).

[25]Delphi VI Survey of the University of Michigan Transportation Research Institute, reprinted in "Everybody's," *Metals Week*, p. 12.

[26]For a breakdown of materials used in a typical family vehicle see USITC, “Alternative Materials in the U.S. Automotive Industry Promote Development of Joining and Bonding Technology,” *Industry Trade and Technology Review*, USITC, Oct. 1997, p. 14.

vehicle, between 1996 and 1997.[27] An annual auto industry survey indicates increased use of aluminum in areas such as engines and oil pans, deck lids and body panels, suspension and steering systems, seats, and steering components.[28] For example, the 1998 model-C5 Corvette contains 700 to 800 pounds of aluminum (the previous version contained only 300 pounds) including a newly designed engine, power train, and frame; and GM will reportedly introduce a new line of aluminum engines (the "PV6") that is to replace its current line of cast iron V-6 engines.[29]

Beyond the increased use of aluminum parts, aluminum-intensive vehicles (containing an aluminum frame or outer body panels) currently are available[30] or in development, including a new Audi model that is to be available in 2000. Along these lines, Chrysler (Dodge Intrepid "ESX2"[31]) and Ford ("P2000"[32]) recently demonstrated prototype passenger vehicles that were developed under the government/industry program, Partnership for a New Generation of Vehicles (PNGV).[33] However, like other aluminum-intensive cars, these are low-volume, luxury cars and not high-volume, medium-priced vehicles. For example, GM's electric car (EV1) costs in excess of $30,000 and the Dodge Intrepid ESX2 is priced at a

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[27]Al Wrigley, "Steel Emerges as Auto Winner," *American Metal Market*, Feb. 24, 1997, p. 8. Industry estimates of aluminum used per vehicle vary, ranging from 196 pounds to 257 pounds per family vehicle in 1996. Compare Al Wrigley, "Aluminum, Steel Make Gains in Family Vehicles," *American Metal Market*, Feb. 26, 1996, p. 6 with "Recent Trends in Automobile Recycling: An Energy and Economic Assessment," ORNL/TM/12628, Mar. 1996, and "Steel vs. Aluminum," *New Steel*, June 1997, p. 44.

[28]For a list of aluminum applications in cars and trucks, see Al Wrigley, "Aluminum, Steel Make Gains in Family Vehicles," *American Metal Market*, Feb. 26, 1996, p. 6; "Automakers See the Light," *Advanced Materials News*, Mar. 1997, p. 13; and Patrick Ninneman, "Competition in Materials: Reducing the Cost of Aluminum," *New Steel*, Dec. 1997, pp. 82-83.

[29]Al Wrigley, "GM Aluminum Engines Coming," *American Metal Market*, Oct. 27, 1997, p. 4.

[30]These are the Audi A8, Honda Acura NSX, Lotus Elise, Jaguar XJS, GM's electric vehicle (EV1), Chrysler's Prowler and Neon Lite, and the 1998 model Porsche 911. For a description of the Acura NSX, see "Recent Inroads--Aluminum," *Advanced Materials News*, Mar. 1997, p. 13.

[31]The Dodge Intrepid ESX2 has an aluminum frame, and a plastic (pigmented polyethylene terephthalate) body. The ESX2, Chrysler's concept PNGV-supercar, differs from other Chryler models that use steel frames in combination with plastic bodies, like the Composite Concept Vehicles (CCV) or the Plymouth Pronto Spyder. For further details of this vehicle, see Al Wrigley, "Chrysler Drives Away From Steel?" *American Metal Market*, Jan. 13, 1998, p. 2.

[32]Ford and Alcan Aluminium developed the prototype P2000, demonstrated in Oct. 1997. This car weighs about 2,000 pounds which is more than 1,300 pounds lighter than the 1998 Taurus. Aluminum and some other light-weight materials are used extensively in place of more conventional metals resulting in an 80-percent reduction in the use of steel. The P2000 was developed as a first step toward fulfilling program goals of PNGV. Reportedly, Ford is likely to use aluminum in developing its PNGV-supercar. See, Al Wrigley, "Ford Demonstrates First Supercar," *American Metal Market*, Nov. 3, 1997, p. 6, and Patrick Ninneman, "Competition in Materials: Reducing the Cost of Aluminum," *New Steel*, Dec. 1997, pp. 82-85.

[33]Under PNGV, automakers are to develop a concept vehicle by 2000 (and a production prototype by 2005) with up to three times the current average fuel efficiency of 26.6 miles per gallon of gasoline with equivalent purchase price while meeting customer requirements for quality, performance, and utility. For a list of PNGV technology areas (e.g., advanced materials, manufacturing, energy conversion, etc.), strategies, and program goals see, U.S. Department of Energy, Transportation Technologies, PNGV, Technology Areas, found at Internet address http://prn.branch.com, retrieved Dec. 17, 1997.

premium of about $18,000 compared with its conventional version, although electric and hybrid propulsion systems rather than aluminum accounts for most of the difference.

Improvements in aluminum alloys and processing have enhanced aluminum's market share in automobile production. Aluminum companies have improved alloys that are more suitable for use in outer body panels as well as for processing in current stamping plants. These include a bake-hardenable aluminum alloy that was developed by Alcan (Canada) and licensed to Alcoa and Reynolds, and a work-hardening series of alloys that also can be easily formed. Automakers have gained valuable design and production experience using aluminum, and process improvements have reduced the defect rates of aluminum parts while increasing productivity. Reportedly, automakers have improved new joining techniques (adhesive-bond welding and use of self-piercing rivets, for example), racks and handling practices for aluminum stampings, and have developed new ways to stamp aluminum.

Aluminum-Steel Competition Remains Intense

Steel companies continue to develop steel grades that are lighter, easier to process, more reliable, and have mechanical properties superior to existing automotive steels. Automakers have increased their use of such special high-strength steels as bake-hardenable (BH), interstitial-free (IF), or high-strength, low alloy steels,[34] as well as the newer forming processes that allow more efficient use of steel. Steel companies also have boosted their levels of customer service, including technical service and just-in-time-delivery, allowing automakers to reduce production costs. Moreover, the joint research and development programs between the auto and steel industries, like the Auto/Steel Partnership and the Ultra-light Steel Auto Body (ULSAB),[35] focus on the more efficient use of steel in automotive design and manufacturing cost reduction.[36] As a result of these developments, steel has won back some of the car parts it earlier had lost to competing materials, including plastics and aluminum.[37]

Outlook

[34]BH steel reportedly accounts for about 65 percent of Ford's outer body panels, and is used by GM for several exposed sheet applications. Interstitial-free (IF) steel is reportedly used by Chrysler for exposed body applications. The yield strengths of these two steels are significantly higher than conventional steels, allowing the use of thinner gauge and lighter weight material.

[35]Estimates of the per-vehicle weight savings achievable under USLAB run to about 26 percent, compared to the 20 to 40 percent reduction suggested by PNGV. According to the steel industry association newsletter, the first ULSAB body-in-white test unit was completed in Sept. 1997, and vendors are producing car sections for presentation in the spring of 1998 for the 11 demonstration bodies to be built under this program. See, American Iron and Steel Institute, *News*, Nov. 1997, pp. 1-2. Also, "ULSAB Parts go into Production," *New Steel*, Aug. 1997, p. 11.

[36]For a description of cooperative efforts, see J. Neiland Pennington, "New GM Minivans Are All Steel," *Modern Metals*, Sept. 1996, pp. 53-56.

[37]Al Wrigley, "Steel Emerges as Auto Winner," *American Metal Market*, Feb. 24, 1997, p. 8. Reportedly Ford will convert the deck lids on its Taurus and Sable cars to steel from aluminum when production of the next generation of those cars begins. Al Wrigley, "Ford Switching to Steel in Taurus," *American Metal Market*, Oct. 27, 1997.

Automakers remain focused on issues of weight reduction, cost, quality, safety, and on using the optimum combination of materials that together meet those criteria. They have gained valuable experience in design and production using aluminum, as can be seen from the increased number of vehicles that are available and parts that have been converted from steel, as well as by the development of PNGV-supercars that meet projected CAFE requirements. However, the higher price of such automobiles may limit the potential aluminum share of the automobile market. Steelmakers also have improved steel grades and worked with automakers in developing processing technologies to reduce manufacturing costs and thus retain the market share of steel. Steel-aluminum competition is certain to become more intense as the next generation of cars goes into design.

Advanced Structural Ceramics: Technical and Economic Challenges

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One of the more promising areas for NMPM is that of advanced structural ceramics. These are materials used in high-performance applications in which a combination of properties, including light weight, wear resistance, high mechanical strength at high temperatures, hardness, stiffness, corrosion resistance, and low density are critical due to the extreme conditions under which these components operate. The combination of diverse properties has made advanced structural ceramics ideal for use in wear-resistant parts and cutting tool inserts, in high volume markets such as energy and other high-temperature applications, and in aerospace and defense-related applications. Total demand for advanced structural ceramics is presently expanding at annual growth rates of approximately 10 percent. Much research effort by private industry and the U.S. Government to commercialize advanced structural ceramics has been dedicated to reducing the cost and improving the fracture toughness of these materials in an effort to make them more cost-competitive with competing materials.

This article was first published in the Industry, Trade, and Technology Review *of August 1993. The concluding section updates U.S. Government and private industry efforts to commercialize advanced structural ceramics. Government funding for research and development declined during 1996/97, but the market for advanced ceramics is expected to continue to expand at historic rates.*

During the last several decades, advanced structural ceramics (ASC)[1] have gained a modest market share in structural applications, such as wear parts, cutting tools, and bearings, that have long been dominated by metal components. Producers of ASC anticipate the increasing use of ceramic products over the next decade in nontraditional markets, such as heat engines, heat exchangers, and bioceramics.[2] These markets are driven by the need to find industrial materials that can tolerate high-temperature, corrosive environments and by concerns for the weight reduction and increased energy

[1] Advanced ceramics exhibit mechanical, electronic, chemical, optical, and high-temperature properties that are superior to those of traditional ceramics. Advanced structural ceramics differ from traditional ceramic goods in that they are made from extremely pure, microscopic powders that are consolidated at high temperatures to yield a dense, durable structure for use in load-bearing or structural applications.

[2] USITC interviews with industry officials, June 1993.

efficiency of aircraft and automotive engines. Such improvements can decrease fuel costs and meet fuel economy and emissions standards. Future success in expanding traditional advanced ceramic markets and developing nontraditional markets depends on increasing the quality and reliability of these products, improving the cost/benefit ratio of ceramic components compared with metallic counterparts, and overcoming end-user reluctance to substitute ceramic parts of metal parts. This article will examine (1) current and potential applications for advanced structural ceramics and (2) industry attempts to overcome obstacles to increased adoption of structural ceramic components.

The most common advanced ceramic materials and some of their industrial uses are shown in figure 1. Table 1 includes some of the principal properties of the most common advanced monolithic ceramics in use today. Monolithic ceramics contain one of these materials while ceramic composites contain fibers that are added to the monolithic material to improve toughness. Parts made of advanced ceramics typically have superior high-temperature strength, higher hardness, lower density, and lower thermal conductivity than conventional metal parts, resulting in greater product durability and more efficient system operation. For example, one ASC producer claims that its ceramic composite wear part used in mineral-processing equipment will last up to 50 times longer than the metal part it replaces.

The U.S. market for ASC products was nearly $500 million in 1992, with three principal markets--wear parts, cutting tools, and bearings--collectively accounting for about 65 percent of domestic ASC consumption. The United States and Japan currently dominate global ASC production with each nation accounting for nearly 25 percent of global production.

ASC products account for only 5 percent of total market share in current applications. But substantial growth of more than 10 percent per annum is expected in response to greater overall demand by end-use industries for light-weight, energy-saving components.[3] Figure 2 shows a chronology of past introductions of advanced ceramic materials and an estimate for possible future applications in ASC products. U.S. demand for all ASC products is projected to rise to $2-3 billion by the year 2000 (figure 3). Principal applications and application requirements of ASC materials are shown in figure 4.

By far, the largest potential markets for ASC parts are those related to automotive engines, which, apart from rare and expensive ceramic turbochargers, currently have virtually no advanced ceramic parts. The advantages of such ceramic parts for automotive engines include increased fuel efficiency due to the ability of advanced ceramics to tolerate high engine operating temperatures; reduced friction, weight, and inertia; and reduction or elimination of cooling systems. The major obstacles to adoption of ASC parts in automotive applications remain the much higher cost of these parts compared with that of metal parts and the resistance of automotive manufacturers to replacing proven metal parts with ASC parts, which are relatively untested in gasoline engine applications.

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[3] Market forecasts are provided by Thomas Abraham, senior industry analyst and editor, *High Tech Ceramics News*, Business Communications Co., Inc., Norwalk, CT.

Figure 1
Current industrial uses of ASC

Type	Description
Wear parts	A wide variety of products in which long wear, high temperatures, and a high degree at chemical corrosion are generated, articularly in the oil industry (e.g., seals, valves and valve components), and the machine tool industry (e.g., nozzles, wear pads, extrusion dies, high-temperature fasteners, grinding wheels, and liners). Ceramic wear parts are also being increasingly used as mechanical seals in automobiles and appliances, due to their longer durability.
Cutting tools	As a result of their superior thermal and hardness properties, ceramics of silicon nitride and zirconia can be used at much higher machining speeds than are tolerated by cemented carbides, which are typically used as inserts tor metal turning and milling operations. It is estimated that ceramic cutting tools are capable of increasing metal-cutting processing times by 200-300 percent. In addition, ceramic tools are less prone to interfacial adhesion with the workpiece they come in contact with than are metal tools.
Bearings	Ceramic bearings are replacing steel and carbide as rolling elements because they have the ability to operate for a moderate length of time with little or no lubrication and offer high speed and acceleration capability. It is estimated that ceramic or ceramic hybrid roller bearings can increase wear life at equipment by 10-fold when compared to traditional steel bearings. Military applications such as ceramic missile bearings may spawn commercial products such as instrumentation bearings, hydraulic, and pneumatic activator systems, and ceramic coatings for use in gas bearings.
Ceramic coatings	Coatings have been developed to protect or lubricate ceramics and ceramic-metal composites (cermets) operating in hostile environments that cause excessive friction and wear at machinery. Coatings of titanium nitride, titanium carbide, and alumina are used to extend the life of tungsten carbide cutting tools by a factor of 2 to 5. Zirconia coatings are being tested as a thermal barrier in diesel engines to prevent the wear of metal pistons and cylinders and have also been used in turbine engines to allow increased combustion temperatures of several hundred degrees F. without increasing the temperature of the metal components in the engine.

Source: U.S. Office of Technology Assessment, Advanced Materials By Design, New Structural Materials Technologies, 1988, p. 52-53.

Table 1
Properties and end-uses of selected advanced ceramic materials compared to tool steel[1]

Material	Flexural strength	Hardness (Vickers)	Fracture toughness	Maximum use temperature	Young's modulus[2]	End uses
	MPa[3]	*GPa*[4]	*MPa m^1/2*	*Degrees centigrade*	*GPa*	
Alumina	310	17	4	1,200	310	Wear parts, cutting tools
Silicon carbide	690	22.4	4	2,000	450	Wear parts, cutting tools, heat exchangers
Silicon nitride	925	15.9	5.5	1,400	315	Wear parts, auto-motive engine applica-tions
Zirconia	1,440	12.8	8.5	800	220	Cutting tools, wear parts, experimental heat engines
Tool steel	5,500	10	98	700	210	Cutting tools, wear parts

[1] Other metals, such as tool steel, often exhibit higher strength characteristics than advanced ceramics at normal operating temperatures, but their strength characteristics fall considerably, compared to ceramics, at relatively high operating temperatures.

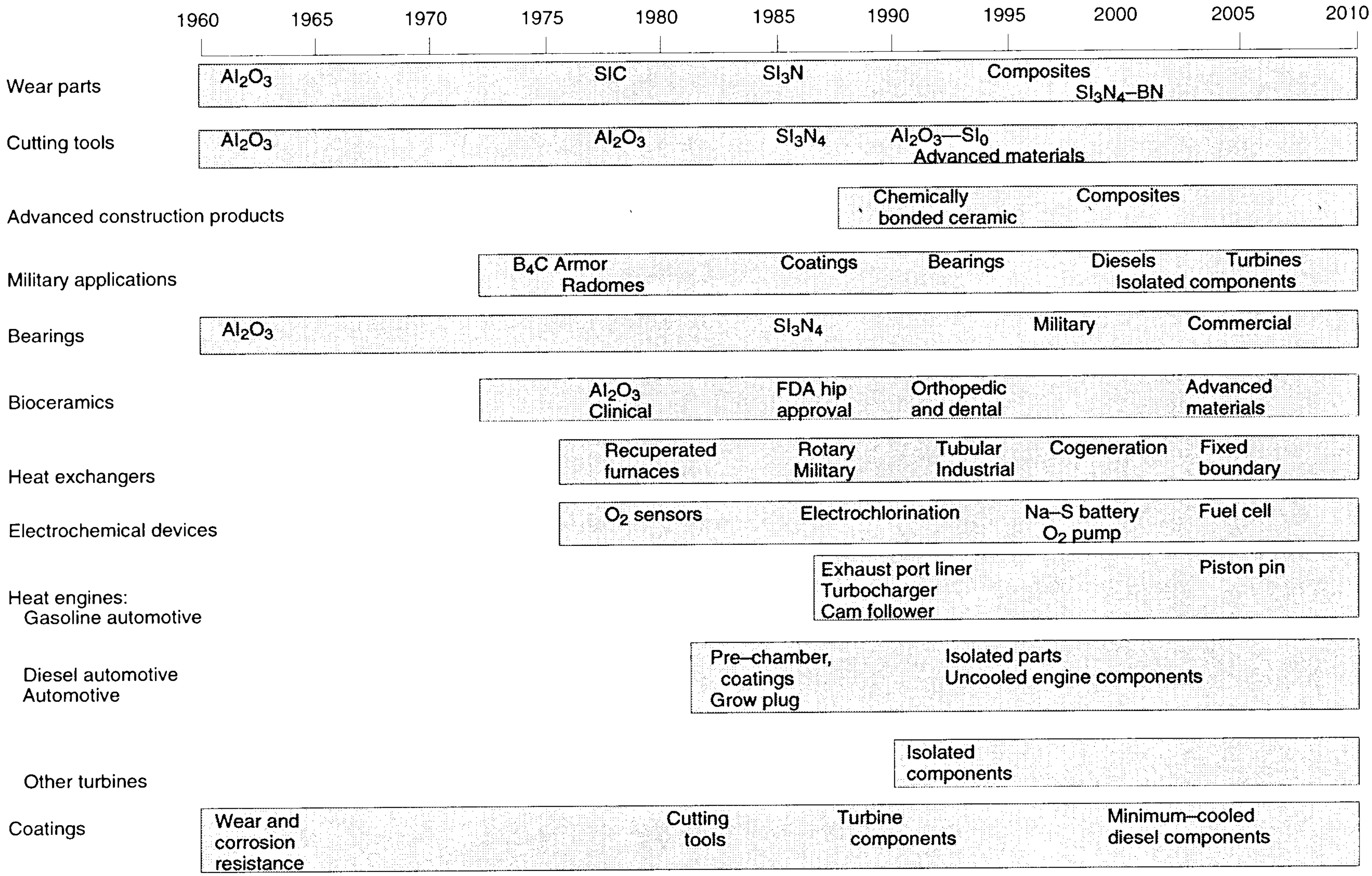
[2] Young's Modulus defines the ratio between stress and strain and is an indicator of the elasticity of a material.

[3] Mega (1,000) pascals. A pascal is a metric measurement of force. One pound per square inch (psi) = 6,894 pascals.

[4] Giga (million) pascals.

Source: Saint-Gobain/Norton Industrial Ceramics Corp.

Figure 5–2
Estimated scenario for implementation of ceramic components in structural application categories



Source: David W. Richardson, "Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites," contractor report prepared for the Office of Technology Assessment and Industry contacts.

Figure 3
Estimated size of current and projected U.S. markets for ASC (in million dollars)

Item	1992	2000
Wear pants	150	540
Cutting tool inserts	100	300
Bearings	75	300
Bioceramics	20	60
Heat Exchangers	20	100
Automotive/heat engine	50	920
Aerospace, defense	80	450

Source: Various sources from 1993 including U.S. Department of Commerce publications and private industry estimates.

Figure 4
Various current and potential applications of ASC and application requirements

Industry	Application	Application requirements
Machine tool . . .	Cutting tools Bearings Wire drawing dies	Wear and corrosion resistance, minimum lubrication requirements
Petrochemical . .	Seals Valves Pump impeller Heal exchanges	Energy-efficient heat regeneration
Automotive	Turbocharger rotors Push rod tips Rocker arms Cylinder liners	Light-weight, high-temperature, corrosion wear-resistance
Defense	Gun liners Ceramic armor	Light-weight, strength, corrosion, and high-temperature resistance

In addition, U.S. automakers require multiple sources of supply, which may affect the proprietary nature of research. Silicon nitride turbocharger rotors are currently the most popular engine application for advanced ceramics. These rotors are much more widely used in Japanese automobiles than in U.S. automobiles because of the use of turbochargers to boost engine horsepower in smaller cylinder Japanese cars. Other potential automotive ceramic components include valves, valve spring retainers, push rod tips, fuel injectors and fuel-injector components, valve lifters, and valve seats.[4]

In the United States one company, Carborundum Co., already mass produces silicon carbide water pump seals, which are sold to Volkswagen AG. In general, however, U.S. automakers are less confident than foreign automakers that a major market for advanced ceramics for use in automobiles will develop, and they are currently less committed to using these products in their automobiles.

Although advanced ceramic materials are not currently used in aircraft engines, the ability of these materials to operate at high temperatures with greater strength than metal alloys promises increased demand. Industry experts forecast that by the year 2010, 20 to 30 percent of the weight of an aircraft engine may be made up of ceramic parts. If this forecast proves accurate, the use of advanced ceramics could reduce the weight of an aircraft engine by 25 percent, with subsequent reduction in fuel consumption of 5 percent. For a typical airliner, this may reduce lifetime operating costs by nearly $18 million, yielding a cost savings of 3.7 percent per passenger mile.[5] Potential ASC aerospace applications include the use of ceramic composites in compressor and fan blades and in nonrotating engines parts.

Initiatives to Reduce Obstacles Facing Advanced Ceramics

There are essentially three challenges that must be met to enable ASC parts to achieve broader market access (1) reducing technical obstacles that affect the performance and reliability of ceramic materials in many critical applications; (2) minimizing higher costs associated with both individual ASC parts and with required system redesigns; and (3) improving end-user acceptance of ceramic parts.

Research and development efforts to improve the quality and lower the cost of advanced ceramics is divided among private industry and government funding. According to the U.S. Department of Commerce, the U.S. advanced ceramics industry spent nearly $190 million on research and development in 1992 while government-funded research and development (principally by the Department of Energy and the Department of Defense) totaled nearly $20 million in 1992.[6] Nearly 75 percent of total funding on research and

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[4] R. Nathan Katz, “Advanced Ceramics Overview and Outlook,” p. 37. Article appears in *Advanced Materials: Outlook and Information Requirements*. Proceedings of a Bureau of Mines conference, Nov. 7-8, 1989, Arlington, VA.

[5] “Advances in composites for Aircraft Engines,” *Ceramic Industry Magazine*, Apr. 1993, p. 75.

[6] Government-funded research has been driven by efforts to find high-strength, high-temperature, corrosion-resistant materials for increased energy efficiency and military applications. U.S. Department of Commerce, *Critical Technology Assessment of the U.S. Advanced Ceramics Industry*, forthcoming summer 1993.

development is composed of spending on ceramics processing, which includes ASC fabrication and powder synthesis.

Initiatives to Reduce Technical Obstacles

Flaws as small as 10 to 20 micrometers can reduce the strength of a ceramic structure to a few percent of its theoretical strength, resulting in failure under excessive loads.[7] Critical flaws in ASC parts that are too small to be detected by conventional analytical techniques are often difficult to eliminate. Ceramic parts are less tolerant of flaws than metal parts because flaws are far more likely to spread in a ceramic part.

Ceramic producers have generally dealt with the problem of the inherent brittleness of ceramic materials by designing ASC products to be tougher and stronger, making them more tolerant of flaws and more resistant to fracture. Some of the more commonly used methods to improve toughness and strength summarized in figure 5-5. Other methods used to improve product quality include improving the quality of ceramic powders and improving the testing of finished products.

Figure 5
Methods to improve ceramic toughness and strength

Change in microstructure

Microstructure design of a single material through alteration of grain size and shape, or the production of ceramic matrix corn sites. n composites ceramic particulates such as whiskers and fibers are introduced to reduce fractures. Advantages offered by ceramic composites over monolithic ceramics include increased strength and reliability, improved wear resistance, high thermal shock resistance, and excellent chemical resistance.

Transformation toughening

Toughening zirconium oxide by the addition of stabilizing oxides has great potential for increased use in low-temperature applications (e.g., hot-metal scissors) or where impact resistance is required. Aluminum oxide has also been transformation-toughened for use in woven preforms, mats, and papers.

Hot-Isostatic Pressing (HIP)

Simultaneously applies high temperatures and pressures to eliminate flaws in silicon carbide, silicon nitride, and zirconia to produce a microstructure that is more tine grained and uniform. This procedure permits parts to achieve maximum strength and density and allows complex net shapes to be produced. Although still at an early stage in commercial development, HIP is being used in a number of high-performance ceramic prototypes such as gas turbine blades and rotors, turbocharger rotors, and various engineering components. Due to the high costs of the process, applications are presently limited to low-volume, high value-added products.

Source: U.S. Office of Technology Assessment, *Advanced Materials By Design*, New Structural Materials Technologies, 1988, p. 39-44.

[7] U.S. Office of Technology Assessment, *Advanced Materials: By Design*, New Structural Materials Technologies, 1988, p. 38.

Improving Ceramic Materials

Because the ASC parts industries rely on ceramic powders as their raw material, the quality of powders is probably the greatest factor influencing the structure and performance of the final product. Generally, the finer and purer the powder, the stronger the finished product. Most commercial ceramic powders are made with an average diameter of 1 micron although powders for use in advanced ceramics are as small as 0.1 micron in size. Research efforts by manufacturers are devoted to making ceramic powders that are purer, more consistent from batch to batch, and which sinter more easily. Unfortunately, current technologies to improve the quality and reliability of ceramic powders are also expensive, thereby limiting their use.

One technology being developed to produce high-quality ceramic powders at low cost is the sol-gel process, which relies on the natural forces of synthetic chemistry rather than on the mechanical skills of the powder processor to produce a more consistent product. The process creates high-purity powders by altering powder characteristics at the molecular level to produce precise particle sizes and to eliminate further grinding or finishing operations. Sol-gel technology is already being used in applications where extremely high purity is required.

Other technologies for improving ceramic powder quality and consistency include rapid solidification, laser processing, and spray pyrolysis. These technologies are currently in an early stage of development and will not be commercially available for a number of years.

Nondestructive Testing

Nondestructive testing, which determines properties of a structural material without altering the material, has long been used for flaw detection in ceramic materials and will play a critical role in development of high-quality advanced ceramics. Testing equipment is being developed that will be able to detect flaws in complex shaped parts, but in a cost-effective manner.

In addition to the design of testing equipment, the design of testing standards to determine performance and reliability is an important component in any attempt to increase the market share of ASC parts. Many end users are hesitant to adopt ASC parts that do not have a long record of reliability as documented by independent testing. The American Society for Testing and Materials (ASTM) is currently taking preliminary steps to develop methods that can predict and improve the strength and durability of these materials. One of the most important properties for determining the service life of advanced materials is “creep behavior,” also called porosity. A number of methods are currently being studied that seek to predict creep behavior. Other research efforts are being made to develop accurate and cost-effective tests to measure tensile strength and high-temperature performance.[8]

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[8] Laurel M. Sheppard, “Innovative Processing of Advanced Ceramics,” *American Ceramic Society Bulletin*, Apr. 1993, p. 54.

According to the ASC industry, these efforts to improve product quality have succeeded in largely eliminating brittleness as a factor adversely influencing the use of advanced ceramics in structural applications. As a result, ASC producers feel the quality and performance of ASC parts are now beginning to compare favorably with metal parts and are actively attempting to convince end users of this fact.[9]

Initiatives to Reduce Costs

Most in the industry argue that to compete effectively against metal parts, ASC parts must cost no more than metal parts and must provide comparable quality and reliability.[10]In specialized applications where the unique properties of ASC materials are desired, these materials may successfully sell at somewhat of a premium when compared to prices of metal parts. At present, the average ASC part still costs two to four times more than a comparable metallic component and this cost differential remains as the single greatest obstacle to large-scale use of ASC materials in such major markets as automotive and aerospace.

According to industry officials, the largest single factor contributing to high production costs for ASC parts is lack of sales volume. Because there are, thus far, no large consumer markets for these items, production runs tend to be small, and average unit costs are higher than for competing metal products. Only by increasing sales volume and achieving the economies of scale that derive from high-volume production will the widespread implementation of newer cost-saving technologies, such as near-net-shape processing, be justified, thereby enabling prices to fall to the level of metal parts. In addition to attempting to encourage the development of a large consumer markets through contacts with the automotive and aerospace industries, ASC producers have also concentrated research and development efforts on technologies to reduce raw material and processing costs.

Because raw materials, principally powders, account for nearly 40 percent of total manufacturing costs, lowering these costs is important. The Ceramic Technology for Advanced Heat Engines Project, a joint research effort undertaken by private industry and the U.S. Department of Energy, was initiated in 1983 to attempt to reduce the cost of high-quality silicon nitride powders from the then current cost of nearly $20 per pound to a cost of less than $10 per pound. In addition, the project hopes to produce silicon nitride powders that are suitable for forming into components for heat-engine applications. Dow Chemical Co. has been selected as subcontractor to produce high-quality silicon nitride powder.[11]

Since nearly 30 percent of manufacturing costs are accounted for by finishing and machining operations required to form a part to its final shape and by nondestructive testing of the part, reduction or elimination of expensive machining and finishing operations is also critical. Labor costs currently account for nearly 30 percent of production costs, with 85 percent of these occurring at the finishing stage. Near-net-shape

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[9] USITC interviews with industry officials, June 1993.

[10] Sujit Das and T. Randall Curlee, "The Cost of Silicon Nitride Powder and the Economic Viability of Advanced Ceramics," *American Ceramic Society Bulletin*, July 1992, p. 1110.

[11] Susan G. Winslow, "Development of a Cost Effective Silicon Nitride Powder," *American Ceramic Society Bulletin*, Apr. 1993, p. 102.

processing[12] is one of the operations that holds the most promise for reducing finishing costs because firms often use an injection-molding forming process to meet manufacturing requirements of high volume and cost effectiveness. By increasing the total yield and volume of ceramic parts produced, near-net-shape processing reduces average unit costs.[13] In Japan, where injection-molding techniques have been used to produce ceramic turbocharger rotors since the mid-1980s, reject rates for parts produced using injection-molding have declined significantly, although they are still above reject rates for metal components.[14] The use of near-net-shape processing would allow many firms in the industry to achieve economies of scale and would allow more firms to exceed break-even production levels. However, the increased use of near-net-shape processing techniques is only cost-effective when production runs are fairly large and the type of products produced are fairly uniform.

Initiatives to Improve End-user Acceptance

Despite significant improvements in the product quality and reliability of ceramics, the continued perception of most designers is that ceramic parts are not adequate for most structural uses because of the potential for sudden failure. Furthermore, end users have had a long and successful experience with metal parts and are reluctant to use advanced ceramic materials because the performance data on these materials are not as well developed. To overcome the perception that ceramics are not viable materials, advanced ceramic companies have developed close working relationships with end users to demonstrate the effectiveness of ASC parts in specific applications. Joint-venture arrangements that allow manufacturers to confer with design engineers of the end-user company are one example of such relationships. Government programs also help bring end-user companies and their suppliers together for a specific purpose, such as the design of a more efficient gas turbine engine.

Another strategy for gaining end-user acceptance is to focus adoption efforts on areas where sudden failure would not cause catastrophic consequences. Advanced ceramic valves are demonstrating their cost-effectiveness in diesel engines where high heat and rough working environments have caused engines to need frequent overhauls to repair metal valves, which wear more quickly. Although still too expensive for cost-conscious automotive manufacturers, ASC producers have been able to demonstrate their strength and toughness in diesel valve applications. As another example, an advanced ceramic manufacturer is developing turbine blades for auxiliary power units for aircraft.[15] By establishing a successful record in these applications, opportunities for adoption of other parts for heat engines could materialize.

[12] Near-net-shape processing describes any forming process that produces a final product that requires little or no machining.

[13] Sujit Das and T. Randall Curlee, "The Cost of Silicon Nitride Powder and the Economic Viability of Advanced Ceramics," *American Ceramic Society Bulletin*, July 1992, p. 1109.

[14] John Mack, "Advanced Ceramics Processing: Cracking the Edge," *Materials Edge,* Aug. 1991, p. 24.

[15] Auxiliary power units are integral gas turbine engines that supply power to aircraft when they are on the ground.

Implications for U.S. Competitiveness

The ability to compete in the international market for advanced ceramics reportedly has important competitive implications for the United States. According to a U.S. Department of Energy survey of global ceramics experts, the U.S. gross national product (GNP) could expand by $11 billion in the year 2000 if the United States were to become the world leading ceramics producer.[16] On the other hand, GNP could decline by $26 billion if foreign manufacturers were to dominate the market.[17]

The United States and Japan currently lead in the manufacture of advanced ceramics, with each nation accounting for nearly one-quarter of total world advanced ceramics production of $153 billion in 1991.[18] Advanced ceramics use in the United States tends, thus far, to be concentrated in specialized applications in the wear part and cutting tool industries. Japanese strength in ASC markets has been built on experience in designing advanced ceramic components for the automotive market, in which Japan leads the United States. In Japan, advanced ceramics are widely used in automotive engines as turbocharger rotors due to the heat-generating characteristics of turbochargers and the greater popularity of turbocharged automobiles in Japan. On the other hand, the United States is believed to lead Japan in the development of ASC parts for other industrial applications and in the production of ceramic-matrix composites.

Although the U.S. ASC industry has overcome many of the technical problems that have prevented grater market access for ASC products, the problems of low-volume production, relative high cost, and end-user resistance to newer, nontraditional applications for these products will take longer to overcome. In these areas, government support of both research and development funding through the Advanced Materials and Processing Program (AMPP) and projects such as the High Speed Civil Transport Program, which win serve to build volume, may greatly hasten the commercialization of these products.

Recent Developments

The U.S. advanced structural ceramics market is expected to continue its pace of rapid growth of the past decade, increasing from $500 million in sales in 1995 to a projected $800 million in 2000, or by 10 percent per annum, matching growth rates experienced by this industry during the past decade.[19]The largest market for advanced structural ceramics remains the market for wear-resistant parts. The market for ceramic cutting tool inserts for the machine tool industry has been aided by the increased commercialization of competitively priced tool inserts made with silicon carbide whisker-

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[16] Dana Gardner, "Making Ceramics Work For You," *Design News*, Mar. 26, 1990, p. 95.

[17] *Ibid*.

[18] *Advanced Materials*, Annual Report of the U.S. Bureau of Mines, table 8, prepared by William J. McDonough and Robert D. Brown, Jr., p. 29, 1991.

[19]Thomas Abraham, "U.S. Advanced Ceramics Market Growth Continues," *Ceramic Industry*, October 1996, pp. 44-45.

reinforced alumina and silicon nitride.[20] Despite its early promise, the market for heat engine ceramics has not developed as rapidly as anticipated due to both technical difficulties and continuing resistance by manufacturers, such as automakers, to substitution of commercially untested new materials for proven materials. However, the area of engine ceramics is still one of active interest due to the potential of ceramics to contribute to significant energy savings. The U.S. Department of Energy (DOE) has initiated a number of programs attempting to encourage the development of turbine engines for automotive, aerospace, and industrial applications. One program has reached the field testing stage with Solar Turbines Inc. (San Diego, CA) to test an industrial turbine engine containing a number of structural ceramic parts, including a ceramic combustor liner, rotor blades, and nozzles. Results, thus far, have been reported as encouraging.[21]

Ceramic composites are beginning to find commercial applications on the strength of their resistance to high temperature and thermal shock, chemical inertness, and exceptional strength. Originally designed for use in gas turbine engines, composites are currently being evaluated for use in aerospace applications, and in equipment such as radiant burners and heat exchangers, where high temperatures and exposure to corrosive chemicals pose a threat to more traditional materials.[22] The Darkstar reconnaissance aircraft, manufactured by Lockheed Martin, is one of the first military aircraft to be designed and built (3,700 have been produced) almost completely with advanced composite materials. The design of the composite portion of the aircraft, drawing on research generated through a U.S. Department of Defense ARPA (Advanced Research Projects Agency) contract, is nearly 25 percent lighter than an equivalent aluminum structure.[23]The principal obstacle to further composite use in commercial applications is cost, in that a composite component may cost 4 times more than a traditional component. The U.S. Government, through ARPA is currently financing a $15 million program with Northrop Grumman to develop low-cost fabrication methods for ceramic composite structural components in an attempt to lower their costs for commercial application and production.[24]

Most advanced structural ceramics are currently produced using such traditional methods of fabrication as injection molding, reaction-bonding, and hot-pressing. A number of nontraditional advanced materials fabrication processes also are being developed which are expected to result in more precise control of material grain size, production of nearer-net shape ceramic shapes, and the use of purer materials substrates for ceramic shapes. These nontraditional technologies include vapor deposition, sol-gel, and hot-isostatic pressing ("HIPping"). Much private and government-related research and development is currently underway to improve these technologies in an effort to lower the cost and improve the properties of advanced ceramic components produced using these methods. Vapor deposition techniques are increasingly being used in the application of superhard coatings to cutting tools and automotive components such as

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[20]Ibid.

[21]David W. Richerson, "Ceramics for Turbine Engines," *Mechanical Engineering*, September 1997, p. P. 83.

[22]James K. Wessel, "Breaking Tradition with Ceramic Composites," *Chemical Engineering*, Oct. 1996, p. 80.

[23]"New Horizons for Aerospace," *R & D Magazine*, Jan. 1996, pp. 28-9.

[24]Laurel Sheppard, "Manufacturing Costs Continue to Challenge Ceramic Composites Industry," *Ceramic Industry*, May 1997, p. 43.

engine blocks, piston rings, and valve stems, to improve their wear and abrasion resistance.[25] Technology for the application of hard coatings for carbide tools has advanced from early single-layer coatings to current multilayer applications. The choice of material layer and total coating thickness can also be tailored to fit particular cutting applications.[26] Sol-gel technology is continuing to find increasing commercial application in the manufacture of films, coatings, powders and grains, fibers, and porous gels for abrasives, construction products, and electro-optical markets. A commercial plant for the manufacture of electrochromic glass, produced using sol-gel technology, will be built in 1998 by Donnelly Corp., while commercial production of limited amounts of aerogel insulation by Nanopore Corp. is currently underway, with additional production expected to sharply increase in 1998. HIPping is a process in which high pressures and temperatures are applied to a component to improve the bonding among the particles. The U.S. Navy is currently using HIPping to manufacture high-value parts such as turbine engine blades. Presently, due to the high cost of the process, HIPping is limited to components in which the value added in improved material properties offsets the additional cost.

The total level of research and development expenditures for structural ceramics-related activities by all agencies of the U.S. Government declined from $136 million in 1996 to $119 million in 1997.[27] The decline in the level of federal research and development spending largely reflects less use of advanced ceramics in designs for military hardware.[28] The U.S. Department of Energy, the National Aeronautics and Space Administration (NASA), and the U.S. Department of Defense are the principal agencies responsible for government research and development spending, accounting for 40 percent, 29 percent, and 25 percent, respectively, of total research and development spending for advanced ceramics in 1997.[29] Most government advanced materials spending is integrated with the efforts of the National Laboratories, universities, and private industry and uses traditional mechanisms of research contracts and grants, consortia, and Cooperative Research and Development Agreements (CRADAs).[30] The goal of these expenditures is to promote commercialization of state-of-the-art materials for both commercial and military use and to meet specific technological objectives, emphasizing development of high-performance commercial and military aircraft; ultra-fuel-efficient and low-emission automobiles; and a durable transportation infrastructure.[31] One important initiative to use advanced structural ceramics is the Partnership for a New Generation of Vehicles (PNGV), a consortium, which includes the U.S. Government and U.S. automakers. Other U.S. Government offices and

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[25]"Thin-film Coatings Make Auto Parts Supertough," *R & D Magazine*, March 1996. pp. 29-30.

[26]H.G. Prengel, W.R. Pfouts, and A.T. Santhanam, "Coating Carbide Cutting Tools," *Manufacturing Engineering*, July 1996, pp. 82-88.

[27]Information compiled by the U.S. Department of Energy, Division of Materials Sciences.

[28]The major defense-related application for advanced structural ceramics is in ceramic armor used in helicopters and on some land-based vehicles. Plans to use these ceramics as armor on more land-based vehicles have been either abandoned or postponed, due largely to budget considerations.

[29]Information compiled by the U.S. Department of Energy, Division of Materials Sciences.

[30]See "New Manufacturing Processes for Materials: Government Policies and Programs Towards Commercialization" in part I of this report for more information.

[31]*The Federal Research and Development Program in Materials Science and Technology*, Dec. 1995, p. 1.

programs making significant contributions to advanced structural ceramic research and development include the following:

- USDOE Office of Transportation Technology's Propulsion System Materials Program focuses on the development of reliable, cost-effective ceramic materials to facilitate their commercial introduction into automotive heat engines.

- USDOE Office of Industrial Technologies seeks to stimulate the development and use of industrial technologies that increase energy efficiency and lower the costs of environmental protection by focusing on technologies to improve process efficiency within the most energy-intensive industry sectors of the U.S. economy.[32]

- Current ARPA activities emphasize the development of affordable manufacturing and fabrication techniques for ceramics, oriented toward finding methods to manufacture low volumes at costs comparable to those of high-volume production.

- The Continuous Fiber Ceramic Composite (CFCC) program is a collaborative effort involving industry, national laboratories, academia, and other government researchers seeking to develop advanced composites for use in CFCC components.

[32]Bill Werst, "Charting Progress," January 1997, document provided by the U.S. Advanced Ceramics Association, Arlington, Virginia.

Metal Matrix Composites May Be Key to More Efficient Automobiles

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Automobile manufacturers are responding to demands for greater fuel efficiency through use of alternate materials such as metal matrix composites (MMCs). Parts made of MMCs offer significant weight savings while maintaining if not improving performance as compared with conventional materials. Over the last decade, MMCs have made slow but steady progress toward mainstream utilization in the automobile industry. Although not used commercially in U.S. production vehicles, the three major U.S. automobile companies are testing MMC parts.

Since this article was first published in the Industry, Trade, and Technology Review *of May 1993, there has been substantial progress in the commercialization of MMCs. The automobile industry uses MMC parts in certain limited production vehicles, and appears poised to expand usage into other vehicles. The concluding section elaborates further on recent developments.*

Environmental concerns, especially in the large automobile markets of the United States, Japan, and the European Community, have caused strict fuel economy and emission standards to be implemented, and more stringent standards are expected. As a result, future automobiles will have to perform more efficiently, using less fuel and generating less pollution. To meet these standards and to maintain competitiveness, automobile producers are seriously considering alternate materials in the design of their products. Incorporating advanced materials, such as metal matrix composites (MMC), into automobiles appears a promising way to achieve significant improvements in performance.[1]

The development of the latest generation of advanced materials has been an important goal of research scientists for a number of decades. Much of the development has been associated with the defense and aerospace industries, in which performance improvement is crucial. Many advanced materials are designed to combine desirable properties of conventional metal, ceramic, or plastic materials into a composite substance. The adaptation of advanced materials into commercial products has been identified as an important method of improving competitiveness. This article describes MMCs, focusing on the types suitable for automobile applications, the structure of the U.S. MMC industry, and the reasons why automobile companies are interested in MMCs.

[1] An advanced material is one that exhibits superior physical properties (e.g., strength, strength-to-density ratios, hardness, durability, etc.) compared with conventional materials. Advanced materials are also referred to as “new ,” “high-tech,” or “high-performance” materials.

MMC Attributes and Applications

MMCs are composed of a metal or metal alloy base (called the matrix) and a reinforcing (usually ceramic) material that is dispersed in the matrix. MMCs typically are stronger, stiffer, operate at higher temperatures, have better abrasion resistance, and have other advantages.

MMC technology was first developed in the early 1960s. Since that time over $1 billion has been invested in research and development (R&D), mostly focused on military and aerospace applications, for which cost considerations are secondary to improved performance. Lower cost MMCs were developed based on this research, and further R&D was undertaken by large primary aluminum producers and chemical companies to develop commercial applications. The automobile industry was targeted as an industry where suitable applications could be found and where the potential for large volumes of consumption is high. Aluminum companies specifically targeted aluminum MMCs as a method of expanding aluminum demand.

MMC properties and production costs are dependent on the type of reinforcement and the manufacturing process. The reinforcing material may be discontinuous or continuous. MMCs with continuous reinforcement have the most desirable properties. However, continuous reinforcement material is more expensive than discontinuous materials, and continuous-reinforced MMCs require costly processes to manufacture. Present production costs for the continuous-reinforced MMC exceed $200 per pound whereas costs for discontinuous- reinforced MMCs can be less than $2 per pound.

The least expensive type of MMC part is the discontinuous type reinforced with particulates,[2] which is relatively inexpensive. This type can be produced using conventional metal casting techniques. However, particulate MMCs can also produced using powder metallurgy processes that are more expensive but that produce MMCs with better physical properties.[3]

The most promising MMCs for automobile applications are the aluminum-based types. Reinforced with particulates of silicon carbide or alumina, aluminum MMCs have been shown to be able to take the place of certain steel and cast iron parts in automobiles with weight savings in excess of 50 percent. Secondary weight savings are also possible, because the use of lighter parts allows the use of lighter support systems.

Aluminum MMCs with particluate reinforcement appear to be practically viable for use in the automobile production process. Small amounts of aluminum MMCs are currently being used as cylinder liners and in pistons of certain Japanese automobiles. Aluminum MMCs can be formed with standard metal-casting techniques with minor modifications. Aluminum MMCs are also amenable to standard machining techniques. Moreover, the raw materials are generally commodity-type items that are readily available. At the present stage of technological development, particulate reinforced aluminum

[2] Other discontinuous reinforcement shapes include whiskers and fibers, which are in general more expensive than particulates.

[3] Powder metallurgy involves mixing metal and particulate powers, forming a shape, and sintering (i.e., heating but not melting).

MMCs for automobile applications can be manufactured at economical production rates and costs.

Structure of the MMC Industry

The structure of the aluminum MMC industry in North America is presented in figure 1. Two MMC producers are primary aluminum companies (Duralcan is owned by Alcan) and appear to be the only firms that are making a significant effort to develop the North American aluminum MMC market for automobile applications. These companies have several advantages over other firms that may want to enter this market, including—

- The ability to generate sufficient internal funds to finance large-scale research and development efforts;
- A vested interest in generating increased markets for aluminum;
- A history of working closely with automobile companies in researching and developing aluminum-based components;[4] and
- A history of involvement in the automotive supply infrastructure. These companies have supplied conventional aluminum parts for many years and it is likely that supplier channels can be adapted to supply MMCs with only minor changes.

The other component of the MMC raw material providers is companies that manufacture the silicon carbide particulates. Numerous sources of this raw material are available. Structurally, MMCs are sold by the producers to companies that form and machine parts. These companies are either independent or are owned by automobile companies.

Duralcan and Alcoa produce silicon carbide reinforced aluminum MMCs using different production processes. Duralcan produces MMCs with a casting process; Alcoa uses a powder metallurgy process. Duralcan's MMC is a low-cost product that will likely be used in the most cost-sensitive areas of automobiles (i.e., brake, driveline, and suspension systems). Alcoa's product is a higher cost MMC that could be most effective in improving automobile engine performance. Connecting rods, pistons, and valve train components are some of the parts Alcoa is targeting for MMCs.

Duralcan's facility in Canada can produce large quantities of MMCs and was built before end-use markets had been established. Duralcan manufactures MMCs in an ingot and billet form. Fabricating companies use these forms to produce automobile parts, either by casting or machining. Duralcan has sponsored collaborations with parts and machining companies to research fabrication, tooling, and welding of MMCs to ensure development of the necessary application technologies.

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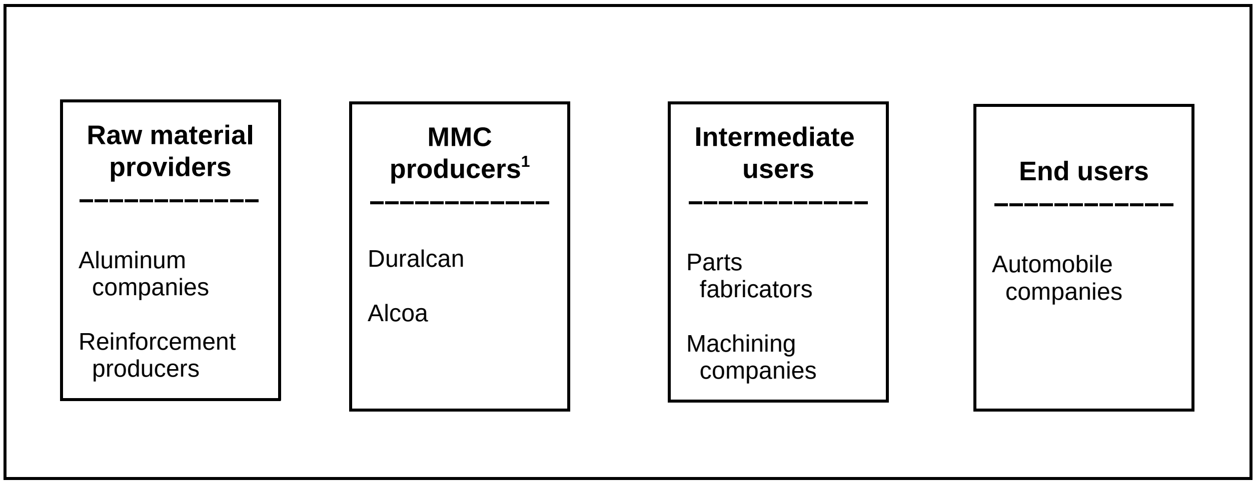
[4] For example, Alcoa has a program with Audi (Germany) to develop an automobile with an aluminum frame.

Figure 1
Structure of the North American metal matrix composite industry



[1] Other companies, such as Advanced Composite Materials Corp., Dow Chemical Corp., and Textron produce MMCs but are targeting different end users.

Source: Interviews of industry representatives by U.S. International Trade Commission staff.

Alcoa presently produces only test quantities of MMCs; however, it would not be difficult to adapt present facilities to commercially manufacture MMCs. In Alcoa's production process, aluminum and silicon powders are mixed and pressed into shape called a biscuit. This shape is heated to bind the particles and is then forged into a part. Subsequent machining may be necessary to achieve final part dimensions, although this "near net shape" process typically requires less machining than the Duralcan process.

U.S. Automobile Companies' Strategic Considerations

Fuel economy is a major regulatory element in the U.S. automobile market. Because of expectations that government-set fuel economy standards will become even more stringent in the future, automobile weight reduction and improved engine performance have emerged as major strategies to meet these standards. Reportedly, Toyota has targeted a 40-percent weight reduction for its automobiles. It appears that automobile companies that cannot reduce the weight of their products or improve the performance of their engines will face a serious burden in meeting fuel economy standards and a possible decline in their ability to compete.[5]

In an attempt to increase competitiveness, the U.S. automobile industry is actively evaluating lighter materials. Cost is the most import consideration in selecting materials. Therefore, conventional lightweight materials, such as aluminum and magnesium are

[5] Companies that cannot meet U.S. fuel economy standards are subject to Government fines.

the first option to replace cast iron and steel. For applications for which conventional lightweight materials perform poorly or cannot meet strength or stiffness requirements, advanced materials are seriously considered. Relative low cost and ease of fabrication make particulate-reinforced aluminum MMCs the most promising advanced material alternative. Duralcan's MMC is currently priced at $1.85 to $2.50 per pound in ingot form (current steel price is under $0.50 per pound).[6] Table 1 lists some of the potential applications of MMCs in automobiles.

Table 1
Potential applications of aluminum metal matric composites in automobiles

System	Component	Advantage over conventional material
Engine	Piston	Higher temperature operation, wear resistance, weight reduction.
	Cylinder liner	Wear and seizure resistance, lower friction, and weight reduction.
	Connecting rod	Higher stiffness, weight reduction.
	Bearings	Weight reduction, reduced friction.
Brakes	Disk rotors	Wear resistance, weight reduction.
	Calipers	Wear resistance, weight reduction.
Driveline	Drive shaft	Weight reduction.
	Gears	Wear resistance.
Suspension . .	Struts	Damping effect, higher stiffness.

Source: Pradeep Rohatgi, “Cast Aluminum-Matrix Composites for Automotive Applications,” *JOM*, Apr. 1991, p. 10.

At present all three U.S. automobile producers are testing MMC parts, but there is no commercial production of U.S. automobiles containing such parts. Industry sources indicate that the first MMC part in a U.S. production vehicle will probably be a drive shaft or a brake rotor, perhaps as early as the 1994 model year.

Japanese automobile companies have been more aggressive in adapting MMC technology to their products. Honda sells a car in Europe with MMC cylinder liners. Toyota is selling a car with MMC reinforced pistons. Reportedly, Japanese automobile companies are more willing to test MMC parts on production automobiles to gain experience with the material even if it is not economically viable. The Japanese companies also have gained MMC experience by developing in-house MMC production capability.

Conclusion

[6] Compared with steel, the higher unit costs of MMCs are offset to some extent by the need to use a smaller quantity for a given part.

Application research and development continues for MMCs. A significant amount of effort is devoted to improving the parts fabrication and machining production stages, because there can be substantial degradation of physical properties by current methods. Some of this degradation may be preventable by using near-net-fabrication processes. The U.S. automobile companies participate in MMC research and development by testing MMC parts, developing compatible parts (e.g., brake pads that work with MMC rotors), and developing design specifications for MMC materials.

Although MMCs offer automobile producers a material that will significantly improve performance, the cost of MMCs and the difficulties in fabrication make it likely that MMC parts will not be used in significant quantities by the automobile producers for the rest of the decade. However, this period will likely be an important stage for the automobile producers in acquiring experience with MMCs in preparation for more intensive use. The ability to make competitive automobiles in the next century may hinge in part on success in this stage.

Recent Developments

Aluminum MMCs are making steady progress toward mainstream commercialization. The most promising market continues to be the automotive industry, where aluminum MMCs offer substantial weight savings and performance improvement in most aspects as compared with conventional materials. The efforts of two leading aluminum MMC makers, Duralcan, a subsidiary of Alcan (Canada), and Lanxide Corp. are described below.

Duralcan uses the stir-casting process to produce MMCs. Ceramic particles, either silicon carbide or aluminum oxide, are mixed with molten aluminum. The mixture is cooled to form ingots, which can be fabricated into parts using conventional casting or metal-forming processes.

Duralcan has met considerable success in marketing its aluminum MMCs to the automotive industry. In 1996, both General Motors (GM) and Chrysler Corp. announced that they would use Duralcan in new limited-production vehicles. GM has integrated rear brake drums made of Duralcan's MMCs into its experimental electric vehicle, the EV1. Chrysler features Duralcan rear brake rotors in its unconventional hot-rod, the Plymouth Prowler. Also unveiled in 1996, Mazda's RX-01 concept car uses Duralcan brake rotors. Duralcan has moved into larger production runs with the standard driveshaft of the 1997 Chevrolet Corvette, which also are optional in the 1997 Chevrolet S-10 pickup truck.

In addition, Duralcan has pursued other applications. The German ICE high-speed train is testing Duralcan brake discs for an estimated weight savings of 13 tons on a entire train. Duralcan expects the ICE to make widespread use of its material by the middle or end of 1998. Metal Composite Technology of Towcester, UK, makes brake discs for 125cc and 250cc motorbikes from Duralcan. Duralcan also is being used for the studs of snow tires in Scandinavia.

Duralcan MMCs are supplied by a plant in Dubuc, Quebec. The Dubuc plant has an annual capacity of 25 million lbs/yr, but this could be expanded to 30-32 million lbs/yr.

The plant is currently operating at about 15 percent of capacity. Duralcan also maintains a marketing division in Novi, Michigan.

Eck Industries (Manitowoc, Wisconsin) molds the brake rotors of the Prowler. The Kelsey-Hayes unit (Livonia, Michigan) of Varity Corp. assembles the rotors into the brake systems. Unidrive Pty Ltd. of Clayton, Australia makes the driveshafts for the Corvette. American Axle & Manufacturing Inc. of Three Rivers, Michigan produces driveshafts for the S-10.

Lanxide has developed two methods of manufacturing aluminum MMCs: the Primex cast process and the Primex infiltration process. The cast process is similar to Duralcan's stir-casting process. In the infiltration process, molten aluminum infiltrates a porous preform part made of silicon carbide and solidifies to form an MMC. This process allows for a higher ceramic content than the cast processes.

In 1996, the Lotus Elise became the first production car to draw on Lanxide's technology. Lanxide aluminum MMCs with 30 percent ceramic content are used in the brake rotors of all four wheels. Lotus incorporated MMCs into the light-weight vehicle at the design stage, enabling MMC brake components to be used. Elsewhere, Lanxide has entered into a licensing agreement with Brembo of Italy for the manufacture of MMC brake rotors and drums in Europe. Lanxide has signed a license with Akebono in Japan for automobile applications and is in intensive discussions with potential partners in the United States.

Lanxide has high hopes for the electronic components market, as well, expecting its sales in electronic components to double in 1997. GM uses Lanxide MMCs in the electronics of both the EV1 and S-10. Motorola communications satellites also incorporate components made out of Lanxide MMCs.

Lanxide maintains a pilot scale production facility in Newark, DE. The company has actively pursued strategic alliances. Lanxide KK is a Tokyo-based joint venture between Lanxide (65 percent) and Kanematsu (35 percent) to promote Lanxide products in Japan. Lanxide KK and Nihon Cement Company are 50-50 partners in a joint venture to manufacture aluminum and ceramic matrix composites in Sendai, Japan.