The Budd Company, Design Center

Composite Materials Promise Increased Fuel Efficiency

In the early 1990s, with fuel prices on the rise and conservation of national concern, both consumers and Congress began to push for stricter vehicle fuel economy requirements. However, the advent of sport utility vehicles dramatically increased the sale of light trucks. And though the fuel economy of light trucks had increased twofold since the 1978 Iranian oil embargo, it still did not approach that of passenger cars. To meet fuel-efficiency demands, many auto parts makers wanted to use composite materials (such as plastics), because of their high strength-to-weight and stiffness-to-weight ratios and superior corrosion resistance. The Budd Company sought funding from the Advanced Technology Program (ATP) to accelerate technically risky research and development (R&D) to produce composite vehicle frames by using an innovative high-volume, cost-effective process. At the close of this ATP project in 1998, the Budd Company had successfully completed a pilot manufacture of structural impact bumpers using its structural reaction injection method (SRIM). However, with cycle times of 3 to 6 minutes instead of the desired 60 to 90 seconds, Budd determined that its SRIM technology was still unsuitable for most automotive applications. The company continues to invest in R&D to further reduce cycle times.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

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Research and data for Status Report 94-02-0040 were collected during October - December 2001.

Light Trucks Generate Heavy U.S. Economic Activity

As U.S. automotive manufacturers recovered from a sharp downturn in sales resulting from the 1990 recession, light trucks played a salient role in the industry's resurgence. By 1994, light trucks, particularly sport utility vehicles (SUVs), accounted for almost 40 percent of all U.S. motor vehicle sales, with manufacturers pushing the limits of their production capacity in order to meet the overwhelming demand for these popular vehicles. Moreover, light trucks represented a U.S. manufacturing stronghold—domestic manufacturers supplied 90 percent of the light trucks sold in the United States in 1994.

However, Congress and consumers were concerned about the poor fuel economy of light trucks and the resultant depletion of natural resources, the increase in American dependence on imported oil, and the financial strain of high fuel costs on light truck owners.

Composites Begin To Lighten the Load of Light Trucks

Vehicle weight is a primary determinant of fuel economy—75 percent of a vehicle's energy consumption directly relates to factors associated with its weight. To improve the fuel economy of light trucks, therefore, manufacturers focused on reducing their weight, primarily through manufacturing methods that use raw materials offering the strength of steel without its heft.

With the highest strength-to-weight ratio of any known material, composites provide the advantages of steel at 25 percent less its weight. Vehicles with composite frames weighing 225 pounds (25 percent less than the conventional 300-pound steel frame), would consume 1.6 percent less fuel than the standard, greatly reducing overall fuel usage over the life of the vehicle.

Other Benefits Enhance the Outlook for Composites

In addition to improved fuel economy, composites offer many other benefits, such as durability, practicality, and affordable redesign. The durability of composites provides superior dent and corrosion resistance. Because several plastic parts can be molded together in one operation, manufacturers can consolidate composite parts for easy assembly. A reduction in noise, vibration, and harshness also makes composites a preferable alternative to steel.

Market trends before this ATP-funded project indicated that manufacturers should place a higher premium on a vehicle's visual appeal than on its fuel efficiency. Fuel-efficient frames had not fared well in the market due to aesthetic reasons. The molding properties of composite frames, however, could allow fuel efficiency and aesthetics to co-exist by giving parts makers the freedom to enhance visual appeal by adding compound curves and parabolic shapes to a vehicle's design. Moreover, these aggressive styling treatments would come at an affordable tooling price, allowing manufacturers to refresh a model's appearance on a year-to-year basis and keep up with the booming market for vehicles. This is impossible with steel, because exorbitant tooling costs prohibit updating steel-based vehicles as frequently as the market demands. On average, the development of tooling for a composite part is twice as fast and four times less expensive than the development of steel tooling, allowing for the rapid production of limited-edition models with low retooling costs.

In addition to improved fuel economy, composites offer durability, practicality, and affordable redesign.

With the advantages of low retooling costs, practicality, and high fuel efficiency, composites seemed to meet all of the demands of the automotive market. Increasing the use of composites in U.S. automotive manufacturing processes promised to strengthen the U.S. position in the lucrative vehicle market, increase the aesthetic and practical appeal of domestic vehicles, save consumers close to $1 billion annually in fuel costs, and make a positive impact on the environment.

Composites Manufacturing Methods Require Further Development

Composites were first used in the body of the 1954 Chevrolet Corvette; however, relatively high material and manufacturing costs have limited their full use. To convince the industry of the value of composites, parts makers focused on improving manufacturing techniques to reduce scrap costs and accelerate cycle times. Whereas steel proves more cost effective for high-volume applications, composites, because of the relatively low tooling investment costs, were beginning to prove their value for lower volume production. Therefore, parts makers sought to optimize manufacturing methods aimed at producing 100,000 to 150,000 parts annually.

To optimize manufacturing methods, however, parts makers had to overcome significant manufacturing method inertia. For decades, researchers had concentrated on developing methods for manufacturing sheet-molded compound (SMC) as the way to introduce composites into vehicles. However, because of serious drawbacks, such as high scrap waste, low impact resistance of SMC parts, costly refrigeration storage requirements, and low material shelf life, manufacturers sought alternative methods. In the 1980s, structural reaction injection molding (SRIM) presented a possible alternative, providing the following advantages over SMC: better structural control of the amount and orientation of fiberglass (which provides early identification of the quality and strength of the part), lower tooling costs, and reduced scrap waste.

However, SRIM had inadequacies that the Budd Company thought it could address through two innovative improvements. Convinced of the potential benefits of implementing these modifications, the company sought ATP funding in 1995 to accelerate the advancement of SRIM techniques so that the technology for a composite vehicle frame would be available for vehicles manufactured in 2000.

Speed-to-Market Is Critical in the Automotive Industry

Composites promised to speed up product development, which had been a U.S. industry weakness. In the automotive industry, the United States requires 60 months and 3.2 million labor hours for product development, whereas Japan boasts a development time of 46 months, using only 1.7 million labor hours. Because composites require less extensive tooling, on average 39 weeks for tooling design and manufacture compared to 50 weeks for steel tooling, they could offer quicker product development once the basic composite technology was in place.

Prior to the ATP award, the pace of SRIM R&D lagged behind the goal to develop the basic technology for a full-frame composite vehicle by 2000. The Budd Company's R&D allocation was $250,000 annually, a rate that translated into a development time of 12 years. ATP's contribution of $2 million reduced the expected development time to just four years, giving U.S. manufacturers a competitive edge in the composites market.

Innovative Use of New Process Advances SRIM Technology

In its submission to ATP, the Budd Company proposed to develop SRIM manufacturing methodologies for a one-piece hollow closed-section light truck frame. By creatively applying a 70-year-old technology known as the slurry process to the production of preforms and by using a disposable film bladder in the molding stage, the company hoped to use SRIM manufacturing to make the process an economical option for parts production. The ultimate output goal was approximately 50,000 to 100,000 units annually. Before the ATP project, which began in 1995, the Budd Company did not have the capability to produce even a limited number of prototypes; the technical risk was simply too high for internal funding. The potential business impact of lighter frames on the automotive industry and the environmental impact of more fuel-efficient automobiles, however, were too significant to ignore. ATP awarded the Budd Company $2 million in cost-shared funds to pursue research and prototype development.

Adapted Slurry Process Proves Cost Effective

The Budd Company's first innovation was to adapt the slurry concept to develop a preform manufacturing process. The slurry process is less expensive than the labor-intensive hand-cut preforms and high-scrap thermoformed preforms. The process involves a tank of water with a hydraulic cylinder mounted beneath it. A cradle is attached to the hydraulic cylinder, upon which a platen rests, covering the surface area of the tank. A perforated screen, shaped to the geometry of the desired vehicle part, is fixed at a cutout in the platen and positioned at the bottom of the tank. Chopped reinforcing fibers and thermoplastic binding fibers are introduced into the water, creating a slurry, which is agitated to produce uniform dispersion. Once uniform dispersion is achieved, the hydraulic cylinder moves the screen rapidly to the surface, capturing fibers as the water passes through, in the fashion of a sieve. The resulting structural preform, now shaped to the geometry of the desired vehicle part, is removed from the screen and placed into an oven to dry.

The next step of the SRIM process, injection molding, uses the Budd Company's second innovation: a low-cost disposable film bladder that acts as a vacuum to hollow out the part. First, two preforms are fit together and clamped. A disposable film bladder, roughly shaped to the geometry of the part, is inserted between the upper and lower preforms and is inflated, thereby defining the hollow surface of the part during the molding process. Catalyzed resins are injected into the mold through flow channels, which pour through the mold cavity to fill the space between the bladder and the preforms. The bladder, a balloon-like vacuum that penetrates the walls of the preforms, withdraws all excess air from the mold cavity, thereby pressing the resins against the pockets and grooves of the two preforms, as in-mold polymerization and curing of the resins occur.

SRIM Process Achieves Technological Advancements

Significant technological advances that Budd achieved during the ATP project include:

- Identification of a durable material to manufacture film bladders strong enough to withstand high heat and pressure and development of a successful nozzle design for the vacuum function of the bladders

- Improvement of the aerial density of finished parts by enhancing the slurry preform process, including modified bubblers for better agitation control, control of the length of time for glass dispersion and the speed for pulling the screen through the slurry, and the patented use of an improved capture method
- Validation of the slurry and molding processes by two successful trial runs that produced prototype SRIM storage boxes and structural impact bumpers

A cost-benefit comparison of the Budd Company's new method compared with the older method revealed a cost savings of 42 percent on a per-unit basis. Moreover, the new slurry process produced lighter parts that exhibited a glass variation of only 10 percent (as opposed to 40 percent associated with other processes) and generated less than 5 percent mold scrap (compared to a scrap rate of 20 percent with other processes).

ATP's contribution reduced the expected development time to just four years, giving U.S. manufacturers a competitive edge in the composites market.

Despite these advances, technical challenges persisted. The Budd Company still needed to address the limitations of bladder technology, as leakage remained a problem and bladders exhibited inferior performance for complex vehicle parts with difficult-to-duplicate preform surfaces. Fine-tuning of slurry process control and molding injection techniques presented other opportunities for SRIM advancement. The Budd Company continued to fund R&D for the SRIM process after the ATP project ended, including its work with the Automotive Composites Consortium to enhance preform technology by focusing on the production of tailgates.

SRIM R&D Intrigues Automotive Industry

During the ATP project, the Budd Company conducted several tours of its plants to generate interest in the potential of SRIM processes, particularly bumper and chassis applications. Participants included Ford Scientific Laboratory and the Carrier Transicold Division of United Technologies. The Budd Company developed a cost model of its SRIM process to illustrate to several low-volume liquid molding companies the advantages of the slurry process as an alternative to labor-intensive hand-cut preforms and high-scrap thermoformed preforms. Budd validated the SRIM method by successfully producing 200 SRIM structural impact bumpers. Samples of SRIM preforms were supplied to one of the molding companies for testing to determine moldability. Additionally, the Budd Company transferred the 200 structural impact bumpers produced from the successful trial run to ETM Enterprises, Inc., a company that had previously limited its efforts to manufacturing SRIM components from only sheet and thermoformed glass preforms. ETM compared Budd's SRIM-processed components with its sheet and thermoformed glass preforms.

In 1999, the Budd Company's parent company, Thyssen AG, merged with Krupp AG. As a result of that merger, the Budd Company remains a U.S.-owned subsidiary, but is now part of Thyssen Krupp Automotive AG, a company that ranks among the largest automotive suppliers.

Conclusion

During its ATP project, the Budd Company reached average cycle times of three to six minutes for the production of prototype structural reaction injection method structural impact beams. However, it did not achieve desired cycle times of under 60 to 90 seconds, which would make SRIM comparable to sheet-molded compound. Because of the high cycle times associated with SRIM, the Budd Company now focuses primarily on SMC components. However, the business benefits of these composite materials remain attractive for manufacturers, and the promise of a manufacturing breakthrough continues to drive investment in composite materials. The Budd Company continues to invest in research and develpment to further develop the methods that emerge in the ATP project. Moreover, the SRIM technology that was developed during this ATP project will contribute to the industry's efforts to optimize manufacturing methods for composites.

PROJECT HIGHLIGHTS
Budd Company, Design Center

Project Title: Composite Materials Promise Increased Fuel Efficiency (Development of Manufacturing Methodologies for Vehicle Composite Frames)

Project: To develop and implement a cost-effective method for manufacturing composite frames for light trucks that are 75 pounds lighter than conventional steel frames, thereby increasing vehicle fuel efficiency.

Duration: 2/1/1995-1/31/1998
ATP Number: 94-02-0040

Funding (in thousands):**

ATP Final Cost	$ 2,000	60%
Participant Final Cost	1,312	40%
Total	$ 3,312	

Accomplishments: The Budd Company validated the structural reaction injection method (SRIM), which incorporates the slurry process and bladder technology, by successfully producing 200 SRIM structural impact prototype bumpers. Budd has written several publications and received the following patents for technologies related to the ATP project:

- "Apparatus for controlling fiber depositions in slurry preforms"
(No. 5,795,443: filed March 13, 1997, granted August 18, 1998)
- "Slurry preform system"
(No. 5,972,169: filed January 15, 1998, granted October 26, 1999)

Commercialization Status: At the conclusion of the ATP project in 1998, the Budd Company demonstrated the capability to produce SRIM structural impact bumpers in approximately three minutes per unit. With this relatively high cycle time, commercialization of the SRIM technology developed during this project was impractical, even for vehicle parts with annual volumes of less than 100,000. However, the successful demonstration of this SRIM process opens up possibilities for commercial applications in industries with low-volume output, such as heavy truck, recreational vehicle, and watercraft industries.

Since the ATP project ended, the Budd Company has focused primarily on sheet-molded compound (SMC) components, having determined that its SRIM technology is currently unsuitable for most automotive applications due to high cycle times. However, the company continues to invest about $40,000 annually in research and development to further develop the methods that emerged in this ATP project. According to The Budd Company's Plastics Division, "the day when a vehicle is all or mostly made of plastics is a long, long way off. But plastics are here to stay in the automotive industry. The characteristics of plastics have become integral to the way stylists think about vehicles of the future and production engineers envision assembly." The Budd Company remains a leader in the growth of composites.

Outlook: The outlook for this technology is uncertain. As high emissions plague various open-molding processes and the industry becomes more environmentally savvy, the Budd Company foresees a possible upswing in the importance of closed-molding processes, including SRIM, that require structural preforms. This shift would make the SRIM technology developed during this ATP project especially valuable, because the unique slurry process has produced more reliable and less expensive preforms than previous methods.

Composite Performance Score: *

Focused Program: Manufacturing Composite Structures, 1994

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** As of December 9, 1997, large single applicant firms are required to pay 60% of all ATP project costs. Prior to this date, single applicant firms, regardless of size, were required to pay indirect costs.

Research and data for Status Report 94-02-0040 were collected during October - December 2001.

Caterpillar Incorporated

New Coating Technology for Stronger, Longer Lasting Wear Parts

In the heavy manufacturing industry, strength, resilience, and reliability are vital characteristics in products. In the early 1990s, Caterpillar developed a research plan to apply functionally gradient material (FGM) coatings onto wear parts in a cost-effective manner so that the coated parts would last several times longer than parts currently available. By spraying a series of coatings designed for high adherence and wear and corrosion resistance onto common, low-cost steel substrates, one could affordably achieve durability and strength. The expected result would represent a breakthrough advancement for part strength, resilience, and reliability—an advance that would otherwise have taken the market more than 10 years to achieve incrementally. Although the potential of the proposed technology impressed Caterpillar engineers, cost pressure in the market would prevent the company from fully capturing the economic benefits of its proposed innovation.

Given the market structure for wear parts, Caterpillar could only slightly increase the cost of its parts, yet purchasers could use these stronger, more resilient parts for many more years than current parts. Therefore, Caterpillar and its five subcontractors (four companies and one university laboratory) submitted a proposal to the Advanced Technology Program (ATP). In 1994, ATP awarded Caterpillar $1.9 million in cost-shared funds to pursue FGM research. Through this three-year ATP project, the team developed new FGM systems that improve contact fatigue and wear and corrosion resistance of components such as gears, undercarriages for heavy earth-moving equipment, and rolls for steel mills. Because Caterpillar used the new technology to enhance several of its products, end users are now realizing the benefits of lower costs and higher quality products. In addition, several firms are marketing the technology for other applications within large mining operations and high-deposition thermal spraying.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

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Research and data for Status Report 93-01-0055 were collected during October – December 2001.

Caterpillar Exceeds Customer Expectations

Gears, bearings, and other components that experience concentrated grinding and wear and tear have traditionally been coated using plating, case-hardening, and hard-facing coating technologies. The coatings were usually applied with a diffusion process and yielded a hardness gradient that did not affect elastic modulus (that is, the force that is applied to elongate material). But the processes were not perfect, and the components usually wore out. However, if coatings were developed that could be sprayed onto the the surface of low-cost steel substrates, the resulting cost savings and product performance could be significant. Functionally gradient material (FGM) systems technology held this promise.

Caterpillar, a worldwide leader in the production of machinery and engines, believed it could reduce overall costs and deliver benefits to its customers through the use of FGM technology. The FGM systems would consist of ceramic and metal composites and graded materials designed for high adherence, wear resistance, increased strength, and corrosion resistance. The use of new combinations of materials was expected to dramatically improve properties and performance over previous coating techniques.

Components that experience concentrated grinding and wear and tear have traditionally been coated using technologies that were not perfect, and the components usually wore out.

FGM has a continuously varying composition and/or microstructure from one boundary to another, and variations may result from gradients of ceramics and metals, metals with varying compositions, or nonmetallics in metals. Certain FGM systems, then, can improve contact fatigue and wear and corrosion resistance of components such as gears, undercarriages for heavy earth-moving equipment, and rolls for steel mills.

Caterpillar's proposed innovations would increase the life span of the company's parts several times over. Nevertheless, the market would allow the company to only slightly increase the price of parts. Customers and end users, therefore, would receive the bulk of the economic benefits flowing from a successful FGM research project.

Caterpillar believed it could reduce overall costs and deliver benefits to its customers through the use of FGM technology.

Rather than abandon the promising technology, Caterpillar established a team to research and develop FGM systems technology and submitted a proposal to ATP in 1994. This research team consisted of Hoeganeas Inc.; Department of Materials Science and Engineering, State University of New York at Stony Brook (SUNY); IBIS Associates, Inc.; Chaparral Steel Company; and St. Louis Metallizing Company.

Caterpillar Defines Specific Project Objectives

When Caterpillar began its ATP-funded project, the goals of the project were explicit; however, as the project got under way, the goals expanded.

The initial goals were to:

- Develop the materials and process technology base necessary to produce new FGM systems to improve the contact fatigue and wear and corrosion resistance of components such as gears for equipment, undercarriages for heavy earth-moving equipment, rolls for steel mills, and wear components for mining equipment

- Eliminate chrome plating to ease environmental concerns

Specific targets set to achieve these goals included:

- Replacing chrome plating on hydraulic cylinder rods, with similar performance and cost, while minimizing environmental concerns.

- Creating abrasive wear applications for track-type tractor undercarriages (track rollers) to achieve a threefold increase in wear resistance at only twice the current materials cost.

- Developing high contact stress gear applications used in track-type tractor final drives with a tenfold increase in contact fatigue life at only 1.75 times the current gear cost.

- Generating stainless clad steel products at a reduced cost.

- Developing a less costly, high-deposition spray process for use in spraying large components. Cost savings would depend on overall labor costs, because the new FGM deposition process would be 10 to 20 times faster than older processes.

As the project progressed, the targets expanded to include the following goals:

- Design and develop 1-mm- to 10-mm-thick FGM coating for chrome plate replacement, abrasive wear resistance (track roller), and high contact fatigue resistance (gear)

- Identify powder compositions for producing cost-effective FGM coating

- Develop a process to incorporate hard particles in powder form
- Determine optimum powder production processes and particle size for water stabilized plasma (WSP) spray systems
- Identify high-velocity oxygen-fuel (HVOF) coating technology for chrome-plate replacement

ATP Project Team Accomplishes Goals

The ATP-funded project resulted in the following major accomplishments:

- Cost-effective processing technology identified to produce FGMs, coatings that gradually change in composition throughout their thickness and may be deposited on steel and other substrates
- Cost-effective consolidation techniques demonstrated for these FGM materials
- WSP technology infrastructure established for limited production of FGM components
- HVOF coating technology identified for chrome-plate replacement
- Powder feed stock materials identified for spraying and spray deposit consolidation technologies to enhance the properties and structures of the sprayed FGM

Originally, three spray processes were evaluated for use in spraying FGM technologies. These processes included WSP technology, axial-injected spray technology, and HVOF spray technology.

The development goals were to establish the powder distribution and spray parameters required for high deposition efficiencies (greater than 80 percent) and high spray rates (greater than 150 lb/hour) using metal powders. A WSP system and an axial plasma spray system at SUNY were used to evaluate the capabilities of these spray technologies. In addition, HVOF spray systems at Caterpillar were used to evaluate coatings produced.

Results for the axial plasma and HVOF systems indicated that, although the current generation of spray guns does have high deposition efficiencies, they are limited in their spray rates to 10 to 30 lb/hour, which is the same as other gas-stabilized plasma torches. This limitation requires additional systems with capital and maintenance costs that are higher than the WSP system, which is capable of spraying metals at 200 lb/hour at deposition efficiencies of 80 percent. The spray coatings were developed with the required density and corrosion resistance to replace chrome plating.

The spray-coating technology developed during the course of the ATP-funded project was rolled out in the late 1990s in place of chrome plating for repair operations at Caterpillar dealers. It also is being considered for implementation in hydraulic cylinder rod production at Caterpillar to replace existing chrome plate operations.

Caterpillar Achieves Wide-Ranging and Sustained Technical and Business Achievements

The benefits resulting from this ATP project are considerable and ever increasing, as demonstrated by the current activities of the participants involved. For example, St. Louis Metallizing and Caterpillar have entered into a joint development agreement to further market the WSP technology, as well as other thermal spray technologies for applications outside those developed for Caterpillar. St. Louis Metallizing is pursuing marketing and production campaigns for HVOF and FGM coatings developed during the project. St. Louis Metallizing also is working with Ford Motor Company to market the spray forming of stamping dies, and it performed work with the WSP 500 as a lower cost way to spray large components.

End users in the marketplace are enjoying sturdier, more durable parts at lower costs, at least 10 years earlier than would have been possible without the ATP-funded project.

In 1998, Caterpillar and St. Louis Metallizing entered into a five-year joint-venture blanket agreement that included sharing knowledge and people between the two companies. In 2001, Caterpillar entered into alliances with Oak Ridge National Laboratory and Albany Laboratories to continue FGM developments started during this project. Caterpillar has contracted with an independent power producer to develop a new generation of lower power WSP systems to satisfy Caterpillar's specific needs for economical spray technologies at spray rates that are lower than the original WSP system.

Conclusion

Caterpillar engineers developed new manufacturing techniques that increased the life of wear parts between threefold and tenfold. Given the cost pressures placed on Caterpillar by the competitive marketplace, the cost of the longer lived parts would have to remain relatively low, and end users would capture most of the economic benefits of the new products. To develop the technology, Caterpillar teamed with several subcontractors and then applied for and received an ATP award of $1.9 million. The project achieved its technical goals, and end users in the marketplace are enjoying sturdier, more durable parts at lower costs, at least 10 years earlier than would have been possible without the ATP-funded project.

PROJECT HIGHLIGHTS
Caterpillar Incorporated

Project Title: New Coating Technology for Stronger, Longer Lasting Wear Parts (Functionally Gradient Materials: Synthesis, Process, and Performance)

Project: To develop new, advanced materials and processing techniques for applying high-performance coatings with continually varying composition on low-cost substrates.

Duration: 2/1/1994-1/31/1997
ATP Number: 93-01-0055

Funding (in thousands):**

ATP Final Cost	$ 1,995	56%
Participant Final Cost	1,556	44%
Total	$3,551	

Accomplishments: The Caterpillar team achieved its research and development goal of producing new FGM systems and realized the following achievements:

- Developed cost-effective processing technology to produce FGMs
- Designed and built a WSP spray system for FGMs
- Replaced previous chrome-plating technologies with environmentally friendly FGMs

The processes enabled goods such as tractor gears to last 10 times longer than before the ATP-funded project, without a concomitant increase in cost. In fact, the increase in cost was less than twofold. Tractor undercarriages, for example, now last three times longer, with only a twofold increase in cost. The tractor owners, operators, and purchasers are enjoying longer lasting parts, lower capital equipment costs, and more efficient use of their resources. Caterpillar received the following six patents for technologies resulting from ATP's cost-shared funding:

- "Process for Reducing Oxygen Content in Thermally Sprayed Metal Coatings"
  (No. 5,707,694: filed October 3, 1996, granted January 13, 1998)
- "Process for Reducing Oxygen Content in Thermally Sprayed Metal Coatings"
  (No. 5,736,200: filed October 3, 1996, granted April 7, 1998)
- "Carbon Coated Metal Powder Depositable by Thermal Spray Techniques"
  (No. 5, 882,801: filed October 3, 1996, granted March 16, 1999)
- "Process for improving fatigue resistance of a component by tailoringcompressive residual stress profile, and article"
  (No. 5,841,033: filed December 18, 1996; granted November 24, 1998)
- "Process for applying a functional gradient material coating to a component for improved performance"
  (No. 6,048,586: filed April 8, 1998; granted April 11, 2000)
- "Component having a functionally graded material coating for improved performance"
  (No. 6,087,022: filed April 8, 1998; granted July 11, 2000)

Commercialization Status: Commercialization is in progress, and products enhanced with FGMs are currently being sold. Products include chrome replacement processes for large mining cylinder rods by Chaparral Steel Company and high-deposition thermal spraying using WSP technology by St. Louis Metallizing. Companies that are using the enhanced Caterpillar equipment are realizing the benefits of lower costs and higher quality products. In addition, other consortium members are leveraging the HVOF technology in their efforts to improve hardness for track rollers, other undercarriage components of heavy machinery, and power transmission gears. In addition, other applications resulting from the ATP project include stainless clad sucker rods and structural steel, track bushings, steel and paper mill rolls, clad rebar, and other structural materials.

Outlook: The use of this technology is expected to spread throughout the industry, decreasing the costs and improving the quality of several products. As a result of this ATP project, alliances and joint ventures have been formed in an effort to continue exploiting the potential of this newly developed technology in the heavy equipment and other industries. The end result of cheaper and more durable parts saves end users significant repair and replacement costs. The outlook for this technology is good.

Composite Performance Score: * * *

** As of December 9, 1997, large single applicant firms are required to pay 60% of all ATP project costs. Prior to this date, single applicant firms, regardless of size, were required to pay indirect costs.

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- IBIS Associates, Inc.
- Chaparral Steel Company
- St. Louis Metallizing Company

Research and data for Status Report 93-01-0055 were collected during October – December 2001.

Ebert Composites Corporation

New Composite Structures to Replace Wood and Steel Utility Poles and Towers

During the early 1990s, population growth placed extensive demand-driven pressure on existing power lines, but electric utilities were hampered in their efforts to meet this demand due to the high cost and growing environmental concerns. For example, steel towers were expensive to manufacture, required large teams and heavy machinery to install, demanded anti-corrosion treatments, and weighed too much to transport by helicopter into wooded areas. Wood poles were not desirable because chemicals from anti-decay treatments could leach from the poles into the water supply and sometimes violated environmental restrictions. Ebert Composites Corporation proposed to radically change the design and manufacture of utility towers and poles to make them cheaper to manufacture, longer lasting, and more environmentally friendly. As an early-stage company, however, Ebert did not have the resources to pursue the high-risk research needed for such an innovative product without jeopardizing the company's survival. In 1994, the company applied for and received funding from the Advanced Technology Program (ATP) to develop its innovative composite structure production process.

Through the ATP award, Ebert created its in-line computer-numerical-controlled (CNC) process to produce machined, pultruded composite lineal structures that were light enough, strong enough, and inexpensive enough to replace existing steel towers. The technology led to a significant reduction in manufacturing time; one leg of a typical steel structure, for example, took 16 hours to manufacture compared to 25 minutes for Ebert's composite pultrusion product. Rather than hiring trucks and maneuvering steel poles into densely wooded areas, Ebert's designs were light enough to be rapidly installed with a helicopter, reducing installation time in wooded areas by several days. Another product, the Ebert utility pole, was ultimately commercialized through a joint venture formed with a company in 1998. The utility pole, which has generated commercial success for the joint venture, provides improved durability, strength, and environmental soundness, as well as reduced costs.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
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Research and data for Status Report 94-02-0025 were collected during July - September 2001.

Steel Towers and Wood Poles Are Costly and Environmentally Questionable

For the past 20 years, the electric power industry has been primarily a cost-driven business, with capital equipment as its biggest expenditure. Bringing electric power to new communities often required stringing power lines from the plant through wooded areas or across other difficult geography. As a result, new roads had to be built to deliver materials and labor because the traditional steel utility towers were too heavy to transport by helicopter. Further, wooden structures were not desireable because the environmentally hazardous chemicals used to treat the wood against rotting could leach into the water supply.

Revolutionary Manufacturing Process for Composite Materials Funded by ATP

Ebert's concept (a corrosion-resistant, lightweight, nonconductive structure) seemed to be an ideal substitute for the steel lattice structures typically used to support large transmission power lines. Moreover, Ebert's existing integrated manufacturing system could be used to manufacture these structures. In this process, filaments from large fiber spools are drawn to a heating die wherein the fibers and resins are molded to the appropriate shape. A clamping system downstream of the heating die pulls the fiber from the spools at the appropriate speed according to the job's specifications. Resin is injected through an impregnation system, impregnates the fiber bundles, and forms the appropriate shape within the heating die. Next, the pultruder pulls cured lineals that are properly molded and are machined by a multi-axis and synchronous computer-numerical-controlled (CNC) machine. The lineals are bar-coded for quick snap-together construction. Using a first-generation system, Ebert created a prototype process through a contract with two local utilities during the mid-1990s. Ebert's CNC machine produced a structure that was nearly 50 percent lighter than steel. The structure also had lower life cycle and installation costs and fewer environmental risks than steel towers or wooden poles.

Ebert's concept (a corrosion-resistant, lightweight, nonconductive structure) seemed to be an ideal substitute for the steel lattice structures.

Though the structural concept was sound, a number of problems remained as barriers to the effective production of Ebert's composite structure. First, the company had to coordinate the process control of pultrusion, machining, and bar-coding in order to develop temperature-compensation techniques so that the product could be machined at elevated temperatures. Second, Ebert had to develop specific multi-axis machining techniques to meet the precise shapes required in construction. Because of these remaining technical challenges, the risks of Ebert's technology were very high; risks were driven even higher by Ebert's status as an early-stage company without a sizeable research and development budget. Corporate partners would not fund the research, venture capitalists did not want to take on this high level of risk, and Ebert could not afford to fund the project internally.

Ebert's composite material technology has superior weight bearing properties over traditional steel lattice angles.

Project success could potentially lower costs across the construction industry as well as reducing chemical hazards in the environment. Therefore, in 1995 ATP awarded Ebert $1 million in cost-shared funds. Ebert's technology could give a wide range of construction industries access to structural elements whose weight-bearing properties were superior to traditional steel lattice angles. These elements offered an innovative system of structural parts for easy-to-assemble, large-scale frame structures. In addition to the geometric advantage, Ebert's product could provide life-cycle cost savings and environmental impact improvements that would help to alleviate demand pressures for electricity.

Ebert hoped that, after further research and refinement, the CNC machine could produce perfectly shaped lineals ready for snap-and-build applications without additional machining, while retaining their cost and environmental advantages. The goal was that computer-assisted designs for utility towers could become a reality on the first attempt.

The cost savings from using composite structures throughout the life cycle of a tower is currently unknown because the product has not been on the market long enough to evaluate its full life cycle. However, data gathered prior to ATP funding suggested that composite pultrusion towers would be significantly less expensive to construct, on an installed basis, when compared to traditional structures. Moreover, composite tower insulators do not need the semi-annual water washings that steel towers require to prevent corrosion tracking, adding to life-cycle/maintenance cost savings.

Ebert Solves Technical Issues Relating to CNC Pultruded Lineals

Ebert faced several expected technical challenges during this project, as well as two additional, unexpected challenges that threatened project success. The company ultimately overcame each challenge.

First, Ebert needed to develop a CNC demonstration unit that could achieve the manufacturing goals before the construction and installation benefits could be realized. Typically, high-speed, five-axis CNC machines use a collection of gears that limit production speed and flexibility. This problem could only be resolved by using a different drive mechanism. Through the ATP project, Ebert researched and designed a new "direct-drive," high-speed design using torque motors. This efficient configuration allowed 40,000-rpm spindles to be mounted to the CNC gantry controlled by the CNC computer. This design was very different from all available five-axis CNC machines and represented a major breakthrough in the cost, simplicity, and high-speed performance of state-of-the-art CNC machines.

ATP support enabled Ebert's research to advance years ahead of where it would have been otherwise.

Second, Ebert needed to synchronize the machining process so that the final product was pulled out of the die at the same speed as the pultrusion process. If the speeds were different, the machine would not function properly. Prior to the ATP project, no synchronization of composite pultrusion machines had been attempted, with the exception of a "flying cut-off saw machine." Since the saws could not use digital positioning, their cuts were inaccurate and could not be used in Ebert's process. Synchronization attempts during the life of the ATP project were not able to meet the exacting requirements for this machine. However, due to partial technical successes overall, the company was able to continue its efforts after the end of the ATP-funded project. Within one year of project completion, Ebert had developed a linear belt encoder that senses the linear travel of a pultruded composite element and feeds this signal to the CNC controls. Since the belt does not slip on the composite, any sudden speed change by the pultrusion machine is digitally transferred to the control so that the fiber feed speeds can be adjusted accordingly. This was the first CNC machine to be coupled electronically and accurately to the speed of a pultruded lineal.

Third, Ebert needed to design an open architecture control system that allows coordinated control of variable sequential pultrusion and machining operations. Open architecture simply was not available for a five-axis CNC machine. Ebert required an open architecture system to adjust both speeds for different lineals and temperature changes so that the lineal could be machined to the correct "cooled" dimension even though the lineal was at an elevated temperature. To solve this problem, Ebert used PC-based hardware to adapt a multi-axis controller from Delta Tau, a motion controller provider, for the CNC machine. The controller was very flexible and allowed even more machining heads than the five axes used to date. Using the five axes, Ebert met its goal of obtaining reproducible machining tolerances that were accurate to 0.001 inches. Detail this fine was critically important in allowing Ebert's machine to work seamlessly with computer-assisted design equipment.

The fourth technical problem stemmed from limits in existing computer-coding technology for CNC manufacturing. Ebert needed to develop advancements in computer-code capability to permit back-to-back machining of detailed composite parts with no interruptions. This would allow for a continuous production process that saves the time and money otherwise used for resetting and refeeding traditional machines. The biggest challenge was meeting the significant memory and storage requirements necessary to save and process sequential CNC code for many different components, while enabling precise end-to-end automation. Ebert devoted significant programming time to designing memory and coding systems for CNC manufacturing, ultimately producing a workable software set.

Company executives commented that without ATP support, this technology would not have progressed as quickly as it did. At the end of the ATP-funded project, executives believed that the funding enabled Ebert's research to advance years ahead of where it would have been otherwise.

Ebert Enters Into Joint Venture To Commercialize its Products

Ebert's commercialization efforts, which began after the conclusion of the ATP-funded project, are ongoing as part of the company's joint venture with Strongwell Corporation. Ebert first met Strongwell, the world's largest pultruder, at an ATP composites-technology-funded-projects meeting. That meeting resulted in Strongwell-Ebert, LLC, a 50-50 joint venture formed in April 1998. Strongwell provided capital and facilities in Bristol, Virginia, and Ebert provided CNC machinery, materials, knowledge, and licenses to its patents.

Advances in manufacturing have reduced a structure's production time from approximately three days to less than two hours.

The joint venture is now producing composite poles at a price that is competitive with traditional poles. The advances in manufacturing have reduced a structure's production time from approximately three days to less than two hours. The lighter poles are also installed more quickly and easily, resulting in cost savings of 50 to 60 percent compared with traditional steel poles.

In 1999, Ebert's electric utility tower earned the prestigious Charles Pankow Award for innovation in civil engineering from the Civil Engineering Research Foundation. In addition, company engineers have published papers in the Society of Manufacturing Engineers and Composite Manufacturing journals and have presented papers at the Composite Manufacturing and Offshore Operations conference.

In 2000, Strongwell purchased the joint venture from Ebert Composites and currently manufactures the products through an Ebert license of patents and technology.

Conclusion

ATP funded Ebert's successful efforts to develop a process to manufacture composite construction materials for the electric utility industry that are stronger, lighter, and less expensive to manufacture and maintain than steel. The use of these materials for utility poles requires less manufacturing and installation time and provides improved durability. The composite poles also have less negative impact on the environment than traditional materials. After the ATP project, Ebert formed a joint venture with Strongwell. The Strongwell-Ebert, LLC, joint venture commercialized an award-winning product for the electric utility industry.

PROJECT HIGHLIGHTS
Ebert Composites Corporation

Project Title: New Composite Structures To Replace Wood and Steel Utility Poles and Towers (Synchronous In-Line Computer-Numerical-Controlled (CNC) Machining of Pultruded Composite Lineals)

Project: To create a process to manufacture composite lineal structures for the electric utility industry that are stronger, lighter, and cheaper to assemble and maintain than steel structures.

Duration: 1/23/1995-5/30/1997
ATP Number: 94-02-0025

Funding (in thousands):

ATP Final Cost	$1,032	77%
Participant Final Cost	303	23%
Total	$1,335	

Accomplishments: This ATP-funded program met its technical goals. Ebert's five-axis CNC machine is capable of accurately tracking and machining composite lineals on a continuous basis. This enabled a 97-percent reduction in manufacturing time for electric utility towers compared to the manufacturing time for typical steel structures. Highlights of the project's accomplishments are:

- Development of synchronous CNC equipment that machines composite pultrusions quickly, accurately, and to precise tolerances.
- Realization of cost savings from using torque motors and linear ball screws to eliminate costly transmission-drive gearing. The 40,000-rpm spindle mounts directly on the end of the machining head, providing the necessary tip speed to machine composites.
- Incorporation of a PC-based, open architecture controller to allow full control of all five axes of motion with flexible programming options, such as temperature compensation and the ability to store a large volume of CNC code for multiple operations.
- Creation of a belt encoder to track the pultruded part and feed a velocity signal to the speed control, enabling the CNC process to be installed with all commercially available pultrusion machines without sacrificing fiber speed or machine accuracy.
- Use of the knowledge gained to improve a 50-axis CNC machine, representing a tenfold increase over the number of axes available at the end of the ATP-funded project.

This ATP-funded project benefited from the following patents:

- "High shear strength pultrusion"
(No. 5,597,629: filed January 26, 1995, granted January 28, 1997)
- "High shear strength pultrusion"
(No. 5,795,424: filed January 26, 1997, granted August 18, 1998)

Ebert Composites also earned a number of distinctions for civil engineering achievements, such as the Charles Pankow Award for innovation in civil engineering from the Civil Engineering Research Foundation (1999). The joint venture shared its ATP-project knowledge through industry publications and presentations, such as the following:

- Publication in a Society of Manufacturing Engineers journal (1999)
- Presentation of a paper at the Composite Manufacturing and Offshore Operations conference (2000)

Commercialization Status: Through Strongwell-Ebert, LLC, Ebert Composites Corporation's technology has been commercialized into composite structures for electric power poles and lattice towers. These products are sold and used throughout the United States within the electric power industry. While exact sales and market share information is proprietary for this privately held company, sales are more than sufficient to fund operations and future research and development projects. When the 50-axis machine is ready, the extremely intricate poles will expand pultruded lineals' utility, and the environmental benefits will make these products an even more attractive option to replace steel towers and wooden poles.

Outlook: As pultruded lineals increase in detail, they will replace numerous structures in diverse industries. The limiting factor is the required detail in lineal shape (a factor that will be overcome with the multi-axis CNC machining center). The outlook for this technology is outstanding within the electric utility industry and could possibly revolutionize other industries as well.

Composite Performance Score: * * *

Number of Employees: 12 at project start, nearly 100 through the joint venture operations as of September 2001

Company:

Ebert Composites Corporation
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Chula Vista, CA 91911-4659

Contact: David W. Johnson
Phone: (619) 423-9360

Research and data for Status Report 94-02-0025 were collected during July - September 2001.

EDO Specialty Plastics (formerly Specialty Plastics, Inc.)

Composite Piping Systems to Improve Oil and Gas Production

From the mid-1980s until 1994, U.S. oil and gas exploration and production steadily declined, forcing a significant increase in U.S. imports of crude oil. For example, in 1994, the United States imported more than 50 percent of the nation's total demand, which was the highest level since 1990. To economically develop U.S. oil production in deep-water locations, the industry needed strong, lightweight materials to replace the heavy alloy traditionally used in oil platforms in seawater. If alloy pipe could be replaced with lightweight advanced composites, for example, benefits would include reduced weight on the platform deck, reduced cost of the piping, and reduced maintenance costs.

Specialty Plastics, Inc., makes composite pipes, fittings, and components for the petrochemical and marine industries. The company proposed to develop an improved method to join composite pipe segments and more efficient, less costly processes for manufacturing the pipe fittings. Because the technology was too risky for private investment, Specialty Plastics submitted a proposal to the Advanced Technology Program (ATP) in 1995 and was awarded cost-shared funding for a three-year project through ATP's focused program, Manufacturing Composite Structures. By the end of the project, Specialty Plastics had successfully developed an innovative, highly reliable joining method. The company had also developed a new manufacturing process for pipe fittings that increases production rates, reduces costs, and enhances component properties.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
* * *

Research and data for Status Report 95-11-0012 were collected during October - December 2002.

Composite Piping Attracts Industry Attention

In 1995, the deep-water offshore oil industry was looking for strong, lightweight materials to replace the heavy alloy piping used on oil platforms in seawater. By reducing the weight of the piping materials on the service deck of a tension leg platform (TLP), the buoyancy of the TLP would increase. This would reduce the amount of structural steel needed below water, thereby significantly reducing the cost of a TLP.

Although carbon steel and copper nickel alloy pipe had traditionally been used on offshore platforms, advanced composites were known to be stronger, more resistant to corrosion, and lighter than steel. For example, composite pipe with a 6-inch diameter weighs 4 pounds per foot, whereas copper nickel pipe with the same diameter weighs 24 pounds per foot. Advanced composites also cost less initially than steel piping and have a longer life cycle. At the time that Specialty Plastics applied for the ATP award, the estimated life cycle of composite piping in seawater was 20 years, compared to 7 years for steel piping.

There were, however, obstacles to using composite piping that were related primarily to the lack of test data to support the materials' long-term durability. Engineers who were used to alloy pipe were uncomfortable with composites. Also, composite pipe fittings were expensive and labor-intensive to manufacture, and the methods used to join composite-to-composite piping and composite-to-alloy piping were unreliable. In addition, oil companies and regulatory agencies, such as the U.S. Coast Guard and the Mineral Management Service, thought that it was too risky to use the largely unproven composite materials for vital services, such as transporting water for extinguishing fires on an oil rig.

Innovative Design Concepts and Manufacturing Processes Proposed

Advanced composite piping had previously been partially developed in a U.S. Navy surface ship program. However, extensive work had not been performed on reliable joining methods and low-cost fittings. When Specialty Plastics decided to continue research and development, composite pipes were still considered an emerging technology. Therefore, this area of research, with a return on investment of six to eight years, was considered too risky for private industry. Thus, Specialty Plastics submitted a proposal to ATP for funding.

Advanced composites were known to be stronger, more resistant to corrosion, and lighter than steel.

An example of Speciality Plastics' joining and fitting of composite-to-composite and composite-to-alloy pipe segments.

Specialty Plastics' primary goals were to develop new technologies for joining and fitting composite-to-composite and composite-to-alloy pipe segments and to develop more efficient, less costly processes for manufacturing the fittings. The company proposed to improve joint technology by developing an integral flange technology and a heat-activated coupling technology. The integral flange is a joining method in which filaments are wound directly onto a pipe or fitting, thereby eliminating the joint. Joining composite components in this way, without the use of mechanical joints, protects the mechanical integrity of the pipe and is considered highly reliable.

A heat-activated coupling system is a simple, cost-effective means of joining composite-to-composite and composite-to-alloy pipe segments. It involves placing the prepreg laminate, made of fiberglass reinforcements impregnated with thermoset resins, over the pipe ends to be joined and applying heat around the laminate so that the thermoset resins cure and the laminate shrinks to seal the joints.

One issue with heat-activated coupling is that the resins do not cure completely and uniformly. Also, because metal is a better conductor and dissipates heat faster, the joining resins cure much more slowly on sections in contact with alloy pipe, resulting in leakage from these joints under normal loading conditions. To overcome these problems, Specialty Plastics planned to develop a computer-controlled heating device integrated with microsensors. The company also planned to design or identify joining resins that had desirable properties based on resin chemistry and curing behavior.

The company proposed to improve joint technology by developing an integral flange technology and a heat-activated coupling technology.

Specialty Plastics also sought to improve adhesive-bonded joints by enhancing the chemical bonding between the adhesive and the composites. Typically, adhesive and composite materials bond poorly due to the use of epoxy vinyl ester resins in fiberglass-reinforced structures and equipment. This has caused the failure of adhesive-bonded joints, generally at the interface between the adhesive and the composite surface. To overcome this problem, Specialty Plastics planned to chemically activate the joining surface so that the adhesive layer would be chemically bonded to it. The company also wanted to find a resin that had a chemical composition compatible with the joining surface.

Furthermore, Specialty Plastics planned to improve fitting manufacturing technology by developing intelligent-filament winding using optical sensors and by developing resin transfer molding (RTM) technology. In intelligent-filament winding, optical sensors are incorporated into a filament-winding machine, which is then programmed so the computer automatically turns the object to be wound and determines the winding process in real time. This improves productivity and assures the quality of the joint. It also substantially reduces the costs of small-volume production and increases production accuracy through in-process monitoring.

Corrosion of metal piping costs approximately $20 billion each year.

Finally, the company explored the use of RTM technology. RTM is a molding process used to produce composite parts in which continuous fibers are placed inside a mold in the form of a two-dimensional woven fabric and injected with resin. Specialty Plastics planned to improve this technology by also using three-dimensional preforms, which could be mass-produced and were strong enough to maintain their shape when injected with the resin. The resin system would be the same as that used for composite pipe.

Specialty Plastics Anticipates Broad-Based Benefits

Specialty Plastics estimated that the market would grow to more than $10 million within 5 years of funding and to more than $40 million within 10 years. Oil companies investing in TLPs could realize potential savings of $20 million in capital investment, as well as additional benefits such as lower maintenance and life cycle costs. These cost savings would reduce the overall operating cost of a TLP and would increase the return on investment to the operator.

An increase in the use of TLPs would lead to an increase in domestic production of oil and gas. This would decrease the nation's need to import large amounts of foreign oil, a U.S. expense of more than $1 billion per week in 1995 and half of the national trade deficit. Increased domestic production would also result in more jobs in the United States; for example, it has been estimated that a $30 million investment in oil and gas production can support 800 jobs in the oil and gas industry and even more in other areas of the economy.

Moreover, improved advanced composite piping systems would benefit industries where the corrosion of metal piping is a problem, such as the petrochemical industry, the commercial marine industry, and the pulp and paper industry. Corrosion of metal piping costs these industries approximately $20 billion each year.

Two New Processes Prove Successful

Specialty Plastics had to meet several requirements to achieve their goals of developing the integral flange, a heat-activated coupling system, enhanced chemical bonding between adhesives and composites, intelligent-filament winding, and RTM. These requirements and the company's related accomplishments are summarized below:

- Develop an optimal manufacturing procedure for integral flanges and computer programs to generate various winding patterns. Develop finite element modeling for integral flanges subjected to tension, bending, or both so that (1) material scraps are reduced, (2) the manual operation is eliminated, and (3) labor costs are reduced. ***Results:*** The company was able to reduce material scraps by 20 percent and labor costs by 20 percent as compared with the manual winding process used at the time.

- Develop a cost-effective process for manufacturing full-face flanges by using the integral flange technique. ***Results:*** The company reduced time and labor costs by 20 percent as compared with the currently used hand lay-up process.

- Complete the development and implementation of an optical system to assist in the design of winding patterns. ***Results:*** A Specialty Plastics achieved a reduction in the cost and a 15-percent reduction in the time required to generate patterns.

- Develop a mold for a reducer joint and an elbow mold, set up RTM experiments, and produce a reducer. ***Results:*** The company compared the final properties of the reducer and the elbow, such as fiberglass content, and found that they increased more than 10 percent by weight. The ability to hold internal pressure on a hydro test was compared with that of conventional reducers and elbows and found to have increased more than 10 percent.

Specialty Plastics achieved the majority of its goals; however, it was unable to improve the surface adhesion of composite materials. The company had sought to increase the operating pressure of composite piping to 400 psi through improved adhesion, but was able to increase it to only 225 psi, which limits the applications of the piping to about 75 percent of the seawater cooling systems on offshore TLPs.

Also, the company's work on RTM was only partially successful, resulting in a modified RTM technology. However, based on the research it performed during the ATP project, today the company is using a modified, state-of-the-art form of RTM technology in which an additional application of resin is applied to the fibers in a wet-layer process outside the mold. This method is not as efficient as the technology originally proposed, but it produces a stronger flange.

Composites Piping Market Increases

In 1998, Specialty Plastics began to market resin transfer molded flanges, reducers, and elbows and started to earn revenue. Their chief customers, Shell Deepwater, Exxon, and Texaco, were all operating in the Gulf of Mexico. The company also adopted process improvements for the RTM of the fiberglass pipe fittings it was already selling. In May 1998, the U.S. Coast Guard approved the use of composite piping in fire systems, which, according to Richard Lea, former President of Specialty Plastics, was a major victory. "It proved that composite materials could endure fire levels with medium-scale fire testing." Since then, the industry in the Gulf of Mexico has used composite piping for fire and seawater systems.

By 1999, Specialty Plastics had completed 38 major projects, and approximately 40 percent of its offshore oil and gas industry revenue came from the sale of composite parts. The company had approximately 50 customers. By the end of 2002, the company had completed 25 additional projects. Overseas companies in Australia, West Africa, and Malaysia are also beginning to purchase the technology.

Specialty Plastics achieved the majority of its goals; however, it was unable to improve the surface adhesion of composite materials.

Specialty Plastics' success attracted attention from prospective buyers, and the company was purchased in December 1998 for $4.5 million by EDO Fiber Science. Specialty Plastics is now a subsidiary of EDO Specialty Plastics and generates annual revenues of approximately $15 million.

From 1995 to 1998, Specialty Plastics published numerous journal papers and presented papers at various conferences in the area of composite materials. In addition, three company employees received awards, including the "1997 Tibbetts Award for SBIR Model of Excellence," sponsored by the U.S. Small Business Administration.

Conclusion

With ATP's assistance, Specialty Plastics developed several innovative composite joining and fitting technologies for composite piping systems. The company also developed a new manufacturing process for pipe fittings that has resulted in higher production rates, lower costs, and improved component properties. The company did not, however, improve the surface adhesion of composite materials, and its work on resin transfer molding (RTM) technology was only partially successful, resulting in a modified, state-of-the-art form of RTM technology.

The reliable joining methods that Specialty Plastics developed during this ATP-funded project have led to an increased use of composite piping systems on offshore tension leg platforms (TLPs) by the oil industry with significant cost savings. Since 1995, the U.S. market for composite piping has grown from less than $2 million a year to approximately $20 million a year, with growth of approximately 20 to 30 percent a year. Composite parts from the new technology have also been sold overseas in Australia, West Africa, and Malaysia.

PROJECT HIGHLIGHTS
EDO Specialty Plastics (formerly Specialty Plastics, Inc.)

Project Title: Composite Piping Systems to Improve Oil and Gas Production (Innovative Development of Joining/Fitting Technology for Advanced Composite Piping Systems)

Project: To develop innovative composite joining and fitting technologies that will enable and stimulate the use of composites in offshore oil and gas production pipelines.

Duration: 9/20/1995-9/19/1998
ATP Number: 95-11-0012

Funding (in thousands):

ATP Final Cost	$1,809	70%
Participant Final Cost	773	30%
Total	$2,582	

Accomplishments: ATP funding enabled Specialty Plastics to successfully develop the following innovative composite joining and fitting technologies. These technologies have enabled and stimulated the use of composites in offshore oil and gas production pipelines.

- Integral flange technology
- Heat-activated coupling technology
- Improved fitting manufacturing technology through intelligent-filament winding using optical sensors

The company also developed a new manufacturing process for pipe fittings that increases production rates, reduces costs, and enhances component properties.

Specialty Plastics attempted to improve the surface adhesion of composite materials in order to increase the operating pressure of composite piping to 400 psi; however, it was not successful. The company did, however, achieve a pressure rating of 225 psi for the piping, which enables it to be used for approximately 75 percent of the seawater cooling systems on offshore tension leg platforms (TLPs).

The company also performed work on resin transfer molding (RTM), which was partially successful. The result was an advanced state-of-the-art form of RTM technology in which an additional application of resin is applied to the fibers in a wet-layer process outside the mold. This method is not as efficient as the technology originally proposed, but it produces a stronger flange.

In addition, from 1995 to 1998, Specialty Plastics published 14 journal papers, presented papers at 17 conferences, and presented findings at 8 conferences in the area of composite materials. The following are examples of the publications and presentations:

- Montestruc, A.N., M.A. Stubblefield, S.S. Pang, V.A. Cundy, and R.H. Lea. "Smoke and Toxicity Tests of Fiberglass-Resin Composite Pipe Samples." Composites, Part B: Engineering. Vol. 28B, p. 287-293. (1997).
- Montestruc, A.N., M.A. Stubblefield, S.S. Pang, V.A. Cundy, and R.H. Lea. "Fire Endurance Tests of Dual-Wall Fiberglass-Resin Composite Pipe." Composites, Part B: Engineering. Vol. 28B, p. 295-299. (1997).
- Pang, S.S., (Keynote Lecturer). "Advanced Composite Piping Systems in Offshore Oil & Gas Industry." Coauthored by S.S. Pang, R.H. Lea, C. Yang, and M.A. Stubblefield. Fourth International Conference on Composites Engineering. Hawaii. (July 6-12, 1997).
- Stubblefield, M.A., C. Yang, S.S. Pang, and R.H. Lea. "Development of Heat-Activated Joining Technology for Composite-To-Composite Pipe Using Prepreg Fabric." Polymer Engineering and Science. Vol. 38, No. 1, p. 143-149. (January 1998).
- Pang, S.S., R.H. Lea, and M.A. Stubblefield. "Advanced Composite Piping Systems in Offshore Oil & Gas Industry." AACP 1998 Science, Engineering and Technology Seminars (SETS). Houston, Texas. (May 23-24, 1998).
- Stubblefield, M.A., R.H. Lea, S.S. Pang, and Yi Zhao. "Innovative Development of Joining/Fitting Technology for Advanced Composite Piping Systems."

Three company employees received awards, including the "1997 Tibbetts Award for SBIR Model of Excellence," sponsored by the U.S. Small Business Administration.

Commercialization Status: In 1998, Specialty Plastics began to market resin transfer molded flanges, reducers, and elbows and started to earn revenue. Their chief customers included Shell Deepwater, Exxon, and Texaco. Specialty Plastics also adopted process improvements for RTM of the fiberglass pipe fittings they were already selling.

Outlook: The market for composite piping has grown significantly, from less than $2 million a year in 1995 to approximately $20 million a year in 2002. Moreover, future growth is estimated at approximately 20 to 30 percent per year. By the end of 2002, EDO Specialty Plastics completed 63 major projects in the Gulf of Mexico. The company is also beginning to sell products from this technology overseas, especially in Australia, West Africa, and Malaysia.

Composite Performance Score: * * *

Number of Employees: 65 employees at project start, 100 as of October 2002

Focused Program: Manufacturing Composite Structures, 1995

Company:
EDO Specialty Plastics
P.O. Box 83277
Baton Rouge, LA 70884-3277

Contact: Richard H. Lea
Phone: (225) 752-0134

Research and data for Status Report 95-11-0012 were collected during October - December 2002.

Ford Motor Company Scientific Research Laboratory and General Electric Research and Development (Joint Venture)

Thermoplastic Automobile Components Could be Easily and Affordably Recycled

Cyclic thermoplastics technology offered an attractive method for developing recyclable structural components for more fuel-efficient automobiles. The technology was unproven and technically risky, however, so private capital was not available for the research. Therefore, Ford Motor Company, General Electric, and five other partners proposed the project to the Advanced Technology Program (ATP), and, in 1992, the joint venture was awarded cost-shared funding for a four-year project. During the ATP-funded project, the joint venture pioneered the use of cyclic thermoplastics in automotive components and other parts. The liquid composite molding process developed during this project is now being used by Ford to manufacture parts for its Austin Martin model. Intellectual property resulting from the cyclic composition research was sold to Cyclics Corporation, which is using the process to produce products ranging from bicycle frames to infrastructure parts such as utility poles and offshore oil rigs.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
* * *

Research and data for Status Report 91-01-0178 were collected during October – December 2001.

Conservation Concerns Drive New Materials Development

During the late 1980s and early 1990s, there was increasing interest in using new materials to achieve weight reductions in automobile manufacturing. This interest grew out of the need to conserve energy and recycle automotive materials. Polymer matrix composites, it was thought, could help the automotive industry address these issues.

There was increasing interest in using new materials to achieve weight reductions in automobile manufacturing.

During this period, the Ford Motor Company Scientific Research Laboratory had been working to develop and evaluate processes to produce large composite structures using polymer-based thermosetting resins systems. Meanwhile, General Electric Central Research (GE) was in the process of identifying properties in molecular compositions of matter that would be utilized in resin development of thermoplastics. Given the research under way by both Ford and GE, tremendous potential existed for developing materials and processes to manufacture composite automobile structural parts through the use of cyclic thermoplastic technology.

In 1991, the world market for advanced polymer matrix composites was \$4.7 billion, with the U.S. share reaching \$2.6 billion or 54 percent of the world market. At the time, polymer matrix composites were predominantly used in the manufacture of military aircraft and missiles, although research indicated that these materials could be used in the automotive industry. Preliminary studies at Ford suggested that the use of carbon fiber/polymer composites could achieve weight reductions in steel body structures of between 34 percent and 65 percent, which could increase the annual market for composite materials by an estimated \$20 billion. Other potential applications included commercial aircraft, airframes and engine structures, non-defense space structures, sports and recreation equipment, mass transit systems, offshore oil exploration and production, and industrial facility applications.

Joint Venture Identifies Material that Meets World-Market Need

In May 2000, a committee of diplomats from the 15 European Union member countries and members of the European Parliament adopted the European Union End-of-Life Vehicle Law. This law requires that manufacturers pay all, or a significant part, of the costs of taking back and recycling the new cars that they sell. As early as 1994, however, Ford and GE had already identified thermoplastic liquid composites as a class of materials that could be easily and affordably recycled.

Existing Methods Lack Required Flexibility

In 1992, when the joint venture submitted its proposal to ATP, thermoset polymer-matrix composites were prevalent in automotive component manufacturing. These components were fabricated using a process called liquid composite molding, which uses a pre-formed shell made from glass fibers combined with a molded foam core to create a pre-form in the shape of the final part. The pre-form is then placed in a heated steel mold and clamped in a low-pressure press. Liquid resin is delivered from a pressurized pump into the mold and, once the resin is cured, the part is removed.

Traditional thermoplastics have been excluded from the liquid composite molding process because they are relatively viscous when melted. This viscosity creates difficulties in establishing a smooth flow of the material through the mold.

Thermoset polymers, when subjected to heat, undergo an irreversible chemical reaction, causing the molecules in the polymer to cross-link, or connect the polymer chains. As a result, the entire finished part becomes a single, large molecule. Thermosets are used in liquid composite molding, in large part because of processing issues. The low viscosity of unreacted thermoset resins facilitates rapid impregnation and wet-out (elimination of voids or imperfection of bonding) of the pre-form. Large, thermoset-based parts are difficult to manufacture, however, because of the heat (exothermic) generated in the process. This heat can reduce the finished product's ability to withstand damage (i.e., its crashworthiness). In addition, thermoset-based parts are difficult to recycle.

Thermoplastics, in contrast to thermosets, can be recycled simply by reheating the material. Traditional thermoplastics have been excluded from the liquid composite molding process, however, because they are relatively viscous when melted. This viscosity creates difficulties in establishing a smooth flow of the material through the mold, even if high pressure is used.

Cyclic Technology Offers Improvements

Like thermosets, cyclic thermoplastics exhibit low viscosity when molten so that they flow like water and low-injection pressure can be used. Moreover, unlike thermosets, cyclic thermoplastics do not have production problems associated with heat generation, which enhances their suitability for use in manufacturing large component parts. Cyclic thermoplastics also are recyclable.

Seven-Member Project Team Obtains ATP Funding

In 1992, a seven-member joint venture submitted its proposal to ATP and received a $5.3 million, four-year award. It proposed to focus its efforts on the use of cyclic thermoplastics in liquid composite molding, also known as resin transfer molding. The joint venture included the following members:

- Ford Motor Company, for automotive research
- General Electric, a major materials supplier and the proprietary owner of the technology
- Pittsburgh Plate Glass, a supplier of glass fiber materials
- American Lisitritz, a composites molding equipment manufacturer
- Rensselaer Polytechnic Institute, for engineering studies
- The University of Tulsa, for recycling research
- The Environmental Research Institute of Michigan, to study the transfer of cyclic thermoplastic technology to parts fabricators

Pilot Production Proceeds

The project team concentrated on laboratory studies of resin chemistry and research and acquisition of a sophisticated melting device. Additionally, it undertook the initial fabrication of a laboratory molding system. Extensive discussions then ensued among team members regarding initiator systems for use in the process, ultimately resulting in the decision to use a low-viscosity liquid as the initiator. Not only were these initiators readily available, but the use of a liquid initiator was preferable because it enabled mixing to occur as the initiator and resin entered the mold.

The next step was research selection and acquisition of an extruder that had the ability to melt and convey the polymer according to the team's specifications. At the conclusion of this step, and with the identification of a process and a primary material, the team began pilot production, which included the following:

- Developing and completing the laboratory molding system
- Continuous monitoring of the processing data generated by the system as development began
- Achieving production of cyclic resin in the required quantities
- Molding and testing of cyclic plaques
- Redesigning and developing a mixing head capable of metering the extreme ratios required

Reevaluation Leads to Changes in Production Approach

The information and data generated throughout pilot production led to the installation of a large-scale system at Ford within the original timeline, as well as the actual production of a prototype. Once production was under way, the team reviewed the prototype results. Actual molded plaque data and cost projections revealed the need to reevaluate the cost approach to resin synthesis and the originally projected physical properties, including recycling potential, in molded composites.

Subsequently, the team carefully studied and then selected a potentially lower cost approach to resin synthesis. With the modifications and adjustments to the process in place, and the project now back on track, the team produced acceptable test plaques in sufficient quantity and quality. Preliminary testing, however, determined that the properties of the cyclic plaques did not meet the established baseline requirements of thermosets. At this juncture, researchers experimented with and evaluated a range of initiators, stabilizers, and antioxidants that could improve the properties of the cyclic thermoplastics.

During this evaluation period, the team selected a core technology and a supplier, and it continued molded component production. Evaluation of the product indicated that the team had achieved the best properties thus far through adjustments in resin metering and mixing. As the project drew to a close, the team manufactured six composite cross-members, three of which were testable.

ATP Support Accelerates Technology Development

Ford and GE determined that the ATP funding accelerated the development of the resin system and processing technology by two to four years. Since private capital was not available because of the risks associated with the project, the joint venture would not have been able to set up and operate a project of this magnitude without ATP funding.

With ATP's encouragement, Ford and GE were able to recognized the importance of their research for the entire automotive community and shared performance data through the auspices of the Automobile Composites Consortium (composed of Ford, General Motors, and DaimlerChrysler), thus enhancing the entire industry's understanding of the liquid composite molding process.

Conclusion

At project completion in 1996, the research team had met its manufacturing cost target of approximately $1 per pound. The team did not, however, achieve its goal of translating key properties from laboratory beaker reactions to materials made under simulated production conditions. Additionally, the joint venture had not fully demonstrated key resin attributes, such as toughness and energy-absorbing capability. As a result of ATP funding, however, the project achieved success in the following areas:

- Substantial data were collected regarding mold flow and filling.
- Eighteen patents were awarded.
- Six cross-member structural parts were manufactured using the liquid composite molding process (although only three were testable).
- Ford is currently using the liquid composite molding process.

In 1999, privately owned Cyclics Corporation, headquartered in Rensselaer, New York, received funding and purchased GE's portfolio of patents related to cyclic thermoplastics. The company has continued to enhance the technology and has developed alliances to manufacture and market resins for applications in the automotive, construction, and powder-coating industries. Cyclics Corporation is also undertaking a number of development projects for direct customers in structural composites and related technology areas.

PROJECT HIGHLIGHTS
Ford Motor Company Scientific Research Laboratory and General Electric Research and Development (Joint Venture)

Project Title: Thermoplastic Automobile Components Could Be Easily and Affordably Recycled (Cyclic Thermoplastic Liquid Composite Molding for Automobile Structures)

Project: To develop a cost-effective use of cyclic thermoplastic composites as structural components to produce more fuel-efficient automobiles.

Duration: 7/15/1992-12/31/1996
ATP Number: 91-01-0178

Funding (in thousands):

ATP Final Cost	$ 5,292	48%
Participant Final Cost	5,735	52%
Total	$11,027	

Accomplishments: The research conducted by the joint venture led to the collection of substantial data regarding mold flow and filling. This information, which the joint venture shared with the Automobile Composites Consortium, enhanced the automobile industry's understanding of the liquid composite molding process. In addition, the research led to the award of 18 patents for the materials and manufacturing processes developed during the ATP project. Moreover, Ford currently uses the liquid composite molding process. The joint venture was unable, however, to manufacture cyclic thermoplastic cross-member structural component parts that tested above the baseline indicators of like-constructed thermosets. Although the joint venture manufactured six cross-members from cyclic thermoplastic material by using the liquid composite molding process, only three of the six were testable.

The following patents were awarded as a result of this ATP project

- "Macrocyclic polyester oligomer preparation with Lewis acid as catalyst"
  (No. 5,321,117: filed November 19, 1992, granted June 14, 1994)
- "Process for making thermoplastic polyester foams"
  (No. 5,348,985: filed January 18, 1994, granted September 20, 1994)
- "Trisstannoxanes useful for polymerizing macrocyclic poly(alkylene dicarboxylate) oligomers"
  (No. 5,386,037: filed June 20, 1994, granted January 31, 1995)
- "Branched polyesters prepared from macrocyclic poly(alkylene dicarboxylate) oligomers"
  (No. 5,387,666: filed June 20, 1994, granted February 7, 1995)
- "Method for polymerizing macrocyclic poly(alkylene dicarboxylate) oligomers"
  (No. 5,389,719: filed June 20, 1994, granted February 14, 1995)
- "Resin molding process utilizing a core prepared from glass beads and a binder"
  (No. 5,492,660: filed August 1, 1994, granted February 20, 1996)
- "Depolymerization process using tin catalysis. Not titanates included"
  (No. 5,407,984: filed August 31, 1994, granted April 18, 1995)
- "Process for preparing macrocyclic polyesters"
  (No. 5,446,122: filed November 30, 1994, granted August 29, 1995)
- "Process for removing linears from cyclics with sieves"
  (No. 5,434,244: filed December 9, 1994, granted July 18, 1995)
- "Polymerization of macrocyclic poly(alkylene dicarboxylate) oligomers"
  (No. 5,466,744: filed January 9, 1995, granted November 14, 1995)
- "Method for polymerizing macrocyclic poly(alkylene dicarboxylate) oligomers"
  (No. 5,527,976: filed January 12, 1995, granted June 18, 1996)
- "Method for polymerizing macrocyclic polyester oligomers"
  (No. 5,498,651: filed June 19, 1995, granted March 12, 1996)
- "Method for polymerizing macrocyclic poly(alkylene dicarboxylate) oligomers"
  (No. 5,591,800: filed November 30, 1995, granted November 30, 1997)
- "Process for producing high ductile polyesters"
  (No. 5,648,454: filed February 14, 1996, granted July 15, 1997)

- "Process for depolymerizing polyesters"
  (No. 5,668,186: filed March 20, 1996, granted September 16, 1997)

- "Titanate catalysts"
  (No. 5,710,086: filed March 20, 1996, granted January 20, 1998)

- "Titanate esters useful as polymerization initiators for macrocylic polyester oligomers"
  (No. 5,661,214: filed August 5, 1996, granted August 26, 1997)

- "Method for producing polyesters"
  (No. 5,663,282: filed August 19,1996, granted September 2, 1997)

Commercialization Status: Ford is currently using the liquid composite molding process to manufacture 30 component parts for its Austin Martin model. In June 1999, Cyclics Corporation, of Rensselaer, New York, bought 50 U.S. and foreign patents from GE. These patents cover cyclic compositions, technology that GE had developed with partial funding from ATP. Cyclics Corporation will market its Cyclic Resin Systems technology and is currently using the technology to produce recyclable bicycle frames, utility poles, and other infrastructural parts.

Outlook: The research conducted on the technology and the processes yielded valuable information to help bring cyclic thermoplastic technology to market. As a result of this ATP project, the manufacture of cyclic thermoplastic automobile parts is under way. Depending on regulatory developments regarding fuel economy and environmental concerns, further development of this technology could take place in the future.

Currently, Cyclics Corporation uses the technology to manufacture environmentally friendly products that range from bicycle frames to infrastructure parts such as utility poles, supports for bridges, and offshore oil rigs.

Composite Performance Score: * * *

Companies:

Ford Motor Company
Scientific Research Laboratory (joint-venture lead) Manufacturing Systems Department
MD 3135, Room 2172, SRL
2101 Village Road
Dearborn, MI 48121

Contact: Dr. Carl Frederick Johnson
Phone: (313) 323-0399

Joint Venture Partner:

General Electric Research and Development
1 Research Circle
Niskayuna, NY 12309

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Subcontractors:

- Pittsburgh Plate Glass
- American Lisitritz
- Rensselaer Polytechnic Institute
- The University of Tulsa
- The Environmental Research Institute of Michigan

Research and data for Status Report 91-01-0178 were collected during October – December 2001.

General Electric Company

Using Corn To Manufacture Plastics

Engineering thermoplastics are used worldwide in applications such as automotive and airplane parts, computer and appliance housings, and bullet-resistant glazing. Engineering thermoplastics could be used in a much wider array of products and industries, but high raw material costs for the monomer parahydrobenzoic acid make such applications prohibitively expensive. Therefore, industry cannot utilize the superior qualities of these materials without a scientific breakthrough that would significantly reduce the material costs of these largely petroleum-based products. General Electric Company (GE), one of the largest producers of engineering thermoplastics, recognized the possibility that corn could be used to make plastics through the use of bioprocessing technologies. Using corn, one of America's most plentiful agricultural products, rather than more expensive fossil fuels, could reduce the costs for certain engineering thermoplastics by 50 percent.

The bioprocessing, however, required such stringent temperatures and controlled environments that the high research costs, along with the technical risk, deterred GE from investing in the project on its own. In 1995, the company submitted a proposal to the Advanced Technology Program (ATP) to replace petroleum-based products with corn that had gone through a series of biochemical processes. GE would conduct the scientific research and initial product tests, then another manufacturer would fabricate the monomer. By the project's end in 1997, however, GE was unable to produce monomers pure enough to make thermoplastics that would meet the needs of industrial applications. However, GE gained valuable knowledge and has been conducting related research since the end of the ATP-funded project.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)

No Stars

Research and data for Status Report 95-05-0031 were collected during October - December 2001.

Current Raw Material Costs Are Too High

Because they require high-cost, petroleum-based monomers (a monomer is a chemical unit forming the base of the plastic) as a foundational building block, engineering thermoplastics manufacturers limit their products to relatively high-priced items that compete in non-price-sensitive markets such as automotive, high-end electrical and appliance, and business machine applications.

The high cost of petroleum-based monomers prevents wider industry use of engineering thermoplastics, thereby limiting access to a product with many properties that are superior to those of similar plastics, including processability, strength, resistance to chemicals and extreme heat, and recyclability. Before the ATP-funded project, the best available cost for the monomer was $6 per pound. The superior properties of the monomer could not be utilized within more price-sensitive markets, however, unless costs were reduced by at least 50 percent.

Corn Viewed as Potential Substitute for Petroleum

GE scientists developed a research plan that envisioned corn as a potential replacement for petroleum for the production of a key ingredient in certain plastics (especially liquid crystal polymers). In theory, corn sugar (glucose) could be turned into an acid, parahydrobenzoic acid (PHB), that would be identical to the acid derived from the petroleum-based products. Specifically, the scientists hoped to develop a biocatalyst of recombinant E. coli with enhanced enzymes to produce PHB from the glucose via fermentation. GE marketing and product development staff determined that the market for engineered thermoplastics could sustain 10 to 30 million pounds of corn-derived PHB annually. To create this new form of PHB, however, GE needed to develop a partnership with a corn wet-miller that had both in-house fermentation experience and access to low-cost glucose.

ATP Provides Funding Support for Corn-Based Polymer Research

GE's internal research and development (R&D) department could not meet rate-of-return requirements to fund the project because of the complexity of the chemical reactions and the risk of failing to generate PHB from the process. Nevertheless, the potential environmental benefit from a corn-based plastic and the superior qualities of this monomer would convince the business community to use PHB if the process could be made more economical. Engineering thermoplastics could be incorporated into electronics, automotive lighting, and automotive drivetrain parts.

The GE research team was unable to achieve its goal of replacing petroleum-based products in engineering thermoplastics.

By enabling commercially viable PHB production, a successful GE project would provide a low-cost, multiuse product with improved processability, strength, chemical resistance, heat tolerance, and recyclability. Moreover, expansion of the corn-based engineering thermoplastics market could have spillover effects for the U.S. agricultural market. If successful, the market for U.S.-produced corn would increase, and the market for imported petroleum would decrease.

To achieve those goals, and to give thermoplastics manufacturers the chance to investigate a biosynthetic process for engineering thermoplastics monomers from corn, ATP provided funding support to GE. Using these cost-shared funds, GE planned to develop an improved set of enzymatic reactions using E. coli, particularly at the end of the bioconversion pathway to PHBs. GE also planned to remove the PHB earlier in the fermentation process to prevent overfermentation, which would lead to less pure PHBs.

Biochemical Processes Unable To Produce Pure PHB

The GE research team was able to create PHB from corn products, which represented a significant scientific achievement. Unfortunately, the PHB created from corn was not pure enough for use in commercial molding processes. Impurities in the PHB led to brittleness in molded plastic parts. Also, moving the technology to production would have required investing significant time and money in equipment and plant retrofits, yet the production volumes were expected to be relatively low. Because of scientific and technical problems, the GE research team was unable to achieve its goal of replacing petroleum-based products in engineering thermoplastics.

Research is ongoing under a newly established Biocatalysis Project that is devoted to the application of biotechnology for the manufacture of monomers.

GE gained a significant amount of information from this unsuccessful project, and the company has continued to research methods to develop pure monomers for thermoplastics from corn. According to internal accounts, the ATP-funded project put GE two to three years ahead of where it would have been without the cost-shared funds. The project saved 800 R&D hours, avoided $10,000 in equipment costs through parallel use, and led to the establishment of a focused project within GE that continued the research after the conclusion of the ATP-funded project. The project led to two patents. Further research could still lead to increases in the use of recyclable thermoplastics and to substantial economic spillover into the petroleum and agricultural industries. GE understood this potential impact and dedicated two scientists and a technician to continuing the research after the ATP-funded project ended in 1997.

Since the ATP project ended, GE has provided $1.5 million in additional funds. Research is ongoing under a newly established Biocatalysis Project that is devoted to the application of biotechnology for the manufacture of monomers and chemicals of interest to GE. Through post-ATP project research, GE has identified other potential applications to take renewable resources, such as fatty acids from corn products, and use a different biochemical process to turn those acids into monomers for use in polyester, nylon, or polycarbonates.

Conclusion

ATP funded an effort to develop a biochemical process that had the potential to turn corn into a building block for industrial-strength plastics. Although it still appears feasible to bioprocess corn as a substitute for petroleum-based products, GE did not fully achieve the project's technical goals. At the project's conclusion, GE management decided not to further invest significant time and money in equipment and plant retrofits because the production volumes were expected to be relatively low. Although the ATP-funded project was not fully successful because of the technical and financial barriers encountered, GE did advance research in using agricultural products in the manufacture of plastics. The company has continued to research other replacements for petroleum-based products in plastics since the conclusion of this ATP-funded project.

PROJECT HIGHLIGHTS
General Electric Company

Project Title: Using Corn To Manufacture Plastics (Biosynthesis of Monomers)

Project: To reduce the raw material costs of engineering thermoplastics by using corn feed stocks that have passed through several biochemical processes, rather than petroleum-based products, as the primary raw material.

Duration: 9/15/1995-10/31/1997
ATP Number: 95-05-0031

Funding (in thousands):**

ATP Final Cost	$ 542	52%
Participant Final Cost	498	48%
Total	$ 1,040	

Accomplishments: Currently, engineering thermoplastics use expensive, petroleum-based products as key raw materials, a process that makes the price of finished goods too high for many manufacturing applications. The GE research team was able to make a monomer from corn that potentially could be used in engineering thermoplastics; however, the monomer was not pure enough. Although the technology failed, the GE research team advanced the body of knowledge about biosynthesizing renewable feedstocks for plastics. The project saved 800 R&D hours, avoided $10,000 in equipment costs through parallel use, and led to the establishment of a focused project within GE that continued the research after the conclusion of the ATP-funded project. The project also led to the following two patents:

- "Method for increasing total production of 4-hydroxybenzoic acid by biofermentation"
  (No. 6,114,157: filed September 25, 1998; granted September 5, 2000)

- "Genetically engineered microorganisms and method for producing 4-hydroxybenzoic acid"
  (No. 6,030,819: filed September 28, 1998; granted February 29, 2000)

Commercialization Status: Although GE was unable to commercialize its technology because of scientific and technical failures, the company is continuing its research into creating a viable product.

Outlook: Even though the particular biochemical processes used in this project failed, continued research has led GE to investigate other bioprocesses to create monomers pure enough to make plastics. Until such research proves fruitful, however, the outlook for this technology is poor.

Composite Performance Score: No stars

Focused Program: Catalysis and Biocatalysis Technologies, 1995

Company:
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** As of December 9, 1997, large single applicant firms are required to pay 60% of all ATP project costs. Prior to this date, single applicant firms, regardless of size, were required to pay indirect costs.

Research and data for Status Report 95-05-0031 were collected during October - December 2001.

Honeywell (formerly AlliedSignal, Inc.)

Metallic Glass to Improve Electric Energy Efficiency

Over the last several decades, many industries have sought ways to reduce energy consumption as well as harmful emissions. A less familiar method is to reduce the loss of electricity that occurs during the distribution and consumption of electric power (hereafter referred to as power loss). In response, AlliedSignal, Inc., proposed to improve the efficiency of the magnetic core materials used for electric-power transformers and motors. The company believed that its proposed technology, thick ductile metallic glass for electric-power applications, could aid the United States' energy-saving efforts. However, because of technical failures in this area by other companies, AlliedSignal was reluctant to fund the research. In 1992, the company applied for funding from the Advanced Technology Program (ATP) to assist in its three-year research and development project. The project began in 1993 and by the end of the project, AlliedSignal had developed thick metallic-glass ribbons for use in electric-power transformers and motors. They were able to demonstrate a 60-percent reduction in core power loss as compared to conventional grain-oriented silicon steel that was commonly used. Moreover, AlliedSignal's technology has been successfully incorporated into anti-theft devices.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
* * *

Research and data for Status Report 92-01-0116 were collected during September 2001 - January 2003.

Energy-Efficient Transmission of High Voltage Proves Problematic

For decades, the electric-energy industry understood that inefficiencies exist in all phases of the electric-power cycle (power-generation, transmission, conversion, and consumption). A primary inefficiency results from magnetic and ductile materials (that is, materials that are easily molded or shaped) that lack the ability to transmit high currents.

Typically, stacked grain-oriented steel wires or plates were used to make the cores of electric-power transformers and motors. Researchers sought alternative materials that had the following specific characteristics: high ductility, superior magnetic qualities, and a high degree of fabrication (cutting and stacking) adaptability. Metallic glass was considered a viable alternative because of its superior characteristics. Additionally, metallic glass was efficient in low-power transformers and motors. However, scientists had not been able to develop metallic-glass ribbon with the thickness needed in high-power electric transformers and motors. The challenge was to create a thick (greater than 75 micrometers [μm]) metallic-glass ribbon capable of carrying high-voltage electricity. Previous attempts consistently delivered brittle materials incapable of being incorporated into functional motors or transformers. These development failures worried AlliedSignal's management, who hesitated to fully fund such a high-risk project. Consequently, in 1992 AlliedSignal turned to ATP for cost-shared funding for the development of its proposed technology. With ATP providing approximately 50 percent of the financing and affirming the technical merits underlying the proposal, AlliedSignal's top management was willing to pursue research and development (R&D) efforts.

AlliedSignal Seeks To Develop Manufacturing Process

AlliedSignal's broad objective was to develop a manufacturing process for producing 75-µm ductile metallic-glass ribbon required for high-power (greater than 100 kilowatts [kW]) stacked-core transformers. To achieve this objective, AlliedSignal had to meet several milestones over the course of the three-year project, including the following:

- Design and fabricate a new casting system
- Define the requirements and demonstrate an air-side cooling system concept
- Cast a 5-cm-wide ribbon with a thickness up to 75 µm
- Produce a 50-µm- to 75-µm-thick, 14.2-cm-wide ribbon
- Produce a 75-µm-thick, greater than 7-cm-wide ribbon with good magnetics

Additional milestones included improving the annealing (i.e., the heating and slow cooling of glass or metal in order to toughen and reduce brittleness and to strengthen or harden the material) and ductility/cuttability processes. Achieving these milestones was essential to the success of the project and its anticipated broad-based economic benefits. Because of the magnitude of AlliedSignal's objectives, the company subcontracted with the Division of Engineering and Applied Sciences at Harvard University and ABB Transmission Technology Institute (ABB) to develop and test specific components.

Subcontractors Assist in Achieving Project Objectives

At the project's completion, AlliedSignal, with the support of Harvard and ABB, successfully achieved the following objectives: (1) developed a casting system that provided significantly higher cooling rates than were previously possible; (2) established conditions for casting metallic-glass ribbon up to 80 µm thick; (3) gained an improved understanding of the correlation between casting conditions and ribbon properties; (4) developed a 53-µm-thick, 14.2-cm-wide ribbon with high-quality magnetic properties; (5) developed a 75-µm-thick, 7.6-cm-wide ribbon with high-quality magnetic properties; (6) constructed equipment and processes for cutting thick ribbon; and (7) incorporated a process for annealing spooled ribbon.

The challenge was to create a thick metallic-glass ribbon capable of carrying high-voltage electricity.

Harvard conducted a fundamental characterization task that revealed that ductility-controlling solidification events occurred near the glass-transition temperature. This analysis was critical in determining optimum conditions for producing metallic glass that would retain quality ductile characteristics. While Harvard's role in the project was to maintain a theoretical perspective, ABB's functional contribution was to improve the cuttability of the metallic ribbons. It was essential that the ribbons be cut properly before they were incorporated into the transformers. If the ribbons were improperly cut, they would cause technical inefficiencies in the transformers, thereby reducing the benefit provided by the thick ribbons. Both ABB and Harvard overcame the challenges they faced, which allowed AlliedSignal to meet its milestones and achieve the overall objectives of this ATP project. AlliedSignal's successful technology resulted in a 60-percent reduction in core losses, a significant achievement for AlliedSignal, Harvard, and ABB.

Several Factors Stall Widespread Technology Integration

Although the electric-power industry agreed that existing technologies needed to be replaced with improved alternatives, the associated replacement costs were significant. Therefore, several studies and analyses have been conducted to determine whether the current technology should be replaced immediately or should be phased out as existing transformers become inoperable or obsolete. These studies and analyses have concluded that replacing worn-out transformers over time is the commercially viable alternative.

In the electric-power industry, thick metallic-glass ribbons are now being used in power transformers. While electric-power motors and generators are expected to incorporate this technology, the adoption cycle will be longer because generators and motors have longer service lives and are more expensive. Once the transformer sector has fully adopted metallic-glass ribbons, efforts will focus on integrating the technology into other areas.

Technology Spills Over into Anti-Theft Devices

Anti-theft devices used primarily in retail stores use a metallic-glass material that is similar to the material used in the improved electric-power transformers. The anti-theft devices use the magnetostrictive properties of the metallic glass; that is, properties that couple the magnetic properties to the mechanical vibration modes of the material. Each device consists of a strip of metallic glass enclosed by a capsule that is attached to the retail item. Sensors at the store's exit door sound an alarm when a magnetostrictive device, commonly called a resonator tag, passes through the exit before a clerk deactivates it.

AlliedSignal's successful technology resulted in a 60-percent reduction in core losses.

The technology AlliedSignal developed during this ATP project has been incorporated into the commercial production of resonator tags. The technology has also opened the possibility of new product designs for anti-theft devices, with a potential market of more than 20 billion resonator tags per year. In addition, the thicker ribbons enable a product extension to magnets for these new resonator systems.

Further R&D Essential for New Product Development

While the electric-energy and the anti-theft-device industries are currently experiencing large-scale benefits from this technology, AlliedSignal, which later merged with Honeywell, is continuing its R&D in the metallic glass technology in order to penetrate additional industrial sectors. The technology is still limited by the following factors: cutting this product is difficult; the magnetic properties need to be improved; and the annealing characteristics are only useful in certain applications. As these problems are overcome, widespread utilization across other industries may be possible.

The technology AlliedSignal developed during this ATP project has been incorporated into the commercial production of resonator tags.

Revenues from the technology have ranged upwards of $100 million since the project's conclusion in 1996 from products that include power transformers and anti-theft devices. AlliedSignal expects its market share in the transformer arena to increase as more transformers become obsolete and are subsequently replaced. In addition, the company expects to incorporate a metallic-glass spin-off technology into electric generators and motors.

Conclusion

ATP's support helped AlliedSignal develop a 53-micrometer (μm)-thick metallic-glass ribbon that demonstrated a 60-percent reduction in core loss over conventional grain-oriented silicon steel. AlliedSignal's management team was initially hesitant to invest fully in the technology because of the high possibility of failure and because of previous failed attempts by other scientists and corporations to create thick metallic-glass ribbons. However, with ATP's support, the company's management moved forward, and the project was successful. Furthermore, the company achieved its ambitious goal of discovering improved annealing and magnetic qualities for its ribbons. The spillover of this technology into the anti-theft device industry is an indication of its broad-based benefits. Without ATP's funding assistance, this technology and its associated benefits would have taken five to seven years longer to achieve.

PROJECT HIGHLIGHTS
Honeywell (formerly AlliedSignal, Inc.)

Project Title: Metallic Glass To Improve Electric Energy Efficiency (Thick Ductile Metallic Glass for Electric Power Applications)

Project: To develop a manufacturing process to produce 75-micrometer (µm)-thick ductile metallic-glass ribbon required for higher power (greater than 100 kilowatts [kW]) stacked-core transformers and generators to reduce wasteful power losses from electricity distribution and consumption in the electric utility industry.

Duration: 4/1/1993-3/31/1996
ATP Number: 92-01-0116

Funding (in thousands):**

ATP Final Cost	$1,967	47%
Participant Final Cost	2,253	53%
Total	$4,220	

Accomplishments: AlliedSignal developed a 53-µm-thick metallic-glass ribbon that demonstrated a 60-percent reduction in core loss over conventional grain-oriented silicon steel. In addition, the company met the following objectives: (1) successfully developed a casting system that provides significantly higher cooling rates than were previously possible; (2) established conditions for casting metallic-glass ribbon up to 80 µm thick; (3) gained an improved understanding of the correlation between casting conditions and ribbon properties; (4) manufactured a 14.2-cm-wide, 53-µm-thick ribbon with high-quality magnetic properties; (5) crafted a 7.6-cm-wide, 75-µm-thick ribbon with high-quality magnetic properties; (6) constructed equipment and processes for cutting thick ribbon; and (7) incorporated a process for annealing spooled ribbon.

Commercialization Status: Metallic-glass ribbons are currently incorporated into many products that are sold worldwide. In the United States, revenues from the technology have ranged upwards of $100 million since 1996 from products that include power transformers and anti-theft devices.

Outlook: Honeywell anticipates that demand for this new technology in electric-power transformers will increase in the future. The company also expects that the technology will be incorporated into electric motors and generators, as old and obsolete units are replaced. At this time, the company continues to conduct research and development to increase the technology's capabilities.

Composite Performance Score: * * *

Company:
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Subcontractors:

- The Division of Engineering and Applied Sciences, Harvard University
- ABB Transmission Technology Institute, Raleigh, NC

** As of December 9, 1997, large single applicant firms are required to pay 60% of all ATP project costs. Prior to this date, single applicant firms, regardless of size, were required to pay indirect costs.

Research and data for Status Report 92-01-0116 were collected during September 2001 - January 2003.

Honeywell, Inc., Technology Center

Generic Neural Network Technology To Improve Complex Materials Manufacturing

By the early 1990s, the functions of complex materials such as composites, ceramics, and semiconductors had multiplied, and their importance to various manufacturing industries had escalated. Despite this expanded role, intelligent manufacturing of complex materials was based on techniques known to a handful of manufacturing engineers rather than on defined methods. To find more efficient and less expensive ways to produce quality products, Honeywell, Inc., wanted to add neural networks (that is, systems that can learn, infer, and model complex processes that lack explicit rules) to optimize the manufacturing processes of new complex materials.

Honeywell teamed with 3M, Sheldahl, and Hercules (now Alliant Techsystems) to examine specific processes to which neural networks might be applied. In 1992, Honeywell applied for and received $2.35 million in cost-shared funding from the Advanced Technology Program (ATP). Without the support of ATP, the other companies would have been unwilling to participate because of the project's high risk. By project conclusion in 1995, Honeywell had confirmed the value of neural networks as a new, advanced control technology. None of the partner companies has commercialized the technology resulting directly from the ATP-funded project because of high initial investment costs. Honeywell continues to explore neural network technology and has developed related products, such as its Profit Sensor software.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

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Research and data for Status Report 91-01-0069 were collected during October - December 2001.

Neural Networks Too Costly for Complex Material Manufacturing

Neural networks are computing systems, modeled on the architecture of the human brain, that can learn and model complex processes even when relationships are not explicitly understood. A neural network consists of processing units (components that actually execute instructions) and direct connections between each unit. Each of these connections has a real-value weight associated with it. Through these weights, the network processes the impact of each variable and the real-time, nonlinear interactions of those variables on the final output. Thus, the neural network produces "recipes" of variables to achieve a particular output.

Honeywell predicted that the benefits of implementing neural networks would apply to a wide variety of U.S. industries. Industries that use complex materials, such as automotive, aerospace, pulp and paper processing, oil refining, and food and beverage manufacturing, could use cost-effective neural network technology to solve their unique production problems. Extending the use of neural networks to the production and application of new, complex materials, however, presented technical challenges. Classic use of neural network technology is designed for manufacturing processes that can utilize a single controller. This is the case, for example, for traditional metal and alloy processing techniques.

Properties of complex materials, such as viscosity, consistency, and porosity, are dependent on multiple variables that interact in nonlinear relationships and change in real time. Manufacturing control over these variables would require the gathering of a large amount of information from multiple sensors specific to each variable, as well as the advanced processing of the data. This effort would result in the need to build specific sensing and controlling (neural network) models for every variable in a complex materials manufacturing process, making classic techniques for complex materials costly for both consumers and developers of neural network technology.

High Technical Risk Threatens Use of Neural Networks

Honeywell believed that generic neural network technology could be used for multiple applications in the production of complex materials, thus eliminating the need to create specific models for each process.

Neural networks and complex materials processing were both emerging technologies, and the combination of these two in a single venture increased the risk of the project. Because of the high risk and the low probability of immediate payback, Honeywell had little incentive to pursue internal research and development (R&D) or to seek venture capitalist funding. These sources would hesitate to provide funding until they saw a proof-of-concept that overcame technical hurdles and demonstrated the ability of neural networks to reduce production costs and improve quality.

Neural networks and complex materials processing were both emerging technologies, and the combination of these two in a single venture increased the risk of the project.

Honeywell had another significant challenge to overcome. The company first needed to become familiar with various industrial settings, which would require its potential customers to open their production facilities to Honeywell's researchers.

This step would introduce another major risk, since prospective customers would have to reveal their product and production process secrets to Honeywell's researchers without the assurance that Honeywell could ultimately assist the companies in improving their manufacturing processes. This risk was so great that, initially, potential customers were not willing to collaborate.

ATP Funding Enables Joint Venture

In order to examine specific processes to which neural networks might be applied, in 1992 Honeywell formed a joint venture that comprised 3M, a leader in the production and utilization of complex materials; Hercules (now Alliant Techsystems), a global supplier of advanced materials for aerospace; and Sheldahl, a producer of complex film and coating products. Honeywell also applied for and received $2.35 million in cost-shared funding from ATP. After defining three specific candidate manufacturing processes, Honeywell then worked to break down the acceptance barrier and to prove the value of neural networks for complex materials processing by developing generic sensor and control technology.

ATP support also allowed Honeywell to undertake the research needed to compete with overseas intelligent processing projects, including the European ESPRIT effort and intense R&D at Yokagawa in Japan and Siemens in Germany.

Honeywell worked to break down the acceptance barrier and to prove the value of neural networks for complex materials processing by developing generic sensor and control technology.

Generic Neural Network Technology Promises Multiple Uses

Honeywell worked with the three companies to achieve better process understanding and control through the development and implementation of neural networks. The group hoped to gain general knowledge that would contribute to Honeywell's broader goal of developing generic neural network technology for multiple applications in the complex materials industry. The companies focused on the precision film-coating process, the filament-winding process, and the continuous flexible circuit boards production process.

Precision Film-Coating Process

With 3M, Honeywell focused on optimizing 3M's precision film-coating process, important to photographic, magnetic, optical memory, adhesives, and paper products. In precision coating, the goal is to achieve consistency and uniformity in coating, with thickness as the quality index. A host of variables in this highly nonlinear and time-variant process, however, add to variance in the final product. To address this variance, Honeywell configured its NeuroCD (cross-directional) neural network controller to predict the required control action to minimize the variance in film thickness. This controller demonstrated robustness and achieved a reduction of variance in the thickness profile from five percent to three percent. In 1994, because of improved process understanding resulting from the ATP research, 3M implemented a new sensor technology that allows equipment to run more efficiently and the controller to reject a process disturbance within one minute, rather than the one hour it took the previous quality controller.

Filament-Winding Process

In its work with Hercules (now Alliant Techsystems), Honeywell concentrated on optimizing Hercules' filament-winding process for the manufacture of composite parts for defense aircraft and missile systems. Given high material costs for this type of manufacturing, it is essential to minimize scrap and defective parts. The filament-winding process, however, takes place in an uncontrolled production environment in which perturbations can create voids (air or gas bubble formations) that cause wrinkling, fiber reorientation, laminate microcracking, and delaminations that decrease tensile strength. Before the ATP project, Hercules experienced void volume fractions of seven percent. The ATP research team aimed to reduce that figure to between three and five percent. The team first developed an empirical model based on neural networks to predict the expected void volume fractions, given a set of input parameters. This model provided sophisticated process understanding, revealing unacceptable variation exhibited during resin impregnation. To remedy the problem, the team developed the manifold impregnation unit (MIU). The team then used a neural network model, hoping to identify problematic process conditions to control and optimize the system.

Honeywell developed a Neural Network Toolkit.

The MIU was enormously successful. It met the target void volume fraction of three to five percent and later received a patent. Alliant Techsystems did not incorporate this unit into filament-winding production, however, because of the significant costs associated with extensive alterations to its complex processes. Prohibitive costs and lack of sufficient process data also prevented further development of the first neural network model. Nevertheless, the model did provide important filament-winding-process knowledge by identifying areas that Alliant Techsystems could refine.

Continuous Flexible Circuit Boards

To improve complex materials processing at Sheldahl, Honeywell examined the production of continuous flexible circuit boards, Sheldahl's most profitable product. Sheldahl's process involved the physical vapor deposition of copper onto thin films via thermal evaporation from heater elements, called boats, which contain "puddles" of molten copper. Although the process functioned relatively well, a problem known as "spitting," which is the uncontrolled ejection of molten globules of copper onto the film, prevented uniform evaporation and deposition of metal onto the film. Honeywell first approached this problem by installing National Instrument's Labview. This neural network tool assists process understanding and enabled the research team to establish closed-loop process control. The research team also designed and applied a coating quality sensor (CQS), a neural network device that reliably detects puddle spitting and predicts the consequences of the process operator's actions, to determine what action inputs cause puddle spitting. In addition, Honeywell and Sheldahl closely observed the thermal and electrical characteristics of the entire system to improve process knowledge. Initial experiments suggested that these improvements accelerated production line speed by 20 percent.

Honeywell Develops Toolkit to Transfer Technology

As a result of its work with the three companies, Honeywell developed a package of software tools as a means to transfer technology to its partners and to incorporate the concepts gained for continued improvement of control approaches for complex materials.

This Neural Network Toolkit also provided an internal resource for Honeywell's continued development of advanced neural network technology. Although the toolkit design was based on the specific problems of 3M, Alliant Techsystems, and Sheldahl, it is generic in its outlook. The toolkit extracts common procedures and practices from various processes to support visualization, modeling, and control strategies. Its visualization tool supports the analysis of process variables, facilitates identification of key relationship trends, and aids in selecting variables for control. The modeling tool provides a user-friendly mechanism for designing, training, and testing neural network models. The toolkit also provides graphic depictions of the three control strategies provided for each of Honeywell's partner companies. By 2001, Honeywell had distributed the toolkit to only the three companies.

ATP Project Defines Worth of Neurocontrol

The four joint-venture participants continue to make use of the ATP-funded developments. For example, the project has allowed Honeywell to explore the previously untapped complex materials market. The company's industrial division continues to develop neural network control strategies, including a parametized neurocontroller for its total downtime controller Total Plant product line and an adaptive cross-direction controller for application to the paper-processing industry.

3M's film-coating process is less variable as a result of the NeuroCD controller. Alliant Techsystems benefits from advanced process understanding,and Sheldahl has improved its production of flexible circuit boards with Lab-view's and CQS's ability to detect and predict outcomes based on hypothetical actions.

The results of Honeywell's research have confirmed that neural network-based approaches to control are useful for complex manufacturing.

Support from ATP at the initial stage of development was critical for both Honeywell's development of neural networks and to cultivate industry curiosity concerning the new technology. Honeywell has encountered acceptance barriers from potential users, however, who are unable to justify the investment in generic neural networks technology when their current processes are functioning adequately.

Conclusion

The results of Honeywell's research have confirmed that neural network-based approaches to process control are useful for complex manufacturing. Currently available neural network technology provides a worthwhile method for process data exploration and empirical process modeling. Honeywell recognizes that developing neural networks that are sufficiently generic and therefore worthy of initial capital investment remains a challenge. Honeywell has continued to explore neural network technology and has developed related products, such as its Profit Sensor software. Because neural networks offer a high-tech, advanced control approach, a great deal of technical research will need to precede any significant business development. The work of the ATP project and resulting technical literature, such as Honeywell's paper, "Neural Networks in Control Systems: A Review," will help guide that development.

PROJECT HIGHLIGHTS
Honeywell Inc., Technology Center

Project Title: Generic Neural Network Technology to Improve Complex Materials Manufacturing (Neural Network Control and Sensors for Complex Materials)

Project: To develop generic sensor and control technology based on neural networks for application to complex materials processing.

Duration: 7/1/1992-6/30/1995
ATP Number: 91-01-0069

Funding (in thousands):

ATP Final Cost	$ 2,138	49%
Participant Final Cost	2,225	51%
Total	$ 4,363	

Accomplishments: This ATP project generated advanced process understanding for neural network controls and sensors for complex materials and established the groundwork for Honeywell's continued development of neural networks.

Alliant Techsystems received the following patent as a result of technology related to the ATP project:

- "Apparatus for fiber impregnation" (No. 5,766,357: filed September 19, 1996; granted June 16, 1998)

Honeywell published the following paper as a result of the ATP project:

- Neural Networks in Control System: A Review

Commercialization Status: By 2001, none of the partner companies had commercialized technology resulting directly from the ATP project. However, Honeywell has continued to explore neural network technology and has developed related products, such as its Profit Sensor software.

Outlook: Honeywell engineers have continued to develop neural networks and have received several patents in this area that build on the work that was completed during the ATP project. Honeywell still notes a persistent acceptance barrier by the industry because of high initial investment costs, but expects that both incremental improvements and innovation breakthroughs will eventually bring advanced neural network technology to complex materials processing, thereby revolutionizing this industry.

Composite Performance Score: *

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Subcontractors:
3M
Sheldahl
Hercules (now Alliant Techsystems)

Research and data for Status Report 91-01-0069 were collected during October - December 2001.

Nanophase Technologies Corporation

Processing Nanoscale Materials for Large-Scale Production

The scientific community is in strong agreement that nanoscale materials, which are less than 100-billionths of a meter in size, exhibit superior chemical, mechanical, electronic, magnetic, and optical properties. When this project was funded in 1992, it was believed that this technology could increase U.S. market share in the diesel engine and ball-bearing industries. At that time, however, these nanocrystalline materials could only be produced in small quantities. Nanophase Technologies Corporation (NTC), with funding from the Advanced Technology Program (ATP), increased its capability to produce nanoscale materials by 25,000-fold and reduced its costs by 20,000-fold. These materials are now used in products as diverse as cosmetics, catalysts, and ceramics.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
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Research and data for Status Report 91-01-0041 were collected during October-December 2001.

Commercial-Scale Production Requires Improved Processes

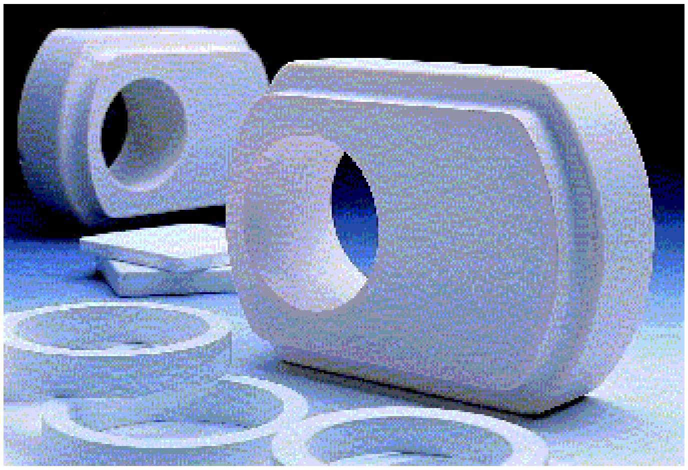
In 1992, nanocrystalline materials could only be produced in small quantities. To solve this problem, Nanophase Technologies Corporation (NTC) submitted a proposal to ATP and received funding for a three-year project. NTC sought to perform the research and development (R&D) necessary to enable the synthesis and processing of nanocrystalline ceramics on a commercial scale. The company's underlying strategy was to develop a multiuse technology that would provide a basis for future scale-ups of other nanoscale materials. NTC used its proprietary gas-phase-condensation (GPC) process as a foundation for the new technology. A unique feature of the GPC process is its ability to form stable and unique material structures.

Manufacturing Techniques Limit Ceramics' Commercial Potential

Even though traditional, industrial-grade ceramics are suitable for general purposes, their use is limited by their low stress tolerances. The molecular breakdown of ceramics limits their marketability, because of either physical- or temperature-limiting characteristics. Moreover, the machining costs of ceramic composites represent up to 95 percent of total production costs, thereby decreasing company profits. When this ATP project began, the chemical and physical properties of most materials used in industrial products did not yield the desired dimensional or stress tolerances. This shortfall resulted in weak components, including engine parts, bearing systems, electronics packaging, precision electrical and optical-fiber connectors, cutting tools, and sealing systems.

Previous methods of manufacturing nanocrystalline ceramics were unsuitable for commercial applications.

The manufacturing and industrial communities recognized that the benefits of using nanocrystalline ceramics could be significant. Previous methods of manufacturing nanocrystalline ceramics, however, were unsuitable for commercial applications and produced only 10 grams of material per day at a cost of $1,000 per gram. NTC realized that the commercial potential of these materials would only be realized if they were synthesized in larger quantities (kilograms and upwards).



Commercialization of nanocrystalline ceramics has led to more resilient and cost-effective products.

NTC Advances Its Gas-Phase-Condensation Technique

Techniques to synthesize particles with dimensions of a few nanometers have existed since the 1980s. NTC proposed to use its proprietary GPC technique to produce particles of nanometer dimensions, often referred to as ultra-fine powder (UFP). This technique involves vaporizing a precursor (usually a metal), then rapidly cooling the vapor to condense out nanocrystals. A subsequent reaction (e.g., oxidation) is then possible. Traditionally, GPC has been performed using systems based on natural convection. These systems are difficult to scale-up, however, so they were only used in the laboratory. The NTC's proprietary GPC process is one-tenth the size and cost of natural convection systems, but can produce materials at rates 100 times faster. NTC believed further development of these systems would establish a viable technique for generating gas-phase-condensed UFP on a commercial scale. NTC would lay the foundation for commercial-scale production of nanocrystalline materials by accomplishing the following goals:

- Scale up production of nanocrystalline ceramic powders already produced in laboratories, from gram quantities to kilogram quantities
- Extend the techniques to other industrially important ceramics
- Develop processing techniques to consolidate the powders into parts
- Comprehensively characterize the properties of the consolidated materials
- Develop a low-temperature, net-shape-forming technique

NTC Creates High-Volume and Low-Cost Ceramic Materials

NTC's successful ATP-funded R&D led to scaled-up production (100 tons per year) and reduced costs. In addition to ceramics, this new process also can produce nanoscale metal oxides, such as titania, that are nearly spherical, close to uniform in size, free of chemical residues, and loosely clustered. This enables the engineering of materials with specific attributes such as high strength or a particular color.

The successful scale-up and integration of these nanocrystalline ceramics on a commercial scale has led to more resilient and cost-effective products. Benefits of the new products include the following:

- Lighter weight
- Longer life span/service life
- Increased resistance to corrosion
- Reduced need for lubricants
- Increased temperature resistance

Although the steel and composite parts now used in end-use products are cheap and relatively effective, replacing them with ceramics will provide significant benefits. Not only will the benefits be realized at a national level, they also will extend to export markets, thereby positively affecting the U.S. trade balance.

ATP's Contribution Is Significant

"Although my company is still very small in revenue size," Robert Cross, the president and chief executive officer of NTC, stated after completion of the ATP project, "we are now the world's leader in the production and marketing of nanocrystalline materials for a wide range of important applications. It was not always that way, and it would not have been possible were it not for the support of the ATP."

In the early 1990s, before the ATP project, NTC had only two employees, limited funds, and no customer base. Buoyed by co-funding from ATP to explore this new process, as of 2001, NTC had 61 employees, a proven technology, and a 24-hour-a-day factory, as well as relationships with major corporations that are testing and selling its products. The three-year ATP project, which ended in 1995, led to the following measurable benefits:

- NTC achieved a 25,000-fold increase in its capability to produce nanoscale materials and a 20,000-fold reduction in costs.
- NTC nanocrystalline titania is now being used in cosmetic sunscreens and is more effective per unit weight compared with the titania in competing products. The demand for this product is expected to increase exponentially. The use of NTC nanocrystalline titania sunscreens was not anticipated at the onset of this project.
- NTC's tests of prototype mechanical seals made with these nanoscale materials demonstrate up to a 10-fold increase in service life, while prototype industrial catalysts are as much as four times more active.
- NTC nanocrystalline titanian coating protects automotive and carpet fibers from ultraviolet-induced damage.
- NTC developed processes to fabricate near-net-shaped ceramics and electronic substrates using alumina nanocrystalline materials.
- NTC developed printing inks for high-opacity jettable inks used in industrial markets.
- NTC-produced iron oxides are incorporated into cosmetic pigments.
- NTC produces nanocrystalline zirconia, ceria, and yttria for use in the manufacture of catalysts and near-net-shaped ceramics.

NTC also was able to secure private venture capital funds from multiple sources and received three patents from the U.S. Patent and Trademark Office.

NTC Has Sustained Its Accomplishments

To date, NTC has achieved the following competitive advantages:

- Received 3 patents directly resulting from the ATP project, with an additional 28 patents licensed or pending in the United States, Europe, and Japan.
- Improved its time-to-market for new products (i.e., a reduction from 18 to 24 months to 12 to 18 months).
- Increased its capital funding to sustain planned development activities and expand its manufacturing capabilities.
- Secured financing through an initial public offering (IPO) in November 1997.
- Maintained $18.6 million in capital with no long-term debt as of September 30, 2000.

NTC also has identified and continues to target four markets that offer promising application for its products: healthcare, advanced ceramics, environmental catalysts, and transparent functional coatings.

Conclusion

As a result of the ATP project, NTC has succeeded in synthesizing and processing nanocrystalline ceramics for commercialization. For example, the development of a production reactor continues to benefit product lines and serves as the test bed for powder synthesis. NTC has solid financial backing from numerous sources and continues to increase its client base, which currently consists of more than 20 companies worldwide.

PROJECT HIGHLIGHTS
Nanophase Technologies Corporation

Project Title: Processing Nanoscale Materials for Large-Scale Production (Synthesis and Processing of Nanocrystalline Ceramics on a Commercial Scale)

Project: To research and develop methods of processing nanoscale materials for commercial-scale production, with an emphasis on nanocrystalline ceramics. The successful scale-up and integration of these nanocrystalline materials on a commercial scale will provide more resilient and cost-effective products. Benefits of this achievement will affect products, such as steel ball bearings, mechanical seals, and the diesel engine, and industries, such as aerospace and fiber optics.

Duration: 7/1/1992-6/30/1995
ATP Number: 91-01-0041

Funding (in thousands):

ATP Final Cost	$ 944	24%
Participant Final Cost	3,009	76%
Total	$3,953	

Accomplishments: NTC successfully demonstrated the applicability of nanoscale materials and developed methods to produce these materials on a commercial scale. The company accomplished the following:

- Achieved a 25,000-fold increase in its capability to produce nanoscale materials and a 20,000-fold reduction in costs.
- Incorporated NTC titania successfully into cosmetic sunscreens, offering increased protection levels and competitive costs at a more effective per-unit weight than competing products
- Signed an agreement to distribute NTC materials to more than 300 companies
- Completed an IPO in November 1997

ITC received the following patents for technologies elated to the ATP project:

- "Method of making nanostructured materials" (No. 5,460,701: filed July 27, 1993, granted October 24, 1995)
- "A system for making nonstructured materials" (No. 5,514,349: filed August 4, 1994, granted May 7, 1996
- "Nanocrystalline materials" (No. 5,874,684: filed May 3, 1996, granted February 23, 1999)

Commercialization Status: NTC currently has a worldwide customer base in excess of 20 companies. The company has accomplished this market expansion based on its increased manufacturing capabilities and the six-month reduction in its time-to-market for new products. In March 1997, NTC signed an exclusive five-year contract with an undisclosed customer to provide nanoscale materials. NTC is currently providing nanoscale materials for a wide variety of applications including cosmetics, sunscreens, printing inks, and catalysts. The company has achieved these advances as a result of ATP's support during its infancy.

Outlook: Expectations for this technology and for the company are strong. The technology has been incorporated into commercial products that are being used extensively across several industries.

Composite Performance Score: * * * *

Number of Employees: Two employees at project start, 61 upon completion of status report

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Research and data for Status Report 91-01-0041 were collected during October - December 2001.

Norton Diamond Film

Accelerated Commercialization of Diamond-Coated Round Tools and Wear Parts

The development of advanced composite and metallic materials progressed rapidly within the U.S. automotive and aerospace industries during the early- to mid- 1990s, as these industries increasingly applied advanced materials to their new and existing products. However, the tooling required to machine hard and sometimes abrasive materials did not keep pace with the industries' advances. Norton Diamond Film and Kennametal, Inc., applied their complementary expertise in synthetic diamond-film technology and ceramic and carbide metal materials to the development of diamond-coated round tools and wear parts. Faced with three significant technical barriers that presented a high degree of project risk, the companies sought funding from the Advanced Technology Program (ATP), and in 1995, the joint venture received cost-shared funds from ATP to explore their proposed innovative methods for chemical vapor deposition (CVD) diamond coating. By project completion in 1997, the companies had demonstrated the viability of diamond-coated wear products and had increased tool life by 10 to 32 times. Although Norton Diamond has dropped its efforts to commercialize the technology, Kennametal has commercialized a diamond-coated end-mill product for the machining industry.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
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Research and data for Status Report 94-01-0357 were collected during October-December 2001.

Manufacturing Industries Strive to Keep Pace with High-Performance Demands

Advances in microelectronics, tooling, automotive, aerospace, and other industries have increased requirements for materials' performance, leading to harder and more abrasive materials. To create a component that has the desired geometry, dimension, and finish, a part must be machined. Machining is a manufacturing process in which a cutting tool is used to remove excess material from a work part. Tools must be able to work on hard and abrasive materials without wearing out quickly, so using the right tool coating is an important function in the machining of parts. Many industries have focused on developing new and innovative methods for coating parts used in tooling and machining, as manufacturers strive to find ways to increase tool life, while minimizing chipping of the coatings themselves.

In the search to find a coating material that could provide the requisite toughness and wear resistance, the industry explored diamond as a coating substance. Industrial diamonds possessed the attractive properties of hardness, transparency, high thermal conductivity, and high resistance to chemical corrosion. The problem with diamond, however, was that manufacturers needed a method to use the diamond in a thin film to coat metal tools to ensure adherence of the film over time. Diamond and metal have very different coefficients of thermal expansion, and when the two are joined at high temperatures and then cooled, residual stresses develop at room temperature and cause the diamond film to pop off.

During the early to mid-1990s, the use of natural and synthetic diamonds as a commercial material faced a number of disadvantages: 1) diamonds were only available in powder or grit form, 2) they were unavailable in sufficient sizes or quantities, and 3) they were prohibitively expensive. Therefore, researchers sought to identify methods for using these valuable substances in a more usable form. The discovery of diamond fabrication by chemical vapor deposition (CVD) allowed companies to overcome these problems and take advantage of diamond's attributes. CVD diamond manufacturing processes coat pure diamond directly onto wear surfaces. However, the use of CVD posed challenges in developing coating methods for complex, convoluted-shaped objects (such as drill bits) and in successfully coating parts containing cobalt.

Partners Foresee Significant Technical Challenges

Norton Diamond, a division of Saint-Gobain, hoped to develop its CVD coating technology into a standard process for producing adherent, uniform diamond coatings on three-dimensional surfaces that could be economically manufactured in large quantities for commercial use. Kennametal's contribution was to prepare special tungsten carbide tools, which promoted the adhesion of diamond films. While the proposed technology had the potential to revolutionize the machining of aluminum and composite materials for automotive, aerospace, and other applications, there were significant technical risks in adhering diamond film to complex, convoluted shapes.

Kennametal's special carbide formula and Norton Diamond's diamond deposition technology gave this project a significant advantage over competing approaches; however, both companies needed to overcome three main challenges to successfully accomplish their mission:

- Improve adhesion of diamond film onto cobalt-containing alloys that comprise the bulk of tools and components
- Demonstrate reliable coating of complicated three-dimensional round shapes
- Coat a large enough number of parts in one deposition to make the process economically sound

Faced with the challenge of overcoming three major technical barriers, the two companies sought ATP funding. With ATP support, Norton Diamond Film and Kennametal, Inc., believed they could combine their technical strengths in synthetic diamond-film technology and ceramic and carbide metal materials, respectively, to explore innovative methods for CVD diamond coating.

Companies Combine Strengths to Develop Diamond-Coating Technology

The companies proposed to develop diamond-coated tools and wear parts that last 10 to 100 times longer than the components available at the time. CVD diamond coating had the potential to improve the productivity of the U.S. industry in the drilling, tapping, reaming, and end-milling of non-ferrous and non-metallic workpiece materials. Through collaboration, the two companies sought to create an enabling technology that would provide more durable tools, lower manufacturing costs, and increase productivity. Norton Diamond and Kennametal officers were enthusiastic about the possibility of accelerating technology development by several generations.

Diamond-Coating Technology Has Far-Reaching Economic Potential

At the time of this project, the successful development of the diamond-coating technology offered promise for a number of industries and applications. The U.S. market for wear components (e.g., seals, dies, and tooling) for high-performance materials, such as tungsten carbide, ceramics, and coatings, was in excess of $1 billion.

The conservative estimate for diamond-film-coated mechanical seals was $100 million annually. In addition to improving the market potential, the development of the technology could lead to lower domestic transportation costs, increased U.S. market share, increased warranty periods for automotive parts, increased production in many industries, and the creation of more jobs for manufacturers and their suppliers.

Joint Venture Advances Technology Via Testbeds and Demonstrated Improvements

Major automotive and aerospace companies, including General Motors, Ford, Boeing, and Cummins, served as testbeds to ensure that the technology was robust enough for the manufacturing environment. The testbed results demonstrated an improvement in tool life of 10 to 32 times the lifespan of existing tools and, in addition, led to process improvements. Norton Diamond and Kennametal were able to minimize thermal-induced distortion of low-precision tools and produce a cobalt-free surface that provided excellent diamond adhesion and distortion-free, high-precision tools.

The companies proposed to develop diamond-coated tools and wear parts that last 10 to 100 times longer than the components available at the time.

The joint venture also demonstrated that convoluted round shapes, such as drills and end mills, could be coated with diamond films that still have good adhesion after more than 1,000 drill operations. This was an important technological advance since delamination from non-planar substrates was a major problem with this technology. Additionally, the companies accomplished the project's primary technical goal by establishing a manufacturing capability for tungsten carbide substrates that promotes the adhesion of diamond films.

Kennametal Pursues Separate Path to Commercialization

Though the collaboration of Norton Diamond and Kennametal was at first synergistic, toward the end of the two-year project, the companies found that they had differing approaches to taking their technology to market. These differences led each company down divergent paths in the development of their technologies. Norton Diamond attempted to market the technology until the summer of 1998. After then, it abandoned its attempts. As of July 2000, Norton Diamond Film no longer existed as a business division within Saint-Gobain.

Kennametal changed its strategy and focused on hot filament CVD technology and invested its own internal funds to take its CVD pretreatment and coating technology to market after the project concluded. Kennametal commercialized a diamond-coated endmill product that it currently supplies to the graphite, nonmetallic materials, and metal machining industries. The market has been slow to adopt the new technology as manufacturers remain cautious of new processes and are reluctant to pay high premiums for them. Kennametal continues its efforts to make tools more robust and to provide them to existing and new industries, such as metal machining.

Conclusion

Norton Diamond and Kennametal combined their expertise in synthetic diamond-film technology and ceramic and carbide metal materials in an effort to develop an effective diamond-coating technique for the automotive and aerospace industries. Together, they were able to demonstrate significant improvements, however, individually, each company decided to pursue a different course in its effort to further develop diamond-coating technologies. Norton Diamond discontinued its efforts to commercialize the technology, but Kennametal went on to develop a diamond-coating technology that is now being used by the manufacturing industry.

PROJECT HIGHLIGHTS
Norton Diamond Film

Project Title: Accelerated Commercialization of Diamond-Coated Round Tools and Wear Parts

Project: To develop diamond-coated round tools and wear parts for automotive and aerospace manufacturing that last 10 to 100 times longer than existing counterparts.

Duration: 5/1/1995-10/31/1997
ATP Number: 94-01-0357

Funding (in thousands):

ATP Final Cost	$1,883	42%
Participant Final Cost	2,609	58%
Total	$4,492	

Accomplishments: The joint venture between Norton Diamond and Kennametal was a successful research and development partnership that accelerated the commercialization of rotary tool products and demonstrated the viability of diamond-coated wear parts. The companies developed testbeds that were installed in major automotive and aerospace companies, including General Motors, Ford, Boeing, and Cummins and demonstrated tool life 10 to 32 times longer than existing tools. They also demonstrated that convoluted round shapes such as drills and seals could be coated with diamond films that have good adhesion after more than 1,000 drill operations. The joint venture resulted in the following patent, which was awarded to Kennametal as a result of technology related to the ATP project:

- "Method of making diamond coated member" (No. 5,701,578: filed November 20, 1996, granted December 23, 1997)

Through this ATP project, the joint venture also strengthened the U.S. position in the competitive global market for rotary tools and wear parts.

Commercialization Status: Prior to this ATP project, Norton Diamond and Kennametal each developed diamond-coating and pretreatment technology for simple, flat shapes, but had not developed the technology for convoluted shapes. Through the ATP-funded project, the companies were able to develop the technology for coating complex parts. After the conclusion of the project in 1997, Kennametal commercialized a diamond-coated endmill product that it currently supplies to the graphite, nonmetallic materials, and metal machining industries.

Outlook: While the use of the technology has not grown as quickly as the two companies anticipated at the beginning of this project, Kennametal continues to offer its diamond-coated product to various industries and continues research and development efforts to create more robust diamond-coating technology. It is anticipated that barriers to making this technology economical enough for widespread acceptance within the manufacturing environment will continue to exist.

Composite Performance Score: * *

Company:
Saint-Gobain Ceramics & Plastics
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Contact: Kevin Gray
Phone: (508) 351-7979

Norton Diamond was a division of Saint-Gobain since 1990. As of July 2000, Norton Diamond was dissolved and employees were transferred to other divisions of Saint-Gobain.

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Research and data for Status Report 94-01-0357 were collected during October-December 2001.

Praxair Surface Technologies, Inc.

Cost-Efficient and Environmentally Friendly Coating Process

Ceramic coatings are among the most durable materials, underlying the performance and extending the service life of equipment parts that must operate reliably in harsh environments, including aircraft landing gear, tractors, oilfield pumps, and gun tubes. However, in the mid-1990s, processes that could apply wear-resistant coatings and that were environmentally friendly had not been developed.

In 1995, Praxair Surface Technologies, Inc., and Surface Solutions, Inc., partnered to develop, test, and evaluate a promising, but experimental, coating technology invented by Surface Solutions. Early work with Surface Solutions' linear magnetron sputtering (LMS) process indicated that it had the potential to apply uniform, high-quality ceramic coatings to the internal surfaces of steel cylinders, but the innovative technology had been demonstrated only on a very small scale. If technical barriers were overcome, ceramic coatings could be applied as cheaply as hard-chrome plate, without generating the hazardous wastes associated with electroplating. The market opportunity, the potential for spillover benefits into other industries, the enabling nature of the technology, and Praxair's unique approach led the Advanced Technology Program (ATP) to award $793,000 in cost-shared funding to the company in 1995. When the project concluded in 1998, Praxair had made significant progress but had not achieved its technical goals. While the company is still interested in the technology, its current financial state prevents any further research and development activities.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)

No Stars

Research and data for Status Report 95-07-0006 were collected during October - December 2001.

Existing Technologies Produce Environmentally Hazardous Waste

Applying metal alloy, refractory metal, and ceramic coatings onto metal and non-metal substrates is an essential step in manufacturing many equipment components. Coatings may reduce costs by enabling simplified fabrication processes, increased product quality, lengthened equipment life, and reduced manufacturing and maintenance costs. In many cases, the coatings provide the only practical way to repair or refurbish equipment. Ceramic-coated surfaces substantially, and sometimes dramatically, increase the mechanical components' ability to resist wear, corrosion, and thermal extremes. Coatings are used extensively by many industries. For example, a modern aircraft gas turbine engine can have more than 800 coated areas on 450 components in order to resist hostile environments, provide sealed surfaces, and reduce the need for lubrication.

Traditionally, technologies used to coat the inside of cylinders, such as chrome electroplating and high-temperature chemical vapor deposition (CVD), produce high-performance coatings, but rely on environmentally harmful processes. Wear-resistant, corrosion-resistant, and environmentally friendly inside-diameter (ID) coatings had not been developed. Surface Solutions, Inc.'s linear magnetron sputtering (LMS) technology had the potential to fill this need.

Cylinder IDs Pose Challenge to Traditional Ceramic Coatings

Manufactured components have different coating requirements. For example, a component may need high surface hardness and abrasion resistance with bulk toughness (i.e., resistance to brittle crack propogation) or, alternatively, it may need an extremely high-temperature-, corrosion- and abrasion-resistant surface with bulk strength. The challenge is to identify or develop a coating that provides the desired functional properties and then to develop the process for applying it effectively to the substrate material. Cylinder ID coatings represent a case where potential higher quality coatings have been identified, but are not used because there is no process to apply them.

Neural networks and complex materials processing were both emerging technologies, and the combination of these two in a single venture increased the risk of the project.

Praxair's research showed that two ceramic hard coatings, titanium nitrade (TiN) and chromium nitrade (CrN), exhibit excellent wear characteristics compared to hard-chrome plate, without the environmental problems. However, the ability of existing coating processes to coat cylinder ID surfaces was limited to cylinder length-to-diameter ratios of less than one. The LMS process had the potential to apply an ID coating on cylinders with length-to-diameter ratios greater than 30 to 1.

Advantages of LMS Technology

The original LMS concept was developed and patented by Surface Solutions. The sputtering technology deposits particles onto the substrate in a uniform and even manner. LMS-applied coatings, if successfully deposited on the inside surfaces of cylinders, would address a longstanding need that could only be met by electroplating or high-temperature CVD.

Both of these processes create environmental problems and cannot deposit coatings such as TiN and CrN that provide superior wear and corrosion resistance. Thus, the use of the LMS process would not only help solve a serious environmental problem, it would also improve (by factors of 5 to 10) the performance of components that previously had to rely on chrome plate for surface treatment. Further, the coatings applied by the LMS process would not only reduce the cost of maintaining many types of equipment, it could also lengthen the operational time of equipment, which is often of much greater value. However, Surface Solutions, a five-person company in 1995, did not have the resources needed to develop the technology to the point of being commercially useful.

Wide Range of Potential Applications

Potential applications for the LMS technology were broad. For example, the lifespan of the hydraulic cylinders on heavy construction and mining equipment can be a critical factor in determining operating costs and sometimes in maintaining the safety of the equipment. Extending the life can lengthen the operating time between overhauls, which would benefit the operator and would also enhance the equipment's marketability for the manufacturer through its ability to offer longer warranties. This is important in the competitive heavy equipment industry where Japanese and other foreign competitors challenge U.S. manufacturers. Other potential applications include extruder and injection equipment, heat exchanger tubes, and gun barrels.

The LMS technology held promise for the production of tubular filters with tremendous improvements in environmental safety over the present state-of-the-art filtration systems. The LMS technology could be used in the generation of anti-coking coatings used in the chemicals and plastics industry, with the potential for significant cost savings. Thus, the knowledge gained from this project might also be of substantial value in developing other uses for coatings applied by the LMS process.

ATP Funds Development of LMS for Heavy Equipment Applications

The promise of using the LMS technology to apply coatings to longer cylinders (up to the industry standard of two meters) was the catalyst that brought together Praxair and Surface Solutions. Praxair partnered with subcontractor Surface Solutions to further develop LMS technology in order to coat cylinders of much greater length-to-diameter ratios than currently possible.

Praxair negotiated an exclusive license with Surface Solutions to use the patented LMS technology in applying coatings to cylindrical components for widespread commercial use. LMS technology would provide an innovative approach to an industry-wide problem in coatings that would also benefit numerous other industries. Praxair had a clear plan to bring to market this technology that could effectively compete with foreign companies. Therefore, in 1995, ATP awarded the company $793,000 in cost-shared funds for a three-year initiative. The overall objective of the ATP-funded project was to improve the durability of heavy equipment by replacing chrome plating with ceramic hard coatings on the inner diameter of cylindrical components. For example, hydraulic cylinders for off-road vehicles operate in dirty environments where components need to be coated to reduce the effects of abrasion and to increase corrosion resistance in order to extend the operating life of the component. The coating materials selected to replace electroplated chrome were CrN and TiN. These coating materials, deposited via the LMS technique onto tubular steel substrates, were expected to improve component service life by at least a factor of four and, at the same time, eliminate the environmental concerns associated with chrome plating. The ATP-funded project's specific objectives were to 1) establish the technical viability of a laboratory prototype LMS system for producing uniform, defect-free, wear-resistant coatings on the inner diameter of cylindrical components two meters long or with length-to-diameter ratios of 30 to 1; and 2) define the performance enhancements attainable by replacing chrome plating with TiN or CrN on hydraulic cylinders and oilfield slurry pumps.

Ultimately, the commercial application of LMS technology would provide several industries with significant broad-based economic benefits, such as increases in efficiency, reductions in cost, and alternatives to chrome electroplating. Praxair hoped to commercialize the technology through three customers with whom it had initiated discussions: General Electric, Halliburton, and Caterpillar.

Delays in Prototyping the System Lead to Limited Results

Design problems with the LMS prototype system plagued the early stages of development. The first problem was the instability of the hollow cathode, and the second was the inability of the chamber-cooling system to tolerate the sustained high-temperature operating conditions necessary for optimum deposition. These problems led to unexpected delays, which shortened the time that was available to spend on optimizing coating conditions, a key part of the technical plan. Coupled with organizational changes within Praxair's upper management and the project management team, the project fell behind schedule.

A second LMS prototype system was designed to overcome the aforementioned technical problems and was capable of applying TiN on cylinders up to 1 meter in length and 152.4mm in diameter. This new system, however, could not coat the inner diameters of longer cylinders (up to two meters) with a uniform thickness, a necessary prerequisite for broad commercialization; nor could it coat cylinders with length-to-diameter ratios of up to 30 to 1. Finally, only limited progress was made on applying CrN coatings to cylinders. Solving these problems proved to be even more difficult than expected, and Praxair's two project objectives were not achieved.

Technical Delays and Financial Problems Halt Cylinder ID Project

At the completion of the ATP-funded project, Praxair's research activities for coating the inner diameter of cylinders with TiN and CrN ceased. A combination of factors led to the decision to stop the development of the technology. Primarily, development had not progressed to a point where Praxair could see clear opportunities worthy of further internal funding. The company acknowledged that the experience from previously unsuccessful R&D projects influenced its decision to cease funding. Secondly, the departure of Praxair's project manager, who had tremendous expertise, left an unfilled void. Finally, the worsening financial condition of Praxair's Surface Technologies division resulted in reduced R&D budgets.

Conclusion

The research and development conducted during this project advanced the coating industry's understanding of the newest form of physical vapor deposition (linear magnetron sputtering). However, the anticipated advantages of LMS technology to improve wear and corrosion properties were not fully realized.

In spite of setbacks in prototype system development, Praxair was able to attain adequate TiN coatings on inner diameters up to 1 meter in length and 152.4mm in diameter, but the project goals of coating the inside of cylinders 2 meters long or with length-to-diameter ratios of 30 to 1 were not realized. Nor were acceptable CrN coatings produced. At the project's completion, further R&D and commercialization of the technology were not pursued.

PROJECT HIGHLIGHTS
Praxair Surface Technologies, Inc.

Project Title: Cost-Efficient and Environmentally Friendly Coating Process (Ceramic Coating Technology for the Internal Surfaces of Tubular/Cylindrical Components)

Project: To improve the durability of heavy equipment by replacing the chrome plating on the inner surfaces of cylindrical components with ceramic hard coatings such as CrN and TiN.

Duration: 9/1/1995-8/31/1998
ATP Number: 95-07-0006

Funding (in thousands):**

ATP Final Cost	$ 793	66%
Participant Final Cost	400	34%
Total	$ 1,193	

Accomplishments: During this ATP project, Praxair successfully utilized the linear magnetron sputtering (LMS) technology to deposit a titanium nitrade coating with uniform color and thickness at a rate of 0.04 microns/minute for cylinders up to 1 meter in length and 152.4mm in diameter.

Commercialization Status: There are no plans to commercialize this technology. Limited technical success and current financial conditions have forestalled the company's ability to pursue further development of the technology necessary for commercial introduction. Praxair remains interested in the commercial potential of using LMS for coating the internal surfaces of tubular and cylindrical components in the heavy equipment industry.

Outlook: The outlook for this technology is poor due to Praxair's current financial condition.

Composite Performance Score: No stars

Focused Program: Materials Processing for Heavy Manufacturing, 1995

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** As of December 9, 1997, large single applicant firms are required to pay 60% of all ATP project costs. Prior to this date, single applicant firms, regardless of size, were required to pay indirect costs.

Research and data for Status Report 95-07-0006 were collected during October - December 2001.

Strongwell Corporation

Composite Materials Sought as Replacement for Steel and Concrete

In 1994, the U.S. Federal Highway Administration estimated that 230,000 of the nation's 575,000 bridges were structurally deficient or functionally obsolete, and they would require an expenditure of $130 billion in public funds in the coming years. Because steel and concrete decay cost the nation billions of dollars for repair and replacement, new technology that lengthened the functional lives and sped the repair of roadways and bridges was clearly needed. Composite materials held this promise. Strongwell Corporation, the world's largest pultruder of fiber-reinforced structural parts, applied for and was awarded $2 million in cost-shared funding from the Advanced Technology Program (ATP) to research and develop a process to manufacture large, fiber-reinforced polymer (FRP) composite structures that could reduce the cost of maintaining the country's existing civil infrastructure.

Strongwell successfully developed a manufacturing process to pultrude a 36 x 18-inch "double-web" I-beam in a vinyl ester matrix known as the EXTREN DWB™. This structural shape is more complex in design and 4½ times stronger than existing composite structural shapes. The large composite structures made of these carbon and glass reinforced polymer composites have attracted interest from state transportation agencies, the offshore oil industry, the construction industry, and the defense industry. Strongwell's beams have been used successfully in two Virginia bridges, but commercialization depends on acceptance by bridge engineers, who are still awaiting test data before they commit to using this new technology. Through a joint venture with Ebert Composite Corporation, the advanced pultruding process Strongwell developed with the help of ATP is being used to manufacture composite poles and towers for electric utility companies and other industries.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
* * *

Research and data for Status Report 94-02-0010 were collected during January - March 2002.

Expense and Technical Barriers Delay Composite Structure Development

The accelerated highway and bridge-building programs of the 1960s and 1970s enabled the United States to build a transportation infrastructure that meets most of the nation's needs. Although the need for new roads is limited, the maintenance of existing roads has become an enormous economic burden. The majority of the nation's roads and bridges were not designed to accommodate the current high volume of business and recreational traffic, let alone future travel needs. U.S. roadways and bridges are breaking down at an alarming rate, and their maintenance is of critical importance.

Manufacturers, designers, and engineers recognized the ability of composites (a hybrid of two or more materials) to produce high-quality, durable products. Several technical barriers, however, were preventing their use.

First, composite materials were expensive and difficult to engineer into structures of appropriate shape and size with adequate stiffness and overall performance for civil structures. Second, the industry lacked experience using fiber-reinforced polymer (FRP) composites as a structural material, and research and development (R&D) had not been performed to determine the size and strength of the equipment needed to produce the large FRP components. Finally, conservative civil engineers have delayed the acceptance of FRP structures by regulatory agencies. Many engineers lack confidence in composite materials for civil infrastructure because not enough testing has been done on their long-term durability.

Strongwell Proposes an Advanced FRP Composite

Strongwell's goal was to design and produce a new, high-strength, advanced FRP phenolic composite that could be used in bridge and building construction. Phenolics are thermosetting resins that cure through a condensation reaction that produces water that must be removed during processing.

Phenolic composites have many desirable performance qualities, including high temperature resistance, excellent thermal insulation, sound-damping properties, and corrosion resistance; therefore, they last far longer than conventional materials, such as steel and concrete.

> ***Strongwell's goal was to design and produce a new, high-strength, advanced composite that could be used in bridge and building construction.***

Strongwell recognized that it would take several years for civil engineers to accept FRP as a replacement for steel and concrete. Rigorous testing, validation, and demonstration of this material would be required to ensure product quality and safety. As a result, Strongwell was unable to attract either internal or external private capital for this project because the return on investment was expected to be greater than 10 years. Because of these barriers, Strongwell submitted a proposal for ATP funding.

Strongwell Identifies Benefits of Large Composite Shapes

Strongwell forecasted that $2 million from ATP could translate into savings of billions of dollars for the bridge construction industry. Successful completion of this research to develop large composite shapes using FRP would represent a major breakthrough in composite technology. As an improved alternative to conventional steel and concrete, it would provide the basis for dramatic improvements in the U.S. road transportation system and other civil engineering and construction applications. U.S. taxpayers would benefit from lower life-cycle costs of existing structures and reduced time and cost to build new structures.

A reduction in the effort required to maintain the nation's highways could lead to less traffic disruption, which would speed the transport of U.S. products by the trucking industry. Moreover, Strongwell envisioned that its new technology would be used in a range of applications, including short-span bridges, offshore oil platforms, and other industrial applications where corrosion is a problem. Additional savings also would be realized in other industries such as aircraft and space.

Revolutionary Shape Solves Key Technical Challenge

Strongwell's objective was to design and produce a 36- x 18-inch FRP phenolic and vinyl ester composite beam that could be used in bridge and building construction. Strongwell intended to build on its expertise in pultrusion (a manufacturing process for composites) to create a structure large enough, as well as strong enough, for civil projects. Pultrusion is used in producing continuous lengths of reinforced plastic parts with constant cross-sections. The process involves pulling these raw materials through a bath of thermosetting resin and then into a heated forming and curing die to produce composite structural shapes. As the reinforcements are saturated with the resin mixture in the resin bath and pulled through the die, the heat from the die initiates the hardening of the resin, and a rigid, cured profile is formed that corresponds to the shape of the die.

One key technical challenge was to design a structure that combined structural strength with corrosion and chemical resistance, as well as one that performed better than existing beams used for infrastructure. Strongwell solicited the expertise of Dr. Abdul-Hamid Zureick, head of the structural engineering and mechanics group of the School of Civil and Environmental Engineering at Georgia Institute of Technology, to assist in the design of the FRP shape.

The double-web I design improved performance, increased the shear load distribution capability of the beam, and improved the stiffness, making the beam resistant to bending; and therefore very useful in building bridges.

"double-web I" or "modified box" beam in which two vertical webs are connected by a flange across the top and bottom. The double-web I design improved performance, increased the shear load distribution capability of the beam, and improved the stiffness, making the beam resistant to bending. The box-like shape also is simple, making it easier for Strongwell to manufacture using the complex phenolic resin process and a vinyl ester resin system.

Another key technical challenge was to create a pultrusion machine capable of manufacturing this large 36- x 18-inch shape while achieving a complete cure of the resin and fiber laminate. Although the company had extensive experience creating pultruded shapes, no shape that large had ever been pultruded using phenolics.

Manufacturing Process Proves Successful In

September 1996, Strongwell manufactured two 8 x 6-inch subscale prototypes of the double-web I-beam using a fiberglass and carbon composite. The first prototype was created with vinyl ester resin, which is less viscous and therefore easier to use in the pultrusion process, while offering excellent corrosion resistance and weight reduction compared with steel. The second prototype was created with phenolic resin, which requires a more sophisticated manufacturing process but provides the added benefit of superior heat resistance. With the help of the Georgia Institute of Technology, Strongwell optimized the beam shape for torque resistance, eliminating the need for support braces. The stiffness of the subscale prototype composite beam is roughly 6.3 msi (millions of pounds per square inch), which is more than twice the stiffness of a standard fiberglass I-beam. The beam also performed well in tests for fatigue, creep (or stretching under tension), and strength under static loading. Strongwell's ability to create the 8 x 6-inch beam encouraged the company to continue its efforts to manufacture the 36 x 18-inch shape. However, Strongwell encountered several technical challenges as it moved forward. The thicker, multicored, closed shape of Strongwell's 36 x 18-inch shape represented a substantial increase in complexity from the small, square tube manufactured using a phenolic matrix.

The pull forces required for this project were unheard of for pultrusion, as was the design of the saw needed to cut the beams. A machine capable of exerting 120,000 pounds of force-more than Strongwell originally anticipated would be needed-was required to pull thousands of tightly packed fibers through a bath of polymeric resin and into molding and curing dies of the required size and shape. Strongwell designed and fabricated a dual-reciprocating hydraulic puller system that uses two clamping and pulling mechanisms. This was one of the first machines to synchronize four large cylinders at one time. At that time, the machine had the largest pull capacity of any pultrusion machine in the world and three times the pulling capacity of Strongwell's next-largest machine.

By the end of 1997, Strongwell had successfully developed the manufacturing process to create the longer double-web I-beam using both a phenolic matrix and a vinyl ester matrix. The company later marketed the beams made with the vinyl ester resin as the EXTREN DWB™.

Strongwell proved that the dissimilar materials of carbon and glass fibers could be combined using either a phenolic or a vinyl ester matrix to create a large structural shape that did not delaminate. The outcome was a 36 x 18-inch structural shape more complex in design with a much better strength-to-weight ratio than conventional steel and concrete shapes.

The company's other tooling accomplishments related to this project include:

- Designing and fabricating a unique start-up winch powered by a clamping and pulling mechanism
- Working with a saw manufacturer, DoALL, Inc., to design and build the largest pivoting head band saw ever created in order to cut the EXTREN DWB™
- Working with BASYS Technologies (currently BIOREM Technologies) to successfully use biofiltration as an emission control during the phenolic process

Widespread Applications of Strongwell's Technology

In 1997, Strongwell used the technology from this project to create one of the first composite short-span vehicular bridges in the United States, the Tom's Creek Bridge in Blacksburg, Virginia. Jack Lesko, an associate professor of engineering science and mechanics at Virginia Polytechnic Institute and State University, is working with Strongwell, the Virginia Transportation Research Council (a National Science Foundation-supported research center at Virginia Tech that focuses on high-performance polymeric adhesives and composites), and the Center for Innovative Technology (CIT) in Herndon, Virginia to test the beams. Testing will assess changes in the composite materials, which, although they do not rust or corrode, may undergo changes in weight, volume, or other characteristics. Test results also will be useful in establishing implementation standards for composite bridges.

When they were used to replace the Thomas Creek Bridge's corroded steel beams, the composite beams provided immediate benefits. For example, the bridge's capacity was upgraded from 10 tons to 20 tons, and the rehabilitation of the bridge took less labor, time and resources. According to Julius Volgi, a Virginia Department of Transportation engineer, "Two people on scaffolding can handle the new beam with their hands, versus having to use a light crane or a backhoe to lift it in place." Furthermore, the entire bridge rehabilitation was completed in five days, which resulted in less inconvenience to the more than 1,000 cars that cross the bridge daily.

As a result of the ATP award, Strongwell has applied some of its new processing technology to its other products, such as a material that combines glass fiber with carbon fiber and the improved use of engineered glass fabrics. Mr. Glen Barefoot, head of corporate marketing, stated, "As a result of developing a large structural beam for vehicular bridge girders, Strongwell has instituted an R&D plan to develop an FRP bridge deck to be used for bridge rehabilitation of new bridges with the double web beam."

Other structural applications of Strongwell's ATP-funded technology have included bridge demonstrations for the U.S. Navy and the Departments of Transportation in Connecticut and Kansas. Strongwell received the Best of Show Award at the Composite Fabricators Association Conference in San Antonio in October 1998. In 1999, Strongwell presented the beam at the International Bridge Conference and Trade Show. Press releases have been published in *Civil Engineering, Engineering News Record, and Composite Technology*.

Strongwell Faces Challenges to Commercialization

Lack of acceptance by bridge engineers of the FRP beam as a structural material to replace steel continues to be a barrier to commercialization and will remain so until years of test data and demonstrations are completed. Bridge engineers are extremely conservative and have limited knowledge of composites and their use as a structural material. The low initial cost of steel and concrete is an important consideration for most new bridge designs. Composites, however, have a higher initial price, but they require much less ongoing maintenance, which reduces overall life-cycle costs.

Strongwell is committed to increasing the acceptance of this technology and is working with the Virginia Technical Institute and CIT to develop a design handbook that will provide a comparative analysis of the composite shape to steel and concrete. CIT provided Strongwell with two $20,000 Innovation Awards to support production of the design book, as well as further testing of the beam.

Other Applications Proposed for Strongwell's Technology

Strongwell's technology is being considered to replace steel in many other applications, including offshore oil platforms where the components' lighter weight, durability, and resistance to salt water and salt air provide significant benefits. On September 30,1997, Strongwell gave a presentation at the Composites for Offshore Operations Conference in Houston, Texas that demonstrated the uses of the ATP-funded composite shape. Since that time, oil companies have expressed interest in substituting composite components for steel to reduce weight on tension leg platforms on large, mobile drilling rigs.

In 1998, Strongwell managers met employees of Ebert Composite Corporation, another ATP awardee. Ebert had designed and demonstrated an affordable manufacturing system that reduced production time for making large structural parts from composite materials. The companies decided to form a joint venture company, Strongwell-Ebert LLC, in Bristol, Virginia. This company, now a wholly owned subsidiary of Strongwell, markets and sells composite poles and towers to electric utilities and other industries.

Strongwell also is talking to the U.S. Navy about using the company's large FRP structures as a replacement for steel. The Navy is interested in the large FRP composites' high strength-to-weight ratio, durability, and inherent resistance to weather and the corrosive effects of salt air, sea, and aggressive chemicals. In 2001, Strongwell completed a bridge that spans 39 feet over Dickey Creek in Sugar Grove, Virginia, a project that represents the first use of Strongwell's full-scale 36 x 18-inch beams. The beams weigh approximately 70 pounds per linear foot—about half the weight of similar steel beams.

Conclusion

Although Strongwell still faces several commercialization barriers, the company is confident that the EXTREN DWB™ and the other large composite shapes developed during the ATP-funded project will gain a larger share in construction markets. "Without ATP funding, we could not have developed the process for creating high-performance composite shapes," stated Mr. Barefoot. The ATP-funded project reduced the time to market for high-performance shapes by approximately 10 years, and Strongwell is confident that once the shapes receive acceptance as a building material, the benefits of decreased installation and maintenance costs will be recognized.

PROJECT HIGHLIGHTS
Strongwell Corporation

Project Title: Composite Materials Sought as Replacement for Steel and Concrete (Innovative Manufacturing Techniques to Produce Large Phenolic Composite Shapes)

Project: To develop large, cost-effective, high-performance composite shapes that last longer and are maintained more easily than the concrete and steel that is now aging and deteriorating in the country's transportation infrastructure.

Duration: 2/1/1995-1/31/1998
ATP Number: 94-02-0010

Funding (in thousands):

ATP Final Cost	$ 2,000	64%
Participant Final Cost	1,142	36%
Total	$ 3,142	

Accomplishments: During this three-year project, Strongwell achieved the following significant accomplishments:

- Developed a manufacturing process to create a 36 x 18-inch double-web I-beam made from vinyl ester and phenolic composites.
- Designed and fabricated a dual-reciprocating hydraulic puller system using two clamping and pulling mechanisms placed in tandem, hand-over-hand, and synchronized by a programmable linear controller. This was one of the first machines to synchronize four large cylinders at one time. At the time, it was believed to have the largest pull capacity of any pultrusion machine in the world.
- Designed and fabricated a unique start-up winch powered by a clamping and pulling mechanism.
- Worked with a saw manufacturer, DoALL, Inc., to create the largest pivoting head band saw ever built.
- Worked with BASYS Technologies to successfully use biofiltration as an emission control.

Commercialization Status: Strongwell continues to present and demonstrate the EXTREN DWB™ beam for a variety of civil infrastructure applications. Strongwell has installed composite beams in two bridges in Virginia and has received substantial interest from oil companies for mobile drilling rig applications. The company formed a joint venture company with Ebert Composite Corporation to manufacture and sell composite poles and towers. Strongwell continues to develop engineering design guidelines so engineers can develop and test the applicability of FRP shapes for other large civil infrastructure projects.

Outlook: Strongwell has received positive response to its high-performance composite shapes; however, industry codes and design standards must be modified to accommodate composite structures before full-scale commercialization of the technology is feasible. Maintaining and rebuilding the U.S. roadway system using composites presents a tremendous market opportunity well into the 21st century.

Composite Performance Score: * * *

Focused Program: Manufacturing Composite Structures, 1994

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Research and data for Status Report 94-02-0010 were collected during January - March 2002.