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Composites Manufacturing Technologies:
Applications in Automotive, Petroleum, and Civil Infrastructure Industries

Economic Study of a
Cluster of ATP-Funded Projects

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Abstract

Composite materials are strong, lightweight, and corrosion resistant, as well as expensive to manufacture and not widely used in large scale industrial applications. In 1994, the Advanced Technology Program undertook a program focused on composites manufacturing in order to trigger the creation of high-performance manufacturing infrastructure for commercial composite parts. From 1994 to 2000, ATP invested $43 million, along with industry partners who invested $39 million, in 22 high-risk projects.

To assess the economic and societal benefits from ATP-funded projects for composites manufacturing, a cluster-study approach was used to combine the methodological advantages of detailed case studies and higher-level overview studies. Five projects were selected for analysis, spanning automotive, offshore oil production, and civil infrastructure applications. Within the cluster of five projects, two projects with the best near-term prospects for commercial deployment were selected for detailed case studies.

Based on primary research and analysis, the cluster study estimates exceptional returns on ATP' s investment in five composites manufacturing projects:

- Benefit-to-cost ratios on ATP's investment ranging from 83:1 to 92:1.
- Net present value of ATP's investment ranging from $892 to $994 million.
- Public rates of return on ATP's investment ranging from 44 to 46 percent.

These measures reflect the estimated benefits to industry users and the general public relative to the ATP investment. Estimated benefits to direct recipients of ATP funding are excluded.

Additional qualitative benefits are reported, including automotive quality improvements, energy production benefits, reduced harmful environmental emissions, and lower levels of traffic congestion in metropolitan areas.

Research performed for this study indicates that ATP's industry partners would not have developed high-risk, low-cost composites manufacturing technologies without ATP support and without ATP facilitation of broad-based industrial joint ventures. The study concludes that the above benefits are directly attributable to ATP's investment.

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Executive Summary

Polymer composites are hybrid materials consisting of reinforcing fibers in a polymer resin, which are formed to a desired shape and engineered to achieve performance specifications.

High-performance composite materials are strong, lightweight, and corrosion resistant, as well as expensive to manufacture and not widely used in large-scale commercial applications.

In 1994, the Advanced Technology Program (ATP) undertook a program focused on composites manufacturing to trigger the creation of an infrastructure for commercial composite manufacturing (Wu 2002). The focused program was aimed at helping U.S. companies develop the technical capability for producing vast amounts of affordable performance composites. This new capacity was to be targeted at large-scale commercial applications in the automotive, offshore oil production, and civil infrastructure industries. The performance benefits of composite materials, validated in the focused program, would then be delivered to other U.S. industries and end users.

From 1994 to 2000, ATP invested $43 million, along with industry partners who invested $39 million, in 22 high-risk projects. Fifteen of the 22 ATP-funded projects reached completion; seven closed early. Upon program completion, significant innovations in composite manufacturing were realized, which can be expected to produce the following results:

- Rapid, high-volume, low-cost manufacturing processes.
- Affordable high performance composites.
- Expanded commercial and industrial utilization.

To assess the economic and societal benefits from the ATP-funded program, a cluster-study approach was used to combine the methodological advantages of detailed case studies and higher-level overview studies. Five projects targeted by the focused program were selected for analysis, spanning automotive, offshore oil production, and civil infrastructure applications. The projects were as follows:

- Vapor-Grown Carbon Fibers for Automotive Applications.
- Composite Production Risers for Offshore Oil Production.
- Innovative Joining/Fitting Systems for Composite Piping Systems.
- Innovative Manufacturing Techniques for Large Composite Shapes.
- Synchronous CNC Machining of Pultruded Lineals.

Within the cluster of five projects, two were singled out as having the most probable near-term prospects for commercial deployment and associated public benefits:

- Vapor-Grown Carbon Fibers for Automotive Applications.
- Composite Production Risers for Offshore Oil Production.

For these two projects, detailed case studies were conducted to identify key technical accomplishments, identify pathways to market, and quantify productivity, capital efficiency, and environmental benefits.

This executive summary describes the results of the cluster study, composed of two detailed case studies and high-level analysis for the remaining three projects. Cluster-study research and analysis were completed during 2002 and early 2003.

COMPOSITE MATERIALS

Composites are systems of at least two component materials, acting in concert, with physical properties that are not attainable by individual components acting alone. Reinforcing fibers provide strength and stiffness. The matrix material binds the fibers together, provides form and rigidity, transfers load to the fibers, and protects load-bearing fiber from corrosion and wear. A technical discussion of composite materials is provided in an appendix.

Engineers can utilize over 50,000 materials for the design and manufacture of engineered products, including metals, polymers, ceramics, and composites. While metals and polymers are currently the dominant materials for engineering applications, composite utilization is gradually increasing due to superior strength, low weight, and improved thermal and electrical performance characteristics. Lower composite manufacturing costs would accelerate this trend, especially in cost-sensitive industrial mass markets.

MARKET APPLICATIONS AND PROJECTIONS

For automotive applications, ATP-funded vapor-grown carbon fibers are likely to be used in the following ways:

- Exterior automotive panels to facilitate electrostatic painting.
- Electromagnetic interference shielding without metal or metal coated enclosures.
- Automotive tires for improved fuel economy.

By 2006, vapor-grown carbon fiber utilization for exterior painting and electromagnetic interference shielding applications is likely to start with a single model year of 90,000 vehicles. By 2010, vapor-grown carbon fibers could be incorporated in one million vehicles for exterior painting and in 1.5 million vehicles for electromagnetic interference shielding. Automotive tire applications are projected to start in 2011 with 1.25 million tires.

For offshore oil production, starting in 2007, ATP-funded composite production risers will be used to reach increasingly deep petroleum reservoirs in the Gulf of Mexico. Over a period of 16 years, lightweight composite production risers are expected to be used in the

- Construction of 15 new oil production platforms.
- Redeployment of 9 existing platforms that have exhausted their underlying reservoirs.

Prior to 2007, as part of a transitional stage, composite production risers could also be used in currently operating Gulf of Mexico platforms to complete remaining production wells and expand production from nearby lateral reserves.

BENEFIT-TO-COST ANALYSIS

Based on primary research and analysis, the cluster study projects high public returns on ATP's investment in five composite manufacturing projects:

- Benefit-to-cost ratios on ATP's investment ranging from 83:1 to 92:1 (base case versus step-out scenarios in 2003 dollars).
- Net present value of ATP's investment ranging from $892 to $994 million.
- Public rates of return on ATP's investment ranging from 44 to 46 percent.

The above indicators point to exceptional returns to the nation on ATP's investment.

For every dollar of ATP's $9 million investment in the cluster of five projects, U.S. industry, U.S. consumers, and the nation can expect to enjoy $83 of quantifiable dollar benefits. If more optimistic step-out scenario conditions prevail, public benefits could reach $92 for every dollar of public investment.

When cash flow benefits from the cluster of five projects are measured against ATP's entire $43 million investment in the 22 projects of the composites manufacturing program, projected public benefits remain at $18 for every dollar of ATP's investment.

These performance metrics reflect the estimated benefits to industry users and the general public relative to the ATP investment. Estimated benefits to direct recipients of ATP funding are excluded.

Performance metrics are estimated on the basis of conservative assumptions, including an average market price of crude oil at $20 per barrel and average retail gasoline price at $1.50 per gallon. If average prices increase to higher levels, the expected benefits from ATP-funded technologies and performance metrics will also increase.

Qualitative benefits, which can not be quantified at this time, illustrate the potential of innovative composites manufacturing technologies to create public benefits along multiple dimensions of societal value. These benefits include:

- Quality improvements for exterior automotive panels.
- Reduced oil consumption from improved automotive fuel economies.
- Increased domestic oil production from reaching substantial new petroleum reserves in the Gulf of Mexico.
- Improved maintainability of offshore oil production risers.
- Reduced harmful environmental emissions from automotive painting processes.
- Reduced traffic congestion in metropolitan areas.

CONCLUSIONS

The cluster study concludes that several ATP-funded composite manufacturing projects have made significant progress toward meeting the necessary conditions for commercial implementation. For the two case study projects, technological advantages are close to being translated into business advantages, including:

- Large-scale production of composite components and products.
- Improved cost competitiveness with traditional engineering materials.

Based on the above elements of progress toward commercial implementation, the cluster study concludes that public returns from ATP's investment have a strong probability of being realized for automotive and offshore oil production. There is also a reasonable likelihood that future benefits will be realized from civil infrastructure applications.

Research performed for this study indicates that ATP's industry partners would not have developed high-risk, low-cost composites manufacturing technologies without ATP support and without ATP facilitation of broad-based industrial joint ventures. The study concludes that the above benefits are directly attributable to ATP investment.

Table ES-1. Summary of Benefits from ATP's Investment in a Cluster of Five Composites Manufacturing Projects

Broad-based economic benefits

For every dollar of ATP's $9 million cost share in the cluster of five projects, U.S. industry, consumers, and the nation can expect to enjoy $83 of public benefits.

For every dollar of ATP's $43 million cost share in the program of 22 projects, U.S. industry, consumers, and the nation can expect to enjoy $18 of public benefits.

Qualitative benefits from the Vapor-Grown Carbon Fiber project

Decreased harmful volatile organic compound emissions from automotive painting operations and reduced environmental compliance costs.

Increased engineering design flexibility and improved dimensional stability from thermal stresses.

Improved fuel economy resulting from reduced tire rolling resistance and the use of lightweight composites.

Qualitative benefits from the Composite Production Riser project

Increased domestic oil production from deepwater Gulf of Mexico reserves.

Improved maintainability of corrosion resistant composite risers in highly saline marine environments.

Qualitative benefits from civil infrastructure projects

Reduced traffic congestion and congestion costs.

Avoided fuel consumption and automotive emissions.

Cross-industry knowledge diffusion

The implementation of new industrial processes, as well as licensing and manufacturing joint ventures, will tend to reveal aspects of the new knowledge to other economic agents.

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Abbreviations and Acronyms

ASI	Applied Sciences, Inc.
Aspect ratio	Fiber length to fiber diameter
ATP	Advanced Technology Program
B:C	Benefit to cost ratio
bbl	Barrels of crude oil
boe	Barrels of oil equivalent
bpd	Barrels of oil per day
Carbonization	Process by which PAN is pyrolyzed into carbon fibers, carried out in an inert atmosphere at temperatures of 1,000° to 1,500° centigrade
Catalyst	Substance added to a polymer resin to initiate the cure
CNC	Computer numerical control for automated machinery
Composites	Reinforcing fiber in a resin matrix. More generally, substances composed of at least two distinctly dissimilar materials acting in concert. The properties of composites are not attainable by the individual components acting alone.
CPR	Composite production risers, for offshore petroleum exploration and production
Cross-linking	Chemical bonding of molecules, which in polymers occurs in the curing transition from liquid to solid
Cure	Irreversible change in the properties of a thermosetting resin by chemical reaction (cross-linking) during which process a composite develops its full strength
E-Glass	Electrical-grade fiberglass commonly used to reinforce composites

EMI	Electromagnetic interference
Fiber debulking	Process to improve handling characteristics of nanoscale fibers
Functional group	Groups of oxygen, nitrogen, and sulfur-based compounds resident on carbon fiber surfaces
GOM	Gulf of Mexico
Graphitization	Process step after PAN carbonization used to obtain higher carbon yield and graphitic microstructure
HNBR	Uncured hydrogen-resistant rubber for CPR fabrication
IRR	Internal rate of return
Lateral reserves	Lateral extensions of existing and probable petroleum reserves
MCI	Metal to composite interface (for composite production risers)
Micron	Millionth of a meter
nm	Nanometer or a billionth of a meter
MMS	U.S. Minerals Management Service, Department of Interior
Modulus	Modulus of elasticity, the ratio of stress (force per unit area) divided by strain (percent deformation of a body subjected to a force)
Morphology	Structural characteristics of carbon fibers
NPV	Net present value
OMB	Office of Management and Budget
OCS	Outer continental shelf
OEM	Original equipment manufacturer
PAH	Polyaromatic hydrocarbon
PAN	Polyacrylonitrile, a conventional precursor of carbon fiber
PEEK	Polyetheretherketone
Polymer	Chain molecule composed of many identical groups, commonly found in plastics
PP	Polypropylene, a matrix material for thermoplastic composites
Precursors	Starting component materials for a chemical reaction
Production well	Hole drilled into the ocean floor, usually cased with pipe, for the recovery of crude oil, condensates, and natural gas
psi	Pounds per square inch

Pultrusion	Continuous process of manufacturing composites with a cross-sectional shape. Process consists of pulling fibers (reinforcing materials) through a resin impregnation bath and through a shaping die, where the resin is subsequently cured.
Pyrograf-III	Brand name for Applied Science Inc. vapor-grown carbon fiber
Pyrolize	Transformation (decomposition) of a compound by the action of heat, in an inert atmosphere. In the context of VGCF manufacturing, pyrolisis is used to remove tars and other hydrocarbons from the surface of the carbon fiber.
Resin	Liquid polymer which, when catalyzed, cures to a solid state
SAPV	Surface area per vehicle
SPAR	Stationary floating platform for offshore oil production. Its structure is that of a vertical floating cylinder attached by means of cables to anchors placed on the seafloor.
Surface area	Surface area of carbon fibers, including the areas of pores, voids, and cavities
Surface energy	Energy states among surface molecules of crystal lattices, as opposed to energy states among internal molecules
Thermal coefficient of expansion	Measures dimensional change in a material when heated and cooled, in inches per degree
Thermoplastic	Group of plastic materials that become elastic or melt when heated and return to their rigid state at room temperature.
Thermosets	Materials that undergo a chemical cross-linking reaction going from liquid to solid or to a semisolid. This reaction is irreversible.
TLP	Tension leg platform, a floating deck structure anchored to pile heads on the seafloor by means of long tendons that are kept in tension. TLPs are used in offshore oil production.
Vinyl ester resin	Thermosetting resin, containing ester of acrylic and/or methacrylic acids, for making polymers that cure to an insoluble cross-linked matrix resin
VGCF	Vapor-grown carbon fiber
VOC	Volatile organic compound, a harmful byproduct of automotive painting process

1. Introduction

The Advanced Technology Program (ATP), National Institute of Standards and Technology (NIST), fosters partnerships among government, industry, and academia by cost-sharing innovative, high-risk research to develop enabling technologies that promise broad economic benefits for the nation. Improved manufacturing processes for composite materials constitute an important class of enabling technologies with substantial promise for large-scale industrial impact and broad-based economic benefits. (See inside back cover for a more detailed description of the ATP.)

More than 50,000 materials are available to engineers for the design and manufacture of engineered products, offering an extensive range of physical and cost characteristics. While metals and plastics are currently the dominant materials, composite materials with superior physical performance characteristics are increasingly used to replace traditional metals and plastic materials in engineered products (Mazumdar 2002).

Polymer composites are hybrid systems of two or more materials, typically containing reinforcing fibers in a polymer matrix. Reinforcing fibers provide strength and stiffness to the composite. The polymer matrix material binds the fibers together, provides form and rigidity, transfers load to the fibers, and protects load-bearing fiber from corrosion and wear. The resulting composites have superior physical properties, such as improved strength, electrical conductivity, and corrosion resistance, which are not attainable by the individual components acting alone.

Despite superior physical properties, the utilization of composites has been generally restricted to military and small-scale commercial applications. Two key factors have been holding back mass-market industrial utilization:

- Labor-intensive and product-specific manufacturing practices that do not lend themselves to high-volume, large-scale applications.
- High relative initial cost of composite materials.

Given composites' potential for broad-based economic benefits as well as current manufacturing and cost limitations, in 1994 ATP undertook a program to develop composites manufacturing technologies in order to trigger the creation of a high-performance manufacturing infrastructure for commercial composite parts. The program would lead to significant innovations in composites manufacturing, resulting in the following:

- Rapid, high-volume, low-cost fabrication.
- Affordable, high-performance composites.
- High strength, lightweight, appropriate electrical conductivity, corrosion, resistance and less maintenance.
- Substantially expanded use of composites in the U.S. automotive, offshore oil production, and civil infrastructure industries.

During 1994 and 1995, ATP funded 22 high-risk projects. If successful, the program was expected to "help U.S. companies develop the technical capability for producing vast amounts of affordable high-performance composites for large-scale commercial applications," and to deliver the performance benefits of composites to U.S. industry and to end users (ATP 2002).

CLUSTER STUDY OBJECTIVES AND SCOPE

ATP conducts economic analyses to assess the short- and long-term benefits of ATP-funded projects to the nation. Economic analyses evaluate the impact of ATP-funded technologies on project participants, on industrial users of new products and processes, and on end users benefiting from new technologies.

To assess the economic benefits from the ATP-funded program for composites manufacturing technologies, a cluster study approach was used to combine some of the methodological advantages of detailed case studies and of higher-level overview studies (see Section 2). Using this hybrid analytical approach, a cluster of five projects from the program was selected for analysis:

- Vapor-Grown Carbon Fibers for Automotive Applications.
- Composite Production Risers for Offshore Oil Production.
- Innovative Joining/Fitting Systems for Composite Piping Systems.
- Innovative Manufacturing Techniques for Large Composite Shapes.
- Synchronous CNC Machining of Pultruded Lineals.

This cluster of projects spanned automotive, offshore oil production, and civil infrastructure applications and included only projects where all ATP-funded technical tasks were completed. In addition, each project in the cluster possessed near-term commercial prospects with identifiable economic benefits for U.S. industry and society at large.

Within the cluster of five projects, two projects were singled out as having the most probable near-term prospects for commercial deployment and substantial associated economic benefits: Vapor-Grown Carbon Fibers (VGCF) for Automotive Applications and Composite Production Risers (CPR) for Offshore Oil Production.

For the remaining 17 projects in the program (beyond the cluster of five projects), seven projects closed out early and 10 projects reached completion. While the commercial prospects and associated economic benefits of these 10 projects can not be assessed at this time, they may also lead to broad-ranging future benefits. These additional benefits can be captured and assessed through future economic analysis.

FIVE PROJECTS IN THE CLUSTER STUDY

Of the five projects in the cluster, one ATP-funded technology focused on automotive applications, two technologies focused on offshore oil production, and two technologies focused on civil infrastructure applications.

Two of the five projects involved large-scale industry joint ventures (JV). Within these JV structures, the ATP cost-share provided financial support to companies leading high-risk technical development efforts and their subcontractors. Industry collaborators, who were typically successful major corporations, were recruited by the JV to participate in technology development, to facilitate testing and prototype development, and to advance commercialization, without receiving ATP funding. In one of the two joint ventures, the Composite Production Riser project, industrial collaborators provided net project funding beyond supporting their own participation.

Vapor-Grown Carbon Fibers for Automotive Applications

The project involved the design, development, and manufacture of nanoscale process technology; performance evaluation of different polymer composites with VGCF reinforcement; and prototyping automotive components using VGCF-reinforced thermoplastic, thermoset, and rubber matrices.

The major technology innovator was Applied Sciences, Inc. (ASI). ASI and its subcontractors were the recipients of ATP funding. The ATP joint venture also included General Motors Corporation and Goodyear Tire & Rubber Co. as industry partners in technology development, prototype testing, and commercialization. The industry partners did not receive ATP funding.

Subsequent to the successful completion of the ATP-funded program, ASI built a full-scale VGCF production facility and is currently completing a second production facility in its Pyrograf Products subsidiary.

Composite Production Risers for Offshore Oil Production

The project involved the design, development, manufacture, and qualification testing (to demonstrate compliance with design requirements) of reliable composite-based components that can significantly reduce platform weight and the capital cost of offshore oil production. The project facilitates oil and gas production from deepwater Gulf of Mexico petroleum reserves by replacing costlier and heavier steel components.

The major technology innovator was Lincoln Composites, formerly Brunswick Composites Corporation. Lincoln Composites and its subcontractors were the recipients of ATP funding. The ATP joint venture also included BP Amoco, Shell Development, and ConocoPhillips as industry partners to participate in technology development, CPR prototype testing, and commercialization. Industry partners did not receive ATP funding. Instead they were a net source of project funding, beyond supporting their own participation.

Innovative Joining/Fitting Systems for Composite Piping Systems

The project developed new processes for manufacturing composite pipe fittings at increased production rates and reduced cost. Expected utilization is for offshore oil and gas piping systems as well as for land-based oil and gas systems. Specialty Plastics, Inc. was the recipient of ATP funding.

Innovative Manufacturing Techniques to Produce Large Composite Shapes

The project developed cost-effective manufacturing processes for large, high-performance composite shapes that last longer and are maintained more easily than the concrete and steel beams that are now aging and deteriorating in the country’s civil infrastructure applications. Replacement of short-span bridges is one important area of application. Morrison Molded Fiberglass Company (now Strongwell Corporation) was the recipient of ATP funding.

Synchronous CNC Machining of Pultruded Lineals

The project developed cost-effective manufacturing processes for making composite-based “snap-and-build” systems for rapid construction of large segmented structures such as electric power transmission towers. Ebert Composites Corporation of San Diego, CA was the recipient of ATP funding.

Appendices 1 and 2 provide more details for the above projects and for the entire focused program of 22 projects (including project title, single company or joint venture project, lead company, year funded, length of project, and funding amounts). An overview of how composite materials are formed and their characteristics is provided in Appendix 3.

2. Analytical Framework and Methodology

ANALYTICAL FRAMEWORK

The performance of publicly funded science and technology programs can be evaluated using alternative analytical approaches. The case-study method is particularly useful for exploring the genesis of projects and for telling the stories of projects, including sponsoring organizations and key champions (Ruegg and Feller 2003). Traditional case-study approaches for assessing the benefits of publicly funded science and technology programs include in-depth case studies of individual projects and overview case studies of many projects.

Detailed case studies generate insights into the industry dynamics and complex causal chains that link innovation to market pathways to public benefits. Case studies can thus support the development of quantitative cash flow estimates for public and private benefits and rigorous analysis of investment performance. However, detailed case studies are labor intensive and costly.

In contrast, overview studies of many projects often aim at identifying observable trends in the flow of public benefits from technology innovations, without developing detailed information about specific technologies, industry, and market factors. Overview studies of many projects can provide a general impression of investment performance and can be cost effective. At the same time, overview studies may fail to generate sufficiently detailed information for quantitative analysis.

The cluster study approach is a hybrid of these two traditional case study approaches and aims at obtaining some of the advantages of detailed case studies and of multiproject overview studies, while avoiding some of their limitations.

GENERAL APPROACH

The ATP program for composites manufacturing technologies recognized a dual challenge: the need to solve high-risk technical problems affecting innovative

The cluster study approach combines some of the advantages of detailed case studies and higher-level overview studies, such as:

- Developing rich insights into industry and market dynamics and commercialization pathways for ATP-funded high-risk technologies.
- Establishing a basis for estimating cash flow benefits to be enjoyed by innovators, industry, customers, and society at large, as well as performance metrics.
- Providing a basis for meaningful generalizations across projects about the effectiveness of ATP investments.

manufacturing processes, and the necessity of demonstrating accelerated compliance with industrial standards and codes and commercial acceptance of new and improved products.

To meet these challenges, the ATP

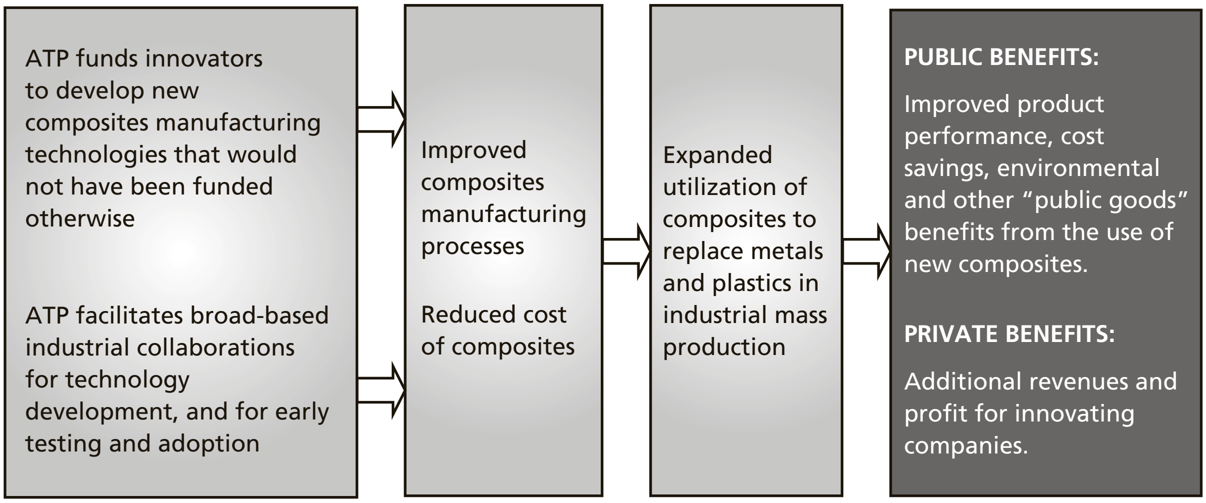
- Funded entrepreneurial firms to develop high-risk, innovative composites manufacturing technologies on a cost-sharing basis.
- Funded projects that would not have been privately funded or would have taken substantially longer to develop without ATP funds.
- Vigorously facilitated the collaboration of major industrial companies to secure industrial-scale platforms for the development, testing, and commercialization of new and improved products. For projects examined in this study, the participating industrial companies did not receive ATP funding but could anticipate some temporary commercial advantages from acquiring know-how as a result of their uncompensated collaboration.

Based on the above approach, new composites manufacturing processes and new industrial products (incorporating advanced composites) emerged that would not have been possible without ATP funding and ATP facilitation.

As indicated in Figure 1, the cluster of ATP-funded innovative composites manufacturing projects will result in a rich variety of social and economic benefits, directly attributable to the ATP.

The causal chain from manufacturing process to improved industrial products includes the intermediate elements of lower composites costs and expanded composite utilization. The resultant social and economic benefits will include:

Figure 1: Flow of Benefits from ATP-Funded Composites Manufacturing Projects



- Capital and operating cost savings.
- Engineering design flexibility and improved manufacturing cycle times.
- Improved product quality and product performance.
- Environmental benefits.
- Energy production and energy conservation benefits.
- Incremental royalty streams to the U.S. Minerals Management Service.
- Knowledge diffusion benefits.

For analytical purposes, benefits are segmented by classes of beneficiaries. Economic benefits enjoyed by the innovating firms funded through ATP are considered *private benefits*. The innovating firm's expectation that these private benefits will be realized is an important precondition for private cost sharing, for completing the remaining technical development tasks after the successful completion of the ATP-funded project phase, and for undertaking the eventual commercialization phase, thereby making it possible for the ATP-funded high-risk technology to yield beneficial social and economic results. In this sense, the realistic expectation of attractive private benefits or rates of return to the ATP-funded innovator is a form of "insurance" that ATP's investment will in fact lead to widespread use.

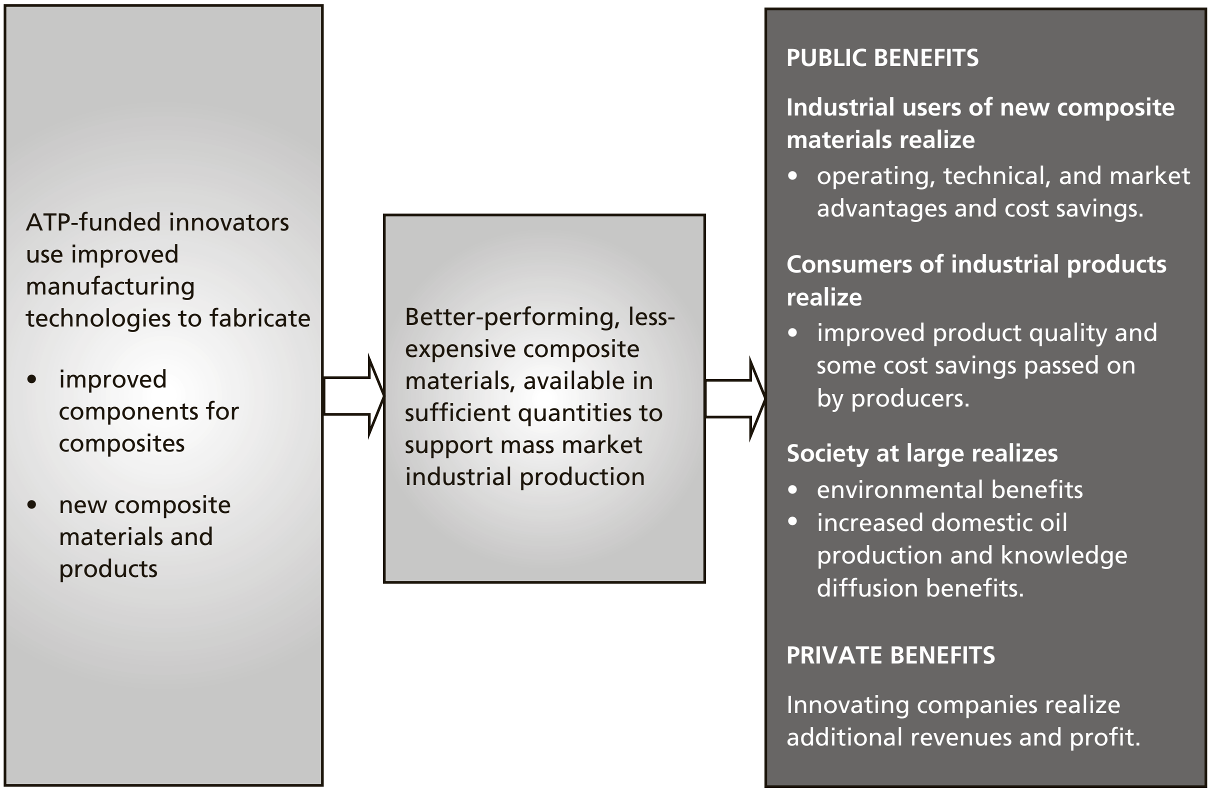
In contrast to private benefits to the innovating firms receiving ATP funding, the economic and social benefits arising from the ATP-funded technology enjoyed by other industrial firms, end users of industrial products, and the public at large are considered *public benefits*.

In microeconomic terms, these public benefits represent "spillover" phenomena. "Spillover" designates that portion of total benefits resulting from the new ATP-funded technology (both public and private) that the innovating firm is unable to capture for itself (Jaffe 1998). Both the theoretical and empirical economics literature suggests that public benefits, or the spillover from ATP investment, can be expected to substantially exceed the magnitude of private benefits (Mansfield et al. 1977).

Beyond public and private distinctions, other allocation dynamics can be posited for public benefits from new composites manufacturing technologies. As indicated in Figure 2, innovating firms provide better-performing and less-expensive composite materials to the industrial sector, which incorporates improved composite materials in its industrial products and retains some of the resulting economic benefits as producer surplus. Through market competition, some or most of these economic benefits are passed on to product end users as consumer surplus (McConnell and Brue 1996). As discussed by Jaffe, it is expected that "innovative products (incorporating improved composite materials) will generally be sold at prices that do not fully capture all of the superiority of the product relative to what was available before," resulting in increased consumer welfare (Jaffe 1998).

In contrast to economic benefits whose allocation among producers and consumers is subject to market forces, some important benefits have a strong "public goods" quality that society at large will be able to enjoy. Examples include reduced harmful

Figure 2: Benefit Allocation from ATP-Funded Composites Manufacturing Projects



ATP-funded innovators use improved manufacturing technologies to fabricate

- improved components for composites
- new composite materials and products

Better-performing, less-expensive composite materials, available in sufficient quantities to support mass market industrial production

PUBLIC BENEFITS

Industrial users of new composite materials realize

- operating, technical, and market advantages and cost savings.

Consumers of industrial products realize

- improved product quality and some cost savings passed on by producers.

Society at large realizes

- environmental benefits
- increased domestic oil production and knowledge diffusion benefits.

PRIVATE BENEFITS

Innovating companies realize additional revenues and profit.

environmental emissions, reduced energy dependence, and knowledge diffusion about the new technology. Regarding the expectation of knowledge diffusion, Jaffe (1998) notes that

> [C]ommercial development and use of new knowledge will tend to cause it to spread, despite any desire of the (innovator) to prevent such spread. Economic exploitation of new knowledge requires the sale of new products or the incorporation of new processes into commercial use. Such commercialization tends to reveal at least some aspects of the new knowledge to other economic agents. Hence the very process of economically exploiting the knowledge that research creates tends to pass that knowledge to others.

METHODOLOGY

In their seminal study of public and private benefits resulting from technology innovation, Mansfield et al. (1977) stress the necessity of undertaking detailed case studies and other empirical work to provide a rich set of non-obvious and often counterintuitive insights into the complex causal chain from innovation, to market pathways, and to the eventual benefits realized by innovators, other industry participants at higher levels in product chains, customers, and society at large.

The need for detailed case studies is justified, in part, by the variety of commercial and market dynamics that are unique and specific to industries. Surface generalizations about these dynamics may sometimes lead to unreliable conclusions and detract from the credibility for analytical results.

In line with Mansfield et al. (1977), our cluster study of composite manufacturing projects uses a detailed empirical approach so as to fully capture the causal connections from technological innovation to public and private benefits in the widely divergent automotive, offshore petroleum, and civil infrastructure industries.

Accordingly, two projects ATP funded in the area of composites manufacturing were selected for detailed case studies, one in the automotive industry and the other in the offshore petroleum industry. These detailed case studies present project history (including an account of the need for ATP funding), the characterization of technical challenges and accomplishments, opportunities for commercial application, pathways to markets, and an extensive identification of all expected benefits, both public and private.

Economic analysis estimated benefits to industry users and the general public and compared them to the ATP investment. Estimated benefits to direct recipients of ATP funding were excluded. For public benefits that could be meaningfully quantified, cash flow estimates were generated for a conservative base case scenario and for a more optimistic “step-out” scenario. Cash flow estimates were used to compute three sets of economic performance measures for comparing the value of public benefits to

Benefit-to-cost ratio is computed by dividing the present value of "public benefit" cash flow estimates (enjoyed by U.S. beneficiaries except the ATP-funded innovator) by the present value of ATP's investment. This measure estimates the benefit to the nation for every dollar of ATP's investment.

Net present value (NPV) is calculated by subtracting the present value of ATP's investment from the present value of public benefits from innovative composites manufacturing technologies. Cash flows are normalized to 2003 dollars and discounted at the 7 percent OMB-mandated rate. This measure describes the net benefit to the nation, in 2003 dollars.

The public rate of return is calculated by iterative solution for a rate at which the discounted value of ATP's investment would equal the discounted value of public benefit cash flows. This measure describes the rate of return to the nation on ATP's investment.

ATP's investments: benefit-to-cost ratios, net present values, and internal rates of return.

Additional ATP projects that had completed their technical goals but whose commercialization prospects are longer term were selected as the remaining three projects in the cluster of five projects. High-level analysis was conducted to review key technical challenges and achievements, as well as future prospects for commercialization and public benefit creation. Measures of performance were computed for the cluster using estimates of currently identifiable benefits. These measures compare public benefits of the two case-study projects with near-term commercialization prospects to the ATP-funded costs of all five projects in the cluster.

3. Vapor-Grown Carbon Fiber Case Study

The U.S. automotive industry operates in a highly competitive global market. To retain its competitiveness, the industry is committed to cost-reduction initiatives, continuous quality improvement, and greater fuel economy, while addressing increasingly challenging emissions standards.

Composites reinforced with vapor-grown carbon fiber (VGCF) have improved electrical conductivity and strength and can provide a broad range of benefits to the automotive industry and to consumers in the form of improved quality, better fuel economy, reduced cost, and lower environmental emissions. These benefits can potentially be achieved through several VGCF automotive applications:

- Electrostatic painting of exterior automotive panels reinforced with VGCF can avoid the use of conductive primers and "off-line" finishing processes, leading to cost, quality, and environmental benefits.
- Enclosures for shielding automotive electronic systems from electromagnetic interference (EMI) can be fabricated from VGCF reinforced composites, leading to cost reduction benefits.
- Automotive tires with VGCF additives will have improved electrical conductivity and stiffness and will contribute to improved fuel economy.

This section describes the results of a case study of the ATP-funded VGCF technology. It presents project history and key technical accomplishments, describes commercial and market applications in the automotive and tire industries, and presents the results of a quantitative economic benefit-to-cost analysis together with a brief discussion of qualitative benefits.

PROJECT HISTORY

Polymer composites reinforced with carbon fiber provide improved electrical conductivity, high strength and stiffness, and other desirable properties. In the past, the widespread industrial utilization of carbon-reinforced composites has been limited by the high relative cost of carbon fiber and the absence of well-defined design rules and proven manufacturing methods to support industrial-scale production (Strong 1989).

These limitations have inhibited widespread U.S. industrial use of composites (American Composites Manufacturing Association 2002). The need to overcome these systemic limitations was a significant factor in ATP's 1994 decision to initiate a program to develop innovative composites manufacturing technologies and to invest in the development of the VGCF technology as part of that program.

In 1994, Applied Sciences, Inc. (ASI), an independent U.S. company, with the support of General Motors Corporation and Goodyear Tire & Rubber Co., submitted a proposal to ATP for the high-risk vapor-grown carbon fiber (VGCF) technology development project. According to ASI's proposal for ATP funding, VGCF was intended as an electrically conductive, high-strength structure for mass production polymer molding processes (automotive panels and parts) and for mass production elastomer molding processes (automotive tires).

In 1995, the ATP cost shared the project with ASI, General Motors Corporation, and Goodyear Tire & Rubber Company. The ATP investment was used to support ASI's technology development efforts. General Motors and Goodyear provided sufficient investment to fund their own activities in technology development, testing, and prototyping. However, General Motors and Goodyear did not receive any ATP funding.

The major technical challenges of the ATP-funded project included the following:

- Creating an adequate interface between the carbon fiber and the polymer matrix to assure uniform infiltration and adhesion and to allow load transfer from the matrix to the carbon fiber reinforcement.
- Developing a deliverable form of the VGCF fiber that would be practical for plastic compounders, who normally work with powder additives.
- Developing manufacturing processes for large quantities of fiber, thus reaching economies of scale and reducing fiber costs to competitive levels.

The project was successfully completed in 2000 and resulted in the development of the following practical design and production methods:

- Controlling VGCF diameter, surface chemistry, morphology, and achieving appropriate interface adhesion.
- Debulking nanoscale fibers to optimize strength and electrical properties and facilitate handling.
- Positioning VGCF manufacturing operations for substantial future cost reductions and industrial-scale production.

ATP funding also contributed to credibility and project momentum, leading to subsequent funding from the state of Ohio and private investors to support the construction of a $3 million pilot production plant and further technical developments, including coal gasification to replace expensive methane feedstock.

Without ATP funding these accomplishments would not have been realized. In particular, the surface state of VGCF fibers and the impact of surface state on composite performance would not have been characterized and "this would have substantially inhibited or effectively stopped the development of industrial-scale application of VGCF composites, outside of specialized niche markets" (Lake 2002 et al.).

HOW DOES IT WORK?

Carbon fiber's electrical properties, strength, stiffness, thermal characteristics, and production costs are strongly affected by the type of precursor and processing parameters.

The conventional manufacturing process for carbon fiber (the defender technology) uses commercially available PAN (polyacrylonitrile) textile as the precursor. PAN fibers are first "stabilized" by thermosetting or cross-linking to ensure that the precursor material does not melt in subsequent processing steps. The thermosetting step is accompanied by a stretching of the fibers, which are subsequently carbonized until PAN fibers are essentially transformed into all-carbon fibers. To avoid internal voids and other material defects, carbonization requires a slow heating rate, eventually reaching 1000°C. To further improve the tensile modulus or stiffness of the fiber, graphitization is carried out at temperatures in excess of 1200°C. After graphitization, the fibers are surface treated, a sizing or coating is applied, and the continuous fibers are wound for shipment (Strong 1989).

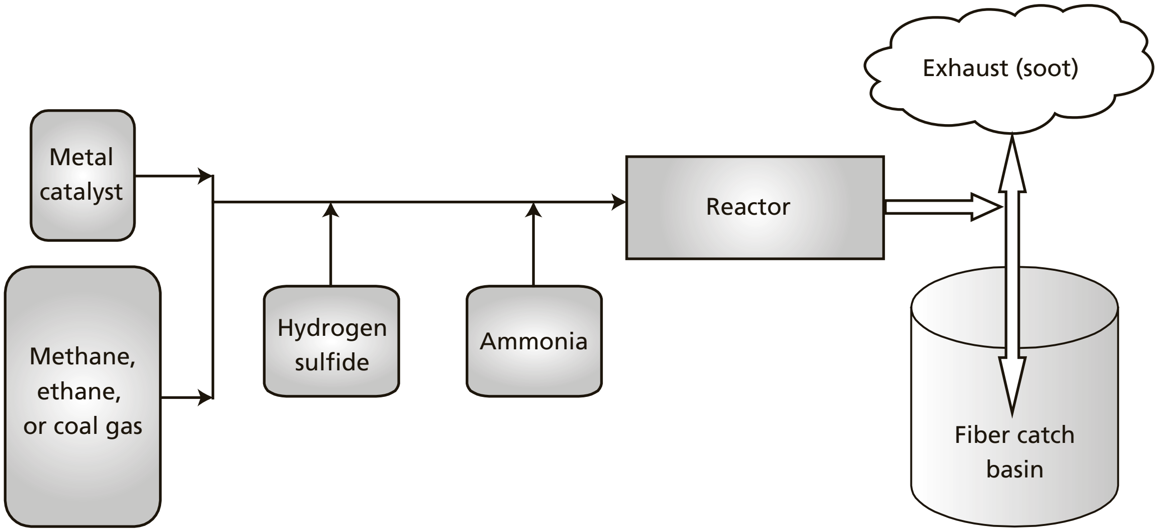
Unlike the complex PAN based processes, the ATP-funded manufacturing process uses a simpler, faster, and cheaper "vapor-grown" production technology (see Figure 3).

As indicated in Figure 3, vapor-grown carbon fiber (branded Pyrograf-III) is produced in the vapor phase by decomposing either methane, ethane, or coal gas in the presence of a metal catalyst, hydrogen sulfide, and ammonia. The catalyzed gas decomposes into carbon and hydrogen and is conveyed to a reactor furnace.

Carbon remains in the reactor for only a few milliseconds, growing into a fiber of 60 to 200 nanometers in diameter and about 100 microns in length. The fiber is entrained in a gas flow, which carries it from the reactor, on a continuous basis, into a fiber catch basin. The fiber is debulked for sale or for additional processing (such as heat treatment).

The above VGCF process overcomes many of the costly production steps and processing limitations of the PAN-derived process and provides an innovative

Figure 3: Vapor-Grown Carbon Fiber Manufacturing Process



Source: Applied Sciences, Inc. 2002.

approach for fabricating high performance fibers at lower cost. Hydrogen, which is about 40 percent by weight of the gas stream, is a potentially useful byproduct that can be used to further improve process economics (Lake 2002a).

TECHNICAL ACCOMPLISHMENTS

The technical accomplishments of the ATP-funded vapor-grown carbon fiber manufacturing technology included four key elements: surface modifications to assure fiber-matrix adhesion; developing user-compatible fiber forms; evaluating the performance of thermoplastic, thermoset, and elastomer composites with VGCF reinforcement; and prototyping automotive components using VGCF-reinforced thermoplastic, thermoset, and elastomer matrices.

Surface Modifications to Assure Fiber-Matrix Adhesion

Prior to the ATP-funded project there was incomplete understanding of the surface state of the vapor-grown carbon fiber. Information about fiber surface area, surface energy, fiber morphology, and the type and amount of nonhydrocarbon functional groups resident on the fiber surface was of interest as all of these features can impact the interfacial bonding between the fiber and matrix materials.

The ATP-funded program developed measurement and estimation techniques for fiber surface area, surface energy, morphology, and functional groups and made it possible to characterize the relationships of these surface parameters to composite performance properties. This body of knowledge was of considerable value in guiding optimization efforts during the evaluation of VGCF properties, which in turn were used to guide further development and refinement of VGCF production processes.

The surface area determination produced values for total surface area (including internal areas of surface micropores) as well as external surface area (without micropores). Processes were developed to decrease the fiber diameter, which resulted in larger relative surface areas. This proved beneficial since increased surface area was found to contribute to improved fiber matrix bonding.

The surface energy of the fiber impacts the ability of matrix materials to wet and spread on the fiber and thus increase fiber matrix adhesion. Surface energy levels were determined using inverse gas chromatographic techniques. It was found that surface energy and adhesion could be increased by the removal of surface layers of polyaromatic hydrocarbons (PAH) produced in the vapor-grown carbon fiber process. Surface energy could be further increased by heat treatment. In addition to promoting better fiber–to-matrix adhesion, higher surface energy levels promoted improved fiber dispersion in the polymer matrix resin.

Prior to the ATP-funded project, there was insufficient knowledge as to the nature and extent of resident functional groups on the fiber surface. The ATP-funded project identified the presence of low levels of oxygenated, nitrogen, and sulfur groups. "Fibers, with such functional groups on the fiber surface, were found to have improved mechanical performance and appropriate levels of electrical conductivity for a variety of composite applications" (Hughes 2003).

The ATP-funded project also contributed to improved fiber structure or morphology. Initially, VGCF consisted of a hollow core with a graphitic sheath and a carbon "overcoat" on top of the graphitic sheath. During the project, the fiber production process was changed to produce fibers with altered morphology (without a carbon coating), resulting in lower cost and higher levels of surface energy.

Developing User-Compatible Fiber Forms

Prior to the ATP-funded project, "as grown" fibers existed in the reactor as a flaky material with very low density (inhomogeneous with respect to density) that could not be efficiently handled by composite manufacturers. The ATP-funded project developed an efficient VGCF debulking process resulting in improved handling characteristics as well as improved fiber-matrix adhesion. As an alternative form of VGCF, ASI determined that the fiber could be produced in paper form, using production processes similar to the paper industry.

Evaluating Composites with VGCF Reinforcement

Prior to the ATP-funded project, there was limited information on the effect of carbon fiber reinforcement on the properties of polymer composites.

The evaluation of VGCF-reinforced thermoplastic composites was completed by the General Motors Technology Center (General Motors 2002), using polypropylene (PP) and nylon 6,6 as matrix materials. It was shown that VGCF increased the tensile strength of PP by up to 300 percent. The increase was linear with increasing concentrations of reinforcing VGCF in the matrix. It was also found that fibers with low surface energy provided weaker adhesion and much lower composite tensile strengths. To a lesser extent, lower fiber surface area was also related to lower composite tensile strength.

Separately, the GM Technology Center tests identified that VGCF-reinforced thermoplastic composites possessed attractive electrical properties, demonstrating substantially improved electrical conductivity in both PP and nylon 6,6 composites. Electrical properties were within required levels for electrostatic painting, EMI shielding, and static electricity dissipation in the automotive industry. The thermal conductivity of VGCF-based composites was determined to be better than the base resin, and VGCF reinforcement could be expected to inhibit thermal warping and result in improved dimensional stability of automotive panels.

The GM Technology Center also completed limited work on VGCF-reinforced thermoset composites with vinyl ester resins. These tests indicated greatly improved electrical conductivity but only slight impact on strength and stiffness. It was found that a mixed fiber structure, using glass fiber in combination with VGCF, provided high electrical conductivity as well as substantially improved stiffness compared with thermosets reinforced with only VGCF.

Preliminary evaluation of VGCF-reinforced elastomer composites was undertaken at the Goodyear Tire & Rubber Co. Initial results indicated “desirable increases” in tensile strength and stiffness, without a buildup of undesirable static electricity.

Prototyping Automotive Components

General Motors used VGCF reinforced composites for prototyping instrument panel parts. GM also identified additional components for prototyping, including fuel hose fittings, oil pans, gas tanks, door panels, seat backs and supports, truck beds, door hinges, engine mounts, and suspension bushings.

Goodyear built and tested prototype tires and indicated that tire properties were very promising and that VGCF costs were the remaining barrier to adoption.

Based on the above ATP-funded accomplishments, VGCF provides a “multifunctional reinforcing structure” with the following performance characteristics:

- Ten times the electrical conductivity of conventional “chopped” carbon fiber.
- Four times the thermal conductivity of fiberglass at ten percent by weight loading.

- Half the coefficient of thermal expansion as conventional carbon fiber at ten percent by weight loading, reducing thermal distortion and increasing dimensional stability.
- "Environment friendly" flame retardancy properties.

The ATP-funded technical accomplishments and resulting performance characteristics enabled ASI to learn how to control VGCF diameter, surface chemistry, and morphology, how to debulk and package nanoscale fibers to optimize strength and electrical properties, and how to accomplish these tasks in an industrial-scale production environment. The ATP-funded project also identified a "65 percent reduction in material costs by learning how to properly handle hydrogen sulfide in a production reactor" (ASI 2002 et al.).

Without ATP funding these accomplishments would not have been realized. In particular, the surface state of VGCF fibers and the impact of surface state on composite performance would not have been characterized and "this would have substantially inhibited or effectively stopped the development of industrial-scale application of VGCF composites, outside of specialized niche markets, such as defense applications" (Lake 2000a).

ATP funding also provided credibility and project momentum, which facilitated subsequent funding from the state of Ohio and from private investors to support the construction of a $3 million VGCF production pilot plant, as well as additional technological developments, including coal gasification to replace expensive methane feedstock.

PRODUCTION CAPACITY AND COSTS

During the summer of 2000, ASI completed construction of a VGCF pilot plant. It has one production line and was built at an approximate cost of $3 million, including engineering and infrastructure costs. This line now supports annual production levels of 100,000 lbs of VGCF. Capacity expansion is expected to be an easily replicable process and the facility could be expanded (by adding additional production lines) up to annual production levels of 5 million lbs. In contrast to the first line, the capital cost of the second line is expected to be about $900,000.

Given the relatively low complexity of the VGCF manufacturing process and correspondingly low capital investments for additional production capacity, capacity expansion is not expected to restrict expanded VGCF utilization, as long as VGCF continues to make progress in meeting automotive industry performance and price expectations.

ASI is currently pursuing additional cost reduction opportunities, including the possible utilization of cheaper VGCF feedstock from coal gasification. Nevertheless, ASI asserts that the $3 to $5 per pound pricing target for VGCF could be met solely on the basis of expanded production and associated economies of scale. In this price range, VGCF is expected to be competitive in the mass production automotive market.

AUTOMOTIVE MARKETS FOR VGCF-REINFORCED COMPOSITES

ASI's marketing efforts for VGCF are focused on automotive applications for electrostatic painting of composite body panels, electromagnetic interference shielding of automotive electronics, and reduced tire rolling resistance. These applications are tied to VGCF providing intrinsic electrical conductivity to composite parts and components.

Automotive Industry Trends

In 2001, North American sales of new light vehicles exceeded 17 million units, evenly split between passenger cars and light trucks (minivans, SUVs, and pickup trucks). Fourteen million units were produced domestically, including a growing share (2.4 million units) by Japanese affiliates and a rapidly growing share by German affiliates (Office of Automotive Affairs 2002). North American markets are expected to grow at only one percent, and there is substantial excess motor vehicle production capacity in the United States and worldwide.

Slow growth, excess capacity, and increasing environmental regulation are expected to accelerate global competition and result in continued cost pressures. According to a BearingPoint survey, auto executives believe that technical innovation will be key to addressing these challenges and ensuring the industry's future prosperity (KPMG 2003). Rapid technological change will have a significant impact on cutting costs through manufacturing and development efficiencies, including through increased use of composites for exterior body components. Composite usage is expected to grow 20 percent by 2009. Another area of technological change is in electrical and electronics systems, used for engine controls, safety, steering, braking, tire sensing, and telematics systems; investment in these technologies is expected to grow from 10 percent of vehicle cost in 1998 to 19 percent by 2009 (University of Michigan 2001).

Motor vehicles are built around common platform concepts, with different models sharing structural elements such as floor plans. Automakers will seek cost reductions by reducing the number of platforms and increasing the number of models that can be built using common platform features (CSM Worldwide 2001).

Technology innovations, tied to platform changes, currently require two to three years to impact automotive production. The industry plans to compress the time that is required to go from a "clean sheet" (starting a new design process from scratch) to the assembly line to less than two years (Sawyer 2001). So called "running changes," within the built-in flexibility of existing platforms, can be accomplished in less than 12 months.

Automotive Composite Utilization

Composite use can lead to weight reduction and improved fuel economy. The use of composites also facilitates making “comparatively cost effective modifications to vehicles … due to lower tooling costs” (Vasilach 2001).

The average North American vehicle weighs about 3,300 pounds and contains approximately 250 pounds of composites (Brown and Gregus 2001). Composites are used for interior trim (instrument panel skin, door trim panels, airbag covers, and so forth), exterior body panels (such as fenders, hoods, and deck lids), and exterior trim and facia. In addition, 42 percent of vehicle bumpers are molded from composites (BRG Townsend 1998) and composites are used in engine compartments for a variety of applications, including protective enclosures to provide electromagnetic shielding for electrical and electronic systems.

In 2000, 29 percent of average automotive SAPV (surface area per vehicle) in the North American market was manufactured from composite materials. The use of composites for exterior body panels and trim is projected to grow at 4.5 percent per year and to exceed 36 percent of SAPV by 2005 (Gregus 2001).

Composite use in North American auto vehicles is expected to grow from 4.2 billion pounds in 2001 to 5.6 billion pounds in 2011. Of this amount, 1.7 billion pounds will be for exterior body panels and exterior trim parts (Broge 2001).

VGCF Automotive Target Markets

The first target market for VGCF is automotive coating and painting. Use of VGCF facilitates efficient electrostatic painting of external parts and panels made from composites.

> Automotive coating and painting (finishing processes) occur between body pressing, welding, and final assembly. The assembled body shell goes through up to 13 distinct steps, including electrocoating, priming, painting, clearcoating, and curing, to become a painted body ready for the assembly line. The finishing process can take about 10 hours, and there is a tendency for this process to bottleneck automotive assembly (Sawyer, n.d.). Finishing operations involve large capital costs, including investments in robotics. “An automotive painting facility can be a $400 million investment” (Banholzer and Adams 2002).
>
> Automotive painting facilities are generally set up to paint steel parts (Vasilach 2001). The standard procedure is a continuous “in-line” process of painting and finishing the entire assembled body and the method of choice is electrostatic painting, where exterior panels are given a negative charge and the paint is given a positive charge and atomized through a special nozzle. Charged exterior panels magnetically attract paint droplets with sufficient force to “pull” paint around

> corners, ensuring a smooth and even coat. This reduces overspray and fogging relative to conventional spray guns and it also provides productivity benefits by reducing color mismatch, rework, scrap loss, and downtime (Couch 2003).
>
> Painting composite surfaces can be more costly and time consuming than steel surfaces. Composite parts and panels typically cannot hold an electrical charge and require the application of conductive primers for electrostatic painting. In addition, they are often painted separately from metal body panels in an off-line process. Off-line painting is an expensive and time-consuming process that can lead to color mismatch and other quality problems and thus extensive rework. As a related problem, composite parts often cannot survive the high temperatures of paint curing ovens.
>
> VGCF's ability to add intrinsic electrical conductivity and to improve thermal conductivity makes it possible to avoid conductive primers, off-line painting, and curing-oven quality problems. This will simplify the finishing process for external automotive body panels made from composites, reduce processing time and costs, and improve color matching.
>
> By eliminating the conductive primer, VGCF utilization will also reduce harmful environmental emissions. Automotive assembly facilities generate 4.5 pounds of volatile organic compound (VOC) emissions per vehicle (General Motors 2002), and 90 percent of these emissions result from the painting and finishing processes. Eliminating the conductive primer coat removes one in five layers with significant VOC content and is projected to result in an 18 percent reduction in VOC emissions. At current levels of composite use in vehicles, VGCF utilization will eliminate 0.23 pounds of VOC emissions per vehicle. With projected increases in the use of composites, the elimination of VOC emissions will be correspondingly higher.

The second target market for VGCF is automotive electronics systems, where VGCF-reinforced composites can be used to provide shielding from electromagnetic interference (EMI).

> Spark plug wires are a significant source of EMI and lead to operating problems when engine management computers receive signals from sensors that have been altered by spark plug interference. Many other electronic devices also emit EMI that can interfere with onboard computers, systems, and sensors (RTP 2000).
>
> With the proliferation of electronic devices in cars and trucks, EMI shielding is becoming increasingly important. Computer chips regulate and monitor ABS brakes, fuel injection, oxygen sensors, navigation equipment, engine controls, and communication systems. In addition, the "next level of systems and embedded sensors will replace mechanical and hydraulic systems with electronic

> micro-systems and include drive by wire, brake by wire, collision avoidance, and other ‘smart car’ features” (Krueger 2001).
>
> To provide EMI shielding, electronic systems are enclosed in metal or composite enclosures. While composites provide design flexibility and lower weight, composite enclosures must be coated with a conductive layer to provide effective EMI shielding. The cost of conductively coated enclosures or die-cast metal enclosures is in the range of $1.00 to $1.50 per part.
>
> Compared to metal or conductively coated enclosures, intrinsic EMI shielding with stainless steel fibers dispersed in a polymer matrix can reduce part costs by 50 percent (RTP 2000). Given very low (by weight) VGCF loading requirements and cost advantages over stainless steel fiber, EMI shielding with VGCF-loaded polymer can be used to further reduce part costs. It is conservatively estimated that VGCF-loaded composites will result in cost reductions of 65 percent per part compared with metal or conductively coated enclosures.

The third target market for VGCF is automotive tires. VGCF can partially replace carbon black and silica additives and improve tire performance.

> Carbon black is an inexpensive additive to automotive tire compounds and provides electrical conductivity to prevent the buildup of static charges during tire operations. To improve tire stiffness, reduce rolling resistance, and improve fuel efficiency, silica is sometimes substituted for carbon black. However, silica has much lower conductivity and can result in the buildup of undesirable electrical charges.
>
> As a tire additive, VGCF can provide directional stiffness, reduced rolling resistance, and improved fuel efficiency while improving electrical conductivity and avoiding static charge buildup. ASI estimates that a partial (20 percent) replacement of carbon black with VGCF additives will lead to a “1.2 percent improvement in fuel economy for passenger vehicles and up to 4 percent improvement for heavy trucks” (ASI 2002a).
>
> According to a major U.S. tire manufacturer, “the technical challenges of VGCF have been largely addressed and the remaining challenges are tied to the economics of scaling up VGCF production, in the most cost effective manner, to effectively support automotive tire mass production.” (ASI 2002a).

VGCF COMPETITIVE POSITION

The carbon nanofiber market for industrial-scale applications is characterized by high prices, low availability, and customer reluctance to enter into development programs due to perceived supply risks. Currently prices range from $90 to $170 per pound and there are four major suppliers, including ASI.

ASI is the low-cost producer in this market and expects to reach further, substantial economies of scale. VGCF prices are projected to reach $30 per pound by 2006, $15 per pound by 2008, and to be under $5 per pound by 2010 (Hughes 2002). With VGCF electrical and thermal properties (ten times the electrical conductivity and half the coefficient of thermal expansion relative to competing carbon fibers), the VGCF cost advantage can be further leveraged by lower fiber loadings in the polymer matrix.

Based on these competitive market conditions, it is expected that VGCF will be economically viable for

- Electrostatic painting and EMI shielding applications at $30 per pound by 2006.
- Automotive tire applications at under $2 per pound by 2011.

AUTOMOTIVE INDUSTRY INITIATIVES

The automotive industry is aware of VGCF's technical and commercial potential relative to electrostatic painting and EMI shielding applications. According to the Materials and Processes Laboratory of the General Motors R&D Center, the "electrical properties of VGCF in polypropylene and VGCF in nylon composites are very attractive compared with those provided by other conventional conducting additives. Because of the low VGCF diameter, the onset of (acceptable) conductivity can be below 3 percent by volume" (Finegan and Tibbetts 2001).

Other active and probable industry initiatives to develop VGCF-reinforced composite panels, parts, and tires are listed below.

- ASI is currently working with a major compounder of polymer resins and a second-tier supplier to automotive OEMs to evaluate VGCF as a possible additive to provide conductivity to composite automotive panels for electrostatic painting. Based on discussions with automotive executives, the probability of VGCF-filled composites being used in a North American assembly plant by 2006 is estimated at 70 percent.
- Discussions with a major automotive electrical supplier indicate that, while there is not yet an active development program for incorporating VGCF into plastic enclosures for EMI shielding, this company and its competitors are "actively aware" of VGCF and consider it to be a promising material for "potentially cheaper, better EMI shielding." Once prices begin to drop, as projected by ASI, plastic enclosures with conductive coating or metal enclosures can be replaced with VGCF-filled composite enclosures through "running changes" within a timeframe of less than 12 months. It is expected that design and production changes will not be platform dependent. The probability of VGCF-filled composites used for EMI shielding in a North American assembly plant by 2006 is estimated at 50 percent.
- Discussion with a major U.S. tire manufacturer indicates awareness and interest in VGCF. An active product development and testing program will become likely

once a price level of $15 per pound is reached (expected in 2008). Design, development, testing, and tooling would require up to three additional years. The probability of VGCF use in North American automotive tires by 2011 is estimated at 40 percent.

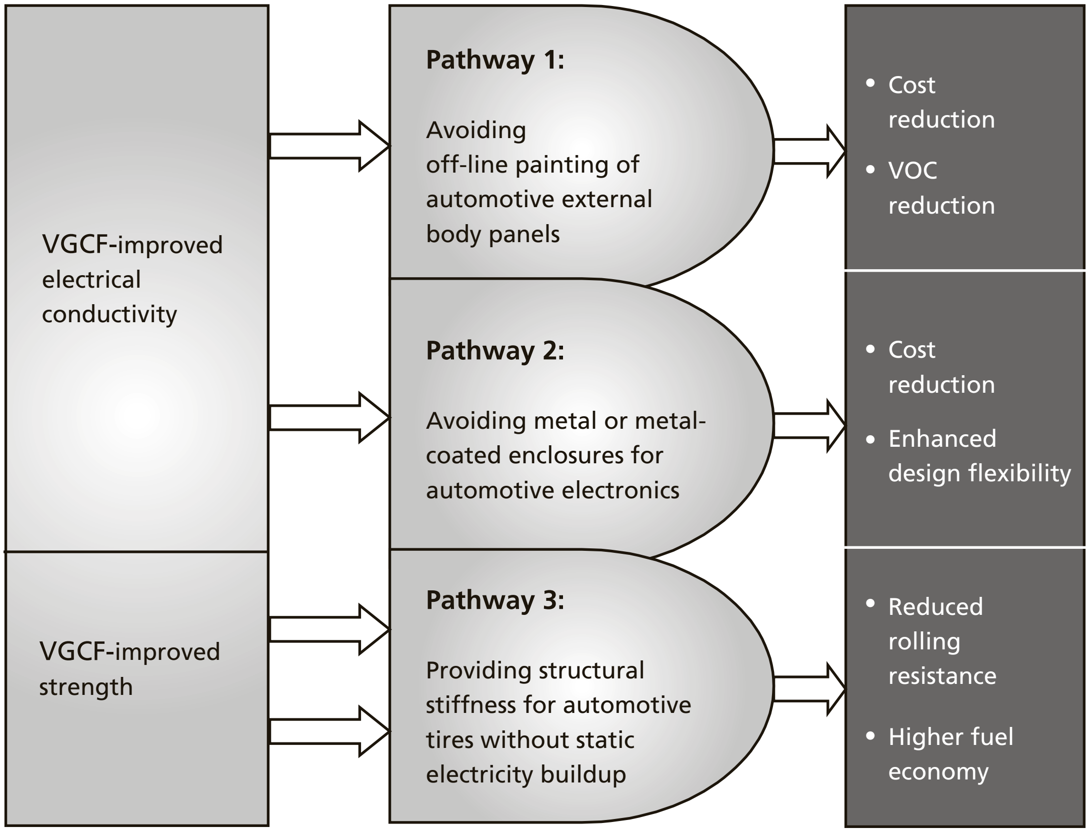
BENEFIT-TO-COST ANALYSIS

Figure 4 summarizes the use of VGCF for automotive composites leading to economic and environmental benefits along three pathways, corresponding to the three target markets.

Pathway 1: Electrostatic Painting

Exterior automotive panels are frequently made from composites. These panels are painted "off-line," which adds cost, slows down production, and results in color mismatch, requiring extensive rework. VGCF's ability to add intrinsic electrical conductivity avoids these costs, reduces production cycle times, improves paint quality, and reduces harmful VOC emissions.

Figure 4: Flow of Benefits from the ATP-Funded VGCF Project



Discussions with OEMs, first- and second-tier automotive suppliers, and automotive industry associations indicated that the timing of VGCF deployment will be significantly influenced by VGCF pricing. It is expected that VGCF will be economically viable for electrostatic painting at $30 per pound, expected to be achieved by 2006 (Couch 2003).

VGCF deployment in industrial-scale production will also be linked to automotive model years, with typical production estimated to range from 60,000 to 150,000 units per model year. For purposes of analysis, the average number of vehicles per model year deploying VGCF is conservatively estimated at 90,000.

First-year (2006) VGCF application for the electrostatic painting application will be limited to a single model year. Subsequent utilization will double for three years and then level off at one million units per year (see Table 1). Thereafter, utilization is projected to continue growing at 10 percent per year, reaching 2.8 million automotive vehicles by 2021, or 16.5 percent of U.S. production. A probability factor of 70 percent is applied to reflect the likelihood that these market projections would be reached (based on discussions with a manufacturer of automotive polymer resins).

Table 1: Market Projections for VGCF Utilization in North American Automotive Production (Numbers of Vehicles in Thousands)

	Pathway 1 VGCF in number of vehicles for electrostatic exterior painting	Pathway 2 VGCF in number of vehicles for EMI shielding	Pathway 3 VGCF in number of vehicles for improved tire performance
Probability	**70%**	**50%**	**40%**
2006	90	90	
2007	180	180	
2008	360	360	
2009	720	720	
2010	1,000	1,500	
2011	1,100	2,000	313
2012	1,210	2,200	625
2013	1,331	2,420	1,250
2014	1,464	2,662	1,875
2015	1,611	2,928	2,500
2016	1,772	3,221	2,750
2017	1,949	3,543	3,025
2018	2,144	3,897	3,328
2019	2,358	4,287	3,660
2020	2,594	4,716	4,026
2021	2,853	5,187	4,429

Base case assumptions for estimating Pathway 1 benefits are as follows:

- Average exterior painting cost for an all-steel U.S. automotive vehicle, painted in-line, is $504 per vehicle (Sawyer n.d.).
- Average exterior surface area of U.S. automotive vehicles, including panels and trim, is 137.2 square feet (Couch 2003).
- By 2005, the polymer content in the exterior surface of an average U.S. automotive vehicle will reach 40.5 square feet or 29.5 percent of exterior surface area (Brown 2000).
- Exterior painting of a car body with 29.5 percent polymer surface area is currently estimated at $606, compared to $504 for an all-steel vehicle. The cost penalty includes the cost of conductive primer, increased production time, reduced productivity, color mismatch, and related rework (BRG 1998). VGCF utilization will avoid the $102 of additional cost.
- Avoiding the application of a conductive primer for off-line painting of polymer panels and trim will reduce VOC emissions during painting and finishing operations. North American automotive assembly operations generate 4.5 pounds of VOC emissions per vehicle and 90 percent of these emissions result from painting and finishing processes (General Motors 2002). The conductive primer coating for off-line painting is one in five layers with significant VOC content. Eliminating the primer coat is projected to result in 0.23 pounds of avoided VOC emissions per vehicle.

For a step-out scenario, exterior surface polymer content is assumed to increase 10 percent over the base case to 44.6 square feet per vehicle, or 32.6 percent of exterior surface area. The cost penalty of off-line painting for the increased surface area is $113 over an all-steel exterior vehicle, compared with $102 for the base case. VGCF utilization will avoid the $113 additional cost.

Pathway 2: Electromagnetic Interference (EMI) Shielding

EMI is important for safe and reliable automotive vehicle operations and is now provided by conductive enclosures made from metal or metal-coated parts. VGCF's intrinsic conductivity eliminates the need for metal parts or metallic coating and leads to cost savings.

Discussions with OEMs, first- and second-tier automotive suppliers, and automotive industry associations indicated that the timing of VGCF deployment for EMI and required VGCF price reduction are the same as for electrostatic painting (Couch 2003).

As for electrostatic painting, VGCF use for EMI shielding will be linked to automotive model years, with typical production ranging from 60,000 to 150,000 units per model year. For purposes of analysis, the average number of vehicles per model year deploying VGCF is conservatively estimated at 90,000.

First year (2006) VGCF utilization will be limited to a single model year. Subsequent utilization will double for four years and then level off at 2.0 million units per year (see Table 1). Thereafter, utilization is projected to continue growing at 10 percent per year, reaching 5.2 million automotive vehicles by 2021, or 30.5 percent of U.S. production. A probability factor of 50 percent is applied (based on discussion with an automotive electrical parts supplier).

Base case assumptions are as follows:

- By 2006, the typical U.S. vehicle will have 26 electronic systems, including automotive steering and control, safety, and communications (based on discussions with a first-tier electronics supplier).
- Each electronic system needs to be effectively shielded within metal enclosures or metal-coated plastic enclosures. The cost of these enclosures is approximately $1 per enclosure (based on discussions with a first-tier supplier).
- Replacing metal enclosures or metal-coated plastic enclosures with VGCF-reinforced composite enclosures results in a 65 percent savings, or $16.9 per vehicle.

For a step-out scenario, replacing metal enclosures or metal-coated plastic enclosures with VGCF composites is expected to lead to 69 percent savings, or $17.9 per vehicle.

Pathway 3: VGCF-Reinforced Tires

In automotive tires, carbon black is used as a tire additive to provide conductivity and eliminate the buildup of static electricity. To improve tire stiffness and to reduce rolling resistance, silica additives are sometimes used to partially replace carbon black additives. Since silica has lower conductivity, its use can lead to the buildup of static electricity.

Using VGCF as an alternative to silica can provide both stiffness and conductivity, leading to reduced rolling resistance and improved fuel economy without a buildup of static electricity.

Discussions with automotive OEMs, first-tier automotive suppliers, and automotive industry associations indicate that VGCF as a automotive tire additive will be economically viable at $2 per pound, expected to be achieved by 2011.

First-year (2011) VGCF utilization will be limited to daily lot sizes of 5,000 tires or 1.25 million tires per year, corresponding to 312,500 vehicles (see Table 1). If this application is successfully developed, lot sizes will double for two subsequent years and then increase by 625,000 units per year for the next two years. Thereafter, VGCF use in automotive tires will increase at 10 percent per year, corresponding to 4.4

million vehicles by 2021. Since there is currently no active development program, the probability of successful deployment is estimated at 40 percent.

Given a probability of deployment under 50 percent, VGCF use for automotive tire applications was not included in the base case analysis. For a step-out scenario, it is assumed that VGCF additives will replace 20 percent of carbon black additives for the above number of vehicles. This will result in reduced tire rolling resistance and improved fuel economy by 1.2 percent (ASI 2002a). For passenger cars with 20.7 miles per gallon CAFE standards, average annual mileage of 12,000 miles, and motor gasoline prices at $1.5 per gallon, the 1.2 percent improvement will result in annual per vehicle savings of 6.9 gallons and $10.4.

Timeframe of Analysis

Timeframes for base case and step-out scenario analyses are 15 years for electrostatic painting and EMI shielding applications and 10 years for the automotive tire applications. These timeframes are reasonable in light of anticipated aggressive VGCF price reductions from $30 dollars per pound in 2006 to $2 in 2011.

ATP and Industry Partner Investments

During the 1995 to 2000 period, ATP invested $2.2 million and its industry partners (ASI, General Motors Corporation, and Goodyear Tire & Rubber) invested $3.2 million in the VGCF technology.

The ATP investment was used to support ASI (an independent small U.S. company that was the technology innovator) and its engineering and technical subcontractors. General Motors Corporation and Goodyear Tire & Rubber Company provided sufficient funding to fully support their own project-related activities including technical development, testing, and the prototyping of automotive parts with VGCF additives. General Motors and Goodyear did not receive ATP funds.

For purposes of cash flow analysis, the ATP investment was normalized to 2003 dollars and assumed to occur in 1998, the midpoint of the five-year investment period. Given the study's focus on measuring benefits to industry users and the nation broadly (that is, public benefits), industry's investment costs relative to the ATP (public) investment were not included in the analysis.

Base Case Economic Analysis

The expected values of cash flow benefits (adjusted for probabilities of VGCF deployment in industrial-scale production) for electrostatic painting and EMI shielding applications are indicated in Table 2. The net present value (NPV) from ATP's investment is $552 million for the two pathways combined. Over 80 percent of NPV

Table 2: Cash Flows and Performance Metrics from VGCF Use in the Automotive Industry ($ Millions, in 2003 Dollars): Base Case

	Electrostatic painting	EMI shielding	Tire applications	Total cash flows
1998	–1.26	–1.25	Included in the analysis of the step-out scenario but not the base case analysis.	–2.51
2006	6.43	0.76		7.19
2007	12.85	1.52		14.37
2008	25.70	3.04		28.75
2009	51.41	6.08		57.49
2010	71.40	12.68		84.08
2011	78.54	16.90		95.44
2012	86.39	18.59		104.98
2013	95.03	20.45		115.48
2014	104.54	22.49		127.03
2015	114.99	24.74		139.73
2016	126.49	27.22		153.71
2017	139.14	29.94		169.08
2018	153.05	32.93		185.99
2019	168.36	36.23		204.58
2020	185.19	39.85		225.04
2021	203.71	43.83		247.55
Net present value	$459 million	$92 million		$552 million
Benefit-to-cost ratio				221:1
Internal rate of return				57%

Note 1: A 1998 base year and an OMB-mandated 7 percent discount rate were used for analysis. Performance metrics were computed from time series assuming ATP investment in 1998 (project midpoint) and prospective cash flow benefits from 2006 to 2021.

Note 2: The NPV calculation for each benefit component assumes investment costs divide equally across benefit components.

derives from VGCF utilization for electrostatic painting. The public benefit is $221 for every dollar invested and the internal rate of return (IRR) is estimated at 57 percent.

Step-Out Scenario Economic Analysis

Table 3 indicates step-out scenario returns on ATP's investment in VGCF technology. The net present value of ATP's investment is estimated at $634 million.

Over 80 percent of the NPV derives from VGCF utilization for electrostatic painting, 15 percent derives from EMI shielding, and four percent from automotive tire applications. The public benefit is $254 for every dollar invested and the internal rate of return is estimated to be 58 percent.

Table 3: Performance Metrics from VGCF Use in the Automotive Industry ($ Millions, in 2003 Dollars): Step-Out Scenario

	Electrostatic painting	EMI shielding	Tire applications	Total
Net present value	$508 million	$94 million	$26 million	$634 million
Benefit-to-cost ratio				254:1
Internal rate of return				58%

Note 1: A 1998 base year and an OMB-mandated 7 percent discount rate were used for analysis. Performance metrics were computed from time series assuming ATP investment in 1998 (project midpoint) and prospective cash flow benefits from 2006 to 2021.

Note 2: The NPV calculation for each benefit component assumes investment costs divide equally across benefit components.

Private Benefits to ATP Industry Partners

Continued motivation to refine and commercially market the ATP-funded technology is a precondition for industrial-scale use. Only with industrial-scale use will the general public come to enjoy the economic, quality, and environmental benefits of VGCF technology.

ASI's annual sales revenues from VGCF products, expressed in 2003 dollars, are expected to reach $35 million by 2007 and $80 million by 2010. These revenues will provide the motivation for ASI, its manufacturing partners, and licensees to continue lowering VGCF costs and actively market VGCF products.

Joint venture members will also realize substantial economic benefits from reduced manufacturing and component parts costs. These benefits will be available to the entire automotive industry, not only to JV participants.

QUALITATIVE BENEFITS

Incorporating VGCF into external automotive body panels will provide sufficient electrical conductivity for painting the entire vehicle (both metal and composite panels) in one combined electrostatic process, avoiding the additional layer of conductive primer for composite materials. Other benefits include the following:

- The elimination of one of five primer layers will reduce harmful VOC emissions and associated environmental compliance costs. Eliminating the separate off-line painting of composite panels will also reduce paint mismatch and other paint quality problems.
- Incorporating VGCF into automotive body panels will improve the thermal conductivity of VGCF-reinforced composites, increase resistance to thermal warping, and improve dimensional stability. VGCF-reinforced composites also have

improved flame retardancy, increasing safety in case of road accidents or electrical and mechanical malfunctioning.
- Incorporating VGCF into protective enclosures to shield automotive electronic systems from EMI (electromagnetic interference) will facilitate the replacement of metal enclosures with composite enclosures, thereby providing significant design flexibility in the engine compartment and other highly constrained internal spaces.
- Incorporating VGCF into automotive tires will provide sufficient electrical conductivity to discharge the buildup of static electricity and reduce the likelihood of electrical shock during vehicle operations and fueling.

* * * * * *

At the time of the ATP funding in 1995, ASI was a new company with 10 employees, including 4 engineers and scientists, and without the financial resources to undertake a high-risk VGCF research and development program. By 2003, ASI had grown to 26 full time employees, including 10 engineers and scientists. According to ASI management, the VGCF project would not have been undertaken without the ATP cost share and the associated qualitative and qualitative benefits would not have been possible.

4. Composite Production Riser Case Study

In offshore petroleum production, steel risers (tubing) are used to bring oil from the seabed to floating production platforms. In deepwater applications (3,000 to 5,000 feet), heavy steel risers require expensive tensioning and buoyancy systems. For ultra-deep operations in water depths of 5,000 to 13,000 feet, the size and weight of conventional steel risers becomes cost prohibitive, inhibiting the exploitation of substantial offshore domestic oil reserves (Silverman 1999).

The use of lighter-weight composite production risers (CPRs) will reduce platform weight together with floatation and tensioning requirements and overcome one of the greatest limiting factors in offshore oil production, that is, increasing riser loads that floating platforms have to support in increasing water depths. However, the cost of CPRs has been significantly higher than steel risers because prior manufacturing techniques have not been optimized and production levels have not achieved economies of scale. When CPR cost disadvantages are overcome, platform lifecycle costs will be reduced, and additional crude oil production from deepwater Gulf of Mexico petroleum reserves will be realized (Johnson 2000).

This section describes the results of a case study of ATP-funded CPR technology. It presents project history and key technical accomplishments, describes commercial and market applications in the offshore petroleum industry, and presents the results of a quantitative economic benefit-to-cost analysis together with a brief discussion of qualitative benefits.

PROJECT HISTORY

The development of fiberglass-reinforced composites for petroleum production started with the efforts of Koch Exploration & Development Company in the 1950s to facilitate crude oil production from highly corrosive wells. The effort was continued by Institut Français du Pétrole (IFP) and Aerospatiale, resulting in proof of concept as well as some development and testing of glass- and carbon-reinforced rigid composite tubes for offshore applications. IFP subsequently attempted to form joint ventures with major petroleum exploration and development companies to complete technical development, to develop standard product specifications, to define design and manufacturing practices, and to conduct reliability testing. However, these joint venture efforts were "shelved due to a lack of sustained participation by the major petroleum companies" (DeLuca 2000).

Lincoln Composites (formerly a division of Brunswick Corporation) learned from IFP's setbacks and recognized the significant commercial and energy independence benefits of CPRs for the offshore petroleum industry. In 1994, Lincoln Composites formed a joint venture with Shell Oil, Amoco, and Conoco corporations, and with technical and engineering service providers Brown & Root, Hydril, and the University of Houston. The joint venture submitted a proposal to ATP to cost share remaining technical development tasks and to facilitate industrial-scale testing and prototyping of CPRs.

In 1995, ATP selected the proposed high-risk project. In addition to cost sharing the high-risk technology development effort, ATP involvement also provided the additional important benefit of "keeping the industry collaborators engaged and making it possible to jointly develop product performance specifications for composite risers" (Johnson 1999).

The project was successfully completed in 2000 and resulted in technical advances, including the development of CPR design and performance criteria, development of high-quality, cost-effective manufacturing processes, and effectively addressing performance monitoring and reliability issues in deepwater saline environments.

Technical and cost efficiency benefits from the CPR project would not have been realized without ATP funding and without ATP's role in motivating industry collaborators to remain "engaged in the development of appropriate CPR product specifications" (Johnson 2003).

Subsequent to commencing the ATP-funded project, Lincoln Composites became independent briefly. It was recently acquired (in 2002) by General Dynamics Corporation. The Lincoln Composites Division of General Dynamics now consists of 250 employees, including 60 engineers. It has potential access to General Dynamics corporate resources to support the completion of the remaining technical tasks and to effectively market and deploy the CPR technology for deepwater offshore oil production in the Gulf of Mexico.

HOW DOES IT WORK?

Composite production risers are hybrid composite structures, consisting of continuous carbon fibers and electrical-grade fiberglass (E-glass) in an epoxy matrix. CPR strength and stiffness are provided by the carbon and glass fibers, with highest strength in the direction of the fibers (Johnson 1999).

As DeLuca (2000) explains:

> Composite risers are designed with fiber orientation and layer thickness tailored to resist the actual load configuration. In offshore riser applications, the tension loads are carried by fibers that are axially oriented or helically filament wound at low angles to the tube axis and pressure loads are resisted by circumferentially placed hoop-wound fibers.

The primary success of composites in a particular application is due to the ability to tailor the composite's superior strength and fatigue properties in a particular direction. Directional tailoring minimizes the amount of material (and weight) in the non-loaded direction. In contrast to composite structures, directional tailoring is not possible in homogenous materials such as steel and titanium (Silverman 1999).

CPR Manufacturing Process

CPRs are fabricated with a laminated composite tube body and a metal-to-composite interface (MCI). The MCI transfers loads between the composite tube body and the metal end fitting. Metal fittings are used for joining risers in a string.

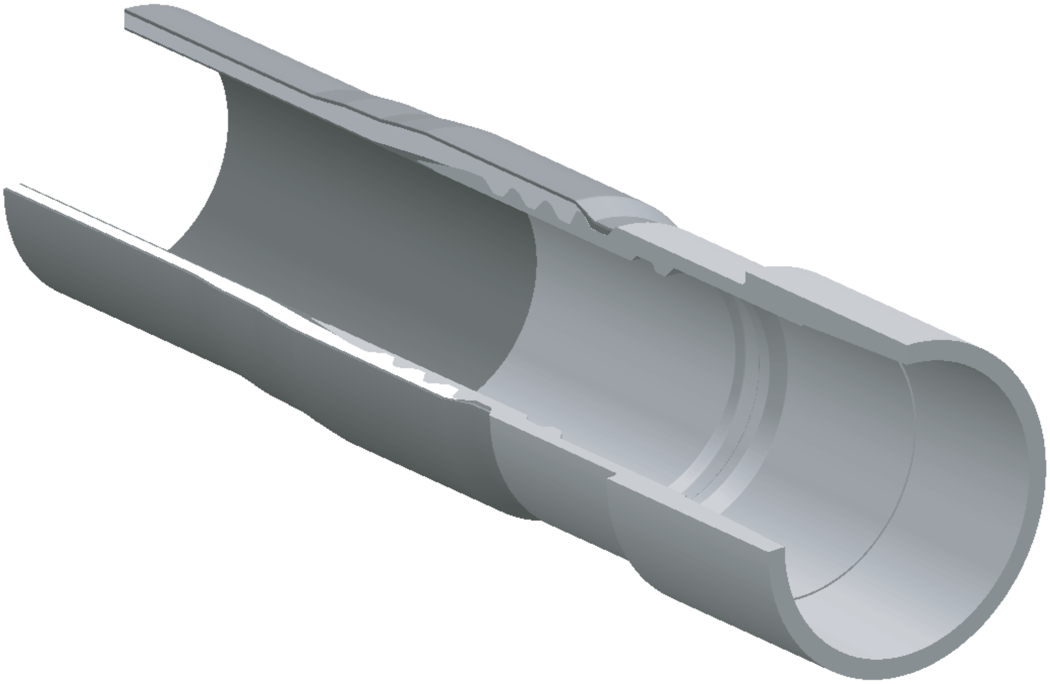
The first step in CPR production involves machining metal end fittings from steel tubing for a "geometric trap" type of MCI design. End fittings are installed on a mandrel and uncured hydrogen resistant rubber (HNBR) is wound onto the mandrel to provide the inner liner of the CPR. Low-angle helically wound carbon fibers are wound over the HNBR and the metal end fittings, reversed through a low-profile dome, and secured between the trap geometry and the dome. Circumferentially oriented E-glass fibers are then hoop-wound to resist pressure loads, and both carbon and E-glass fibers are impregnated with epoxy resin during the winding process. The methods of impregnation and fiber tensioning are proprietary.

Next, "the mandrel wound assembly is removed from the winding machine and placed in a rotating cure dolly. After a curing process, the assembly is replaced on the winding machine, where another layer of HNBR is spiral wrapped on the outside of the assembly. Over the HNBR is wound a layer of glass hoops and a glass helical layer which compact the HNBR elastomer and provide extra abrasion protection." This is followed by a final curing process (Johnson 1999). Figure 5 provides a cutaway view of the CPR and MCI.

TECHNICAL ACCOMPLISHMENTS

A viable CPR structure has to achieve functional specifications, including resisting internal and external pressures, fluid containment, structural support, and resisting chemical corrosion and other environmental attack. It must also be cost competitive with steel risers. Relative to these functional specifications, the ATP-funded project faced technical challenges in the following areas:

Figure 5: **Wound-in Metallic End Fittings with Traplock Composite-to-Metal Interface**



Source: Johnson 2003.

- Optimized CPR design criteria had to be developed to avoid both overdesign (leading to unnecessary high cost) and underdesign (leading to system deficiency).
- A high-quality manufacturing process was needed that could be cost-effectively operated on a fully industrial scale.
- Effective performance monitoring was needed of complex stresses and strains inside CPR specimens, as was detection of local failures inside CPR specimens.
- CPR reliability was a primary industry concern, particularly in regard to the possible degradation of CPR material properties, strength, and fatigue life, due to to the possibility of localized microscopic failures inside the composite structure.

To address these technical challenges, CPR tubes and joints (metal-to-composite interfaces) were successfully designed, fabricated, and tested. Performance variables as well as static and cyclic fatigue curves were generated, showing compliance with initial functional specifications and performance criteria. Tubes and joints were shown to have adequate safety margins, and the CPR design methodology was shown to have achieved the cost, weight, and performance goals of the project. Most significantly, the test results for full-scale joint performance were shown to be nearly identical to test results for scaled-down prototypes.

In specific terms, the ATP-funded project resulted in the following technical accomplishments:

- CPR functional and performance requirements were developed for structural, operational, and environmental conditions for a range of loading scenarios (from 300 years of steady loading to 30 years of steady loads followed by 3 hours of 100-year hurricane loading). Also, material allowances were developed based on 0.999999 long-term reliability factors.
- An advanced design methodology was developed for CPR tube and joint failure predictions.
- A detailed design was completed for CPR tubes to (1) reduce joint fiber stresses, (2) eliminate microcracking and interlaminar failure, and (3) optimize fiber mesh structures, laminate layer thickness, and cure cycles.
- MCI joints were developed to meet required fatigue criteria, using a threaded connection adapted to the geometry of the multiple traplock configuration with wound-in metallic end fittings.
- An assessment was completed of manufacturing cost effectiveness. A survey was conducted of carbon fiber suppliers and an initial cost model developed to identify opportunities for material and labor cost reductions. It was established that cost reductions would move the CPR cost structure below the total system breakeven point with steel risers.
- Probabilistic formulations and methodologies were developed to (1) estimate CPR failure probabilities and reliability levels for longitudinal and transverse failure modes, (2) determine the long-term safety index for a CPR tube body, and (3) determine the long-term safety index for a CPR system, as a function of the number of tubes in a riser string.
- Testing was completed of 75 full-scale diameter/short-length tube specimens and 90 prototype MCI joints to empirically characterize specimen strength and fatigue performance.
- Advance design technology was validated for CPR detail design, showing a high correlation of the above test results with performance projections from the advanced design methodology.
- The development of a CPR quality assurance plan was completed.
- An integrated methodology was developed to facilitate CPR sea trials or in-situ tests. This methodology will facilitate CPR qualification testing required for widespread future industry acceptance of composite riser technologies for deepwater offshore oil production.
- The fabrication of two full-length CPR specimens and the testing of specimens to factory acceptance levels were completed. Also, CPR tooling was designed and fabricated to be used once full commercialization is achieved.

These accomplishments would not have been achieved without ATP cost sharing and without ATP facilitation of the broad-based industry joint venture.

OFFSHORE OIL PRODUCTION TRENDS

Lincoln Composites' current CPR product development and marketing efforts are focused on offshore petroleum production in the Gulf of Mexico, and in particular on the affordable exploitation of deep and ultra-deep petroleum reserves.

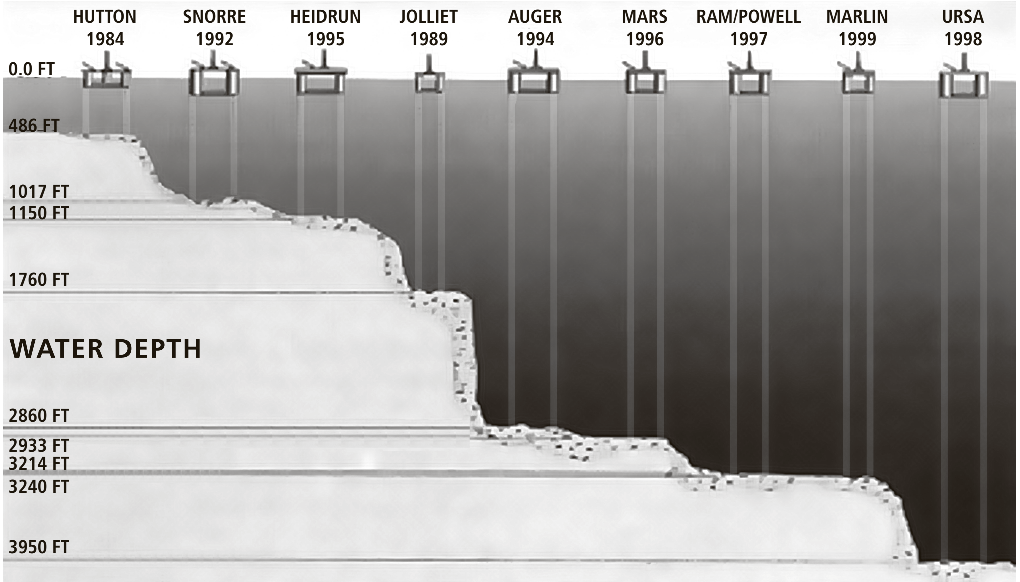
Offshore Industry Trends

In 2001, U.S. crude oil production was 2,118 million barrels and net imports reached 3,398 million barrels (U.S. Energy Information Administration 2003), indicating a 61.6 percent energy dependence on imported petroleum.

The Gulf of Mexico outer continental shelf (OCS) is a major source of petroleum, accounting for 30 percent of domestic crude production (Readinger 2003). Gulf of Mexico reserves are estimated at 32 billion boe (barrels of oil equivalent), of which 15 billion boe have been confirmed. Gulf of Mexico annual production reached 522 million barrels in 2000 and is further expected to grow.

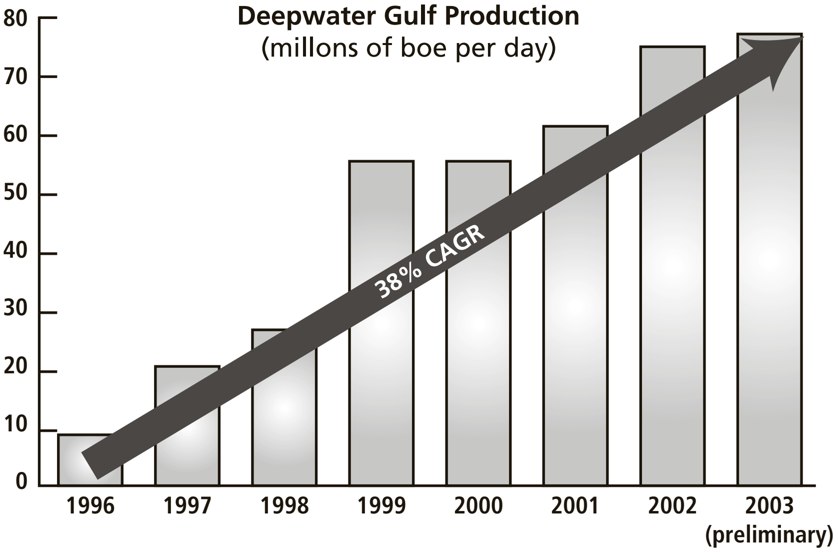
1984 to 1998 trends in the Gulf of Mexico reflect production increasingly from deepwater reserves (Figure 6). Year 2000 deepwater production was 271 million barrels (MMS 2001).

Figure 6: Recent History of Deepwater Developments



Source: U.S. Minerals Management Service, Gulf of Mexico Region, Offshore Information, March 1999.

Figure 7: **Deepwater Production Rates and Compound Annual Growth Rate (CAGR) of Deepwater Production in the Gulf of Mexico**



Source: K&M Technology 2003.

Currently there are over 7,400 active leases in the Gulf of Mexico, 53 percent in deep water. Industry has plans for 97 deepwater production projects and 575 deepwater exploration projects utilizing these leases (Lytal 2000). Figure 7 summarizes Gulf of Mexico deepwater production trends, showing a 38 percent compound annual growth rate (CAGR).

The average size of deepwater discoveries is many times larger than shallow water fields. In active deepwater projects, fields contribute more than 73 million boe, or 12 times the average production in shallow water fields (Baud 2002).

A recent U.S. Minerals Management Service (MMS) release stated that fourteen new Gulf of Mexico deepwater projects began production during 2002 and twelve deepwater discoveries were made, three in 8,000 feet or greater water depth (MMS 2003).

New technologies such as the ATP-funded CPR technology will be required to exploit deepwater discoveries, particularly discoveries in 6,000 feet of water or greater.

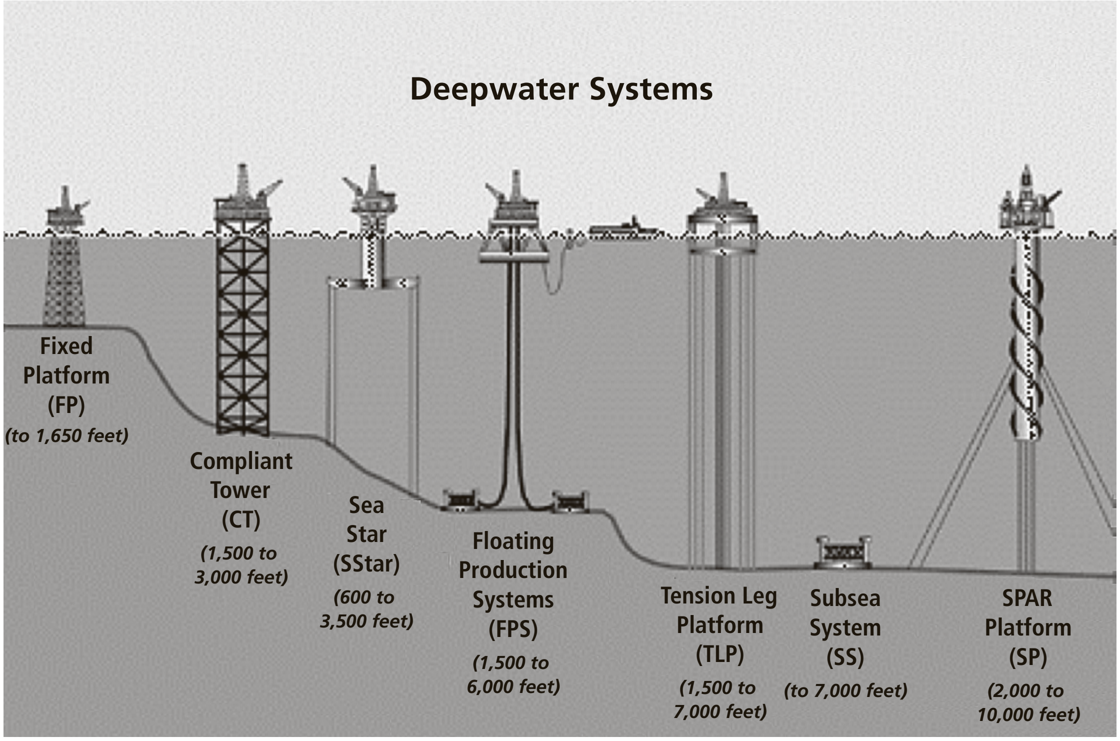
Offshore Industry Forecasts

Figure 8 identifies seven common types of production platforms suitable for Gulf of Mexico operations at various water depths and reservoir sizes.

A fixed platform (FP) is supported by piles driven into the seabed and is economically feasible for water depths up to 1,650 feet. The compliant tower (CT) is a narrow, flexible tower that can operate in water depths of up to 3,000 feet. The Sea Star or floating "mini tension leg" structure is suitable for smaller reservoirs and operates in water depths up to 3,500 feet. The floating production system (FPS) is anchored in place and can be dynamically positioned using rotating trusters. Connected to wellheads on the ocean floor this system can be used in water depths up to 6,000 feet. Subsea systems (SS), connected to nearby platforms, can operate at great depths. However, the drilling and completion cost penalties of subsea systems make these arrangements less preferable than floating structures.

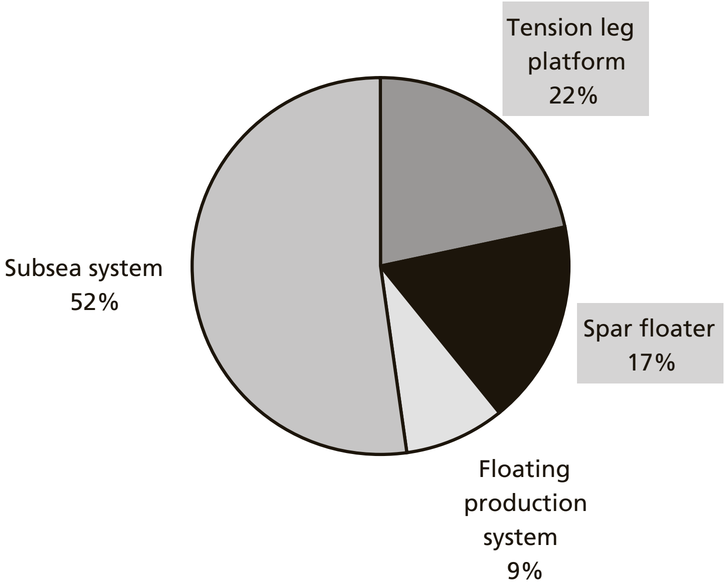
The ATP-funded CPR technology is expected to be most appropriate for TLPs (tension leg platforms) and for SPAR platforms, which are vertical floating cylinders (Johnson 2003). TLPs and SPAR platforms consist of floating structures held in place by vertical tendons connected to the sea floor. As indicated in Figure 9, TLPs and

Figure 8: **Seven Types of Offshore Oil Production Platforms**



Source: U.S. Minerals Management Service, Gulf of Mexico Region, Offshore Information, October 1999.

Figure 9: **Market Share of Tension Leg and SPAR Platforms in the Gulf of Mexico**



Source: Lincoln Composites 2003.

SPAR platforms account for 39 percent of announced Gulf of Mexico deepwater projects. It is expected that the availability of the CPR technology will significantly expand the operating reach of TLPs and SPAR platforms beyond 6,000 feet of water depth.

Worldwide, it is estimated that "there will be up to 22 deepwater projects each year during the next decade" (Hillegeist 2001). Of these, 10 are expected to be located in the Gulf of Mexico with 39 percent, or four projects, likely to use TLP or SPAR platforms. Of these four projects each year, one is expected to be located in excess of 6,000 feet water depth. Each year, this one project will be a strong candidate for the ATP-funded CPR technology (Johnson 2003), corresponding to the second pathway in the following section.

PATHWAYS FOR CPR DEPLOYMENT

In discussions with Lincoln Composites and major oil company representatives, three pathways were identified for the commercial deployment of the ATP-funded CPR technology.

- Pathway 1: On platforms originally designed for steel risers, CPR will be used to make connections to the remaining new wells. The reduced CPR weight will increase the number of risers that platforms can support, increase payload capacities, and increase production from lateral reserves.

- Pathway 2: On new platforms designed for CPR, lighter-weight CPRs will make it possible to reach large new deepwater petroleum reserves economically.
- Pathway 3: To facilitate the redeployment of out-of-production platforms that have gradually exhausted their underlying reservoirs, lighter-weight CPRs can replace steel pipe, making it possible to redeploy platforms in water depths two or three times their original nameplate specifications.

OFFSHORE INDUSTRY INITIATIVES

A representative of Shell Exploration & Production Technology Company stated that "the ATP-funded CPR technology is of considerable commercial interest to Shell International and is under active review for possible Gulf of Mexico deepwater deployment." In the absence of cost-effective technologies for ultra-deep production (6,000 feet water depths), Shell could lose its investment in several leases ready to expire within the next few years.

Dr. Mamdouh Salama of ConocoPhillips said that the company intends to install 10 CPR risers in its Magnolia TLP, currently under construction. He indicated a "95 percent certainty that CPR technology, developed with ATP-funding, will be approved by the Minerals Management Service and will be used in the Magnolia TLP." Dr. Salama also indicated that ConocoPhillips recently gave serious consideration to the redeployment of the Joliet TLP in ultra deepwater (per Pathway 3). While lighter-weight CPR was not yet available to facilitate redeployment at the time of that decision, "Joliet remains available for future redeployment, which could become economically attractive with CPR risers" (Salama 2003).

PLATFORM PROJECTIONS WITH COMPOSITE RISERS

Based on discussions with Lincoln Composites, major oil company representatives, regulators, and other industry participants, the benefits of composite production risers are generally recognized by major petroleum exploration and production companies. As long as CPR is cost competitive, these benefits will include reduced weight per foot of production riser, lower system lifecycle costs, ability to reach greater water depths, and improved protection from seawater temperatures and corrosion.

Composite production riser deployment is projected to commence in 2004 and proceed as indicated in Table 4. The probability of reaching these projections is estimated to be 75 percent.

Given the presence of two competing initiatives to develop composite production risers, it is conservatively assumed that the ATP-funded CPR technology will capture a one-third share of projected CPR deployment.

Table 4: Projected Gulf of Mexico Tension Leg and SPAR Platforms with Composite Production Risers

Year	Pathway 1 Existing TLP platforms with CPR for remaining wells	Pathway 2 New TLP and SPAR platforms designed for CPR	Pathway 3 Redeployed TLP platforms with CPR for all wells
2003			
2004	Existing TLP		
2005	Existing TLP		
2006	Existing TLP		
2007		New TLP	Redeployed TLP
2008		New TLP	
2009		New SPAR	Redeployed TLP
2010		New TLP	
2011		New TLP	Redeployed TLP
2012		New SPAR	
2013		New TLP	Redeployed TLP
2014		New TLP	
2015		New SPAR	Redeployed TLP
2016		New TLP	
2017		New TLP	Redeployed TLP
2018		New SPAR	
2019		New TLP	Redeployed TLP
2020		New TLP	
2021		New SPAR	Redeployed TLP
2022			
2023			Redeployed TLP

BENEFIT-TO-COST ANALYSIS

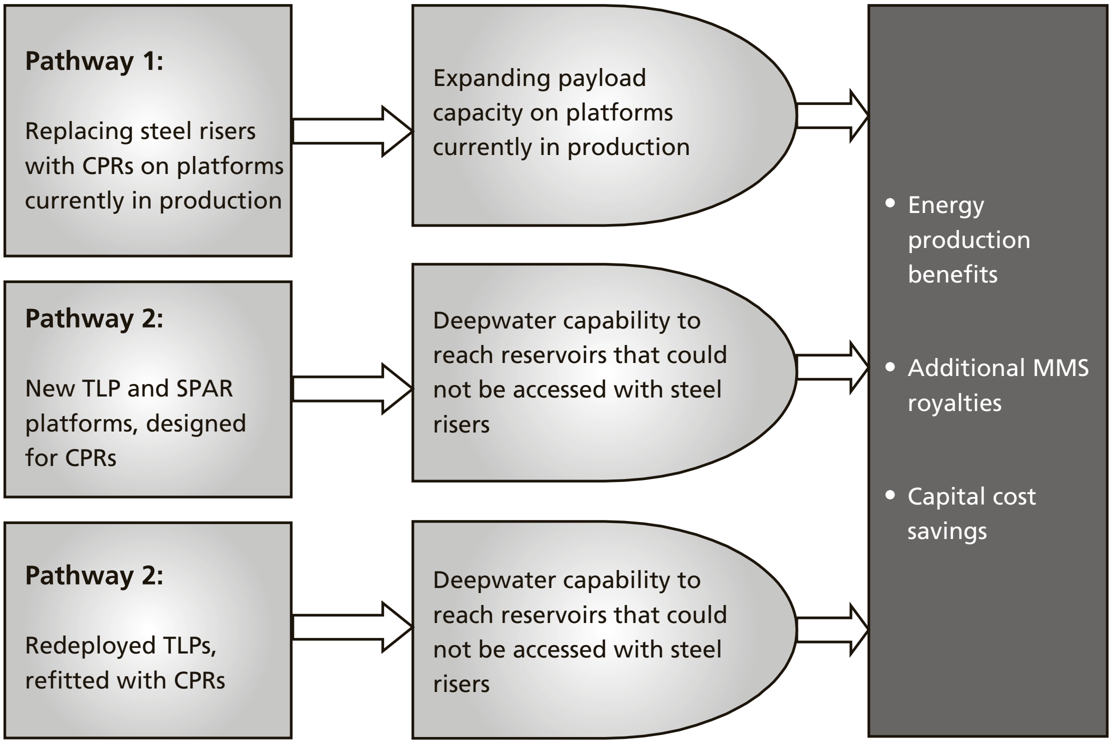
CPR utilization will result in significant economic and energy production benefits by facilitating affordable crude oil production from Gulf of Mexico reserves at increasing water depths along the three pathways described above. Figure 10 illustrates the flow of benefits.

Pathway 1: CPR Deployment on Currently Operating Tension Leg Platforms

On operating TLPs originally designed with steel risers, completed production wells will remain connected to steel risers. Additional production wells brought online after 2004 will be completed with CPRs.

Due to the weight advantage of composites, for every three wells completed with CPR, the platform's payload capacity will be increased to support one additional

Figure 10: Flow of Benefits from the ATP-Funded Composite Production Riser Technology



composite riser to be connected to an additional production well. While the additional production well is not part of the TLPs original design, it is assumed that the size and configuration of the reservoir will permit the connection of additional wells and that replacing three steel risers with four composite risers will thereby increase production by 33 percent.

As indicated in Table 5, deployment of four CPRs on one TLP each year for four consecutive years will increase the annual production of three platforms by 12 risers. This is the estimated Gulf of Mexico market segment for CPR utilization, for Pathway 1. It is expected that the ATP-funded CPR technology will capture a one-third share of this market segment, or four CPR riser columns, each in excess of 6,000 feet in length.

The base case assumptions for estimating benefits along Pathway 1 include additional crude oil production and associated royalties for the U.S. Minerals Management Service (MMS), which would not have taken place without lighter-weight CPRs increasing platform payload capacity. Positing that each additional well produces 10,000 bpd (barrels per day), or 3.5 million barrels per year, and that crude sells at

Table 5: Expected Number of Production Wells Completed with CPR on Existing Tension Leg Platforms

	CPRs replacing steel risers			Additional CPRs			Access to additional wells via CPR use
	TLP1	TLP2	TLP3	TLP1	TLP2	TLP3	
2003							
2004	3			1			1
2005	3	3		1	1		2
2006	3	3	3	1	1	1	3
2007	3	3	3	1	1	1	3
2008		3	3		1	1	2
2009			3			1	1
Total							12

$20 per bbl (barrel), additional MMS royalty payments, at 12.5 percent of crude selling price, are $2.50 per bbl of raised crude. According to industry experience for Gulf of Mexico operations, each production well is expected to produce crude oil at the above rate for 10 years (Johnson 2003).

As this pathway represents a limited transitional stage toward the deployment of CPR in Gulf of Mexico platforms, only a base case analysis is conducted for Pathway 1.

Pathway 2: CPR Deployment on New Platforms Designed for CPR

By 2005, a major oil company will start the design and construction of new TLPs and SPAR platforms with lighter CPR risers. Assuming a 24-month design and construction cycle, the first new TLP will come on line in 2007.

As indicated in Table 6, the market for new platforms designed with composite production risers is projected to consist of 10 new TLP and 5 new SPAR platforms brought online in the Gulf of Mexico over the 2007 to 2021 period. Each TLP has 30 wells, of which 25 are used for production and 5 for reinjection. Each SPAR platform has 14 wells, of which 9 are used for production and 5 for reinjection. Over the 2007 to 2026 period, 370 wells will be completed on TLP and SPAR platforms. Of these, 75 wells will be used for reinjection and 295 for petroleum production.

This is the estimated market segment for Gulf of Mexico CPR utilization for Pathway 2. It is expected that the ATP-funded CPR technology will capture a one-third share of this market segment or 122 CPR columns, each in excess of 6,000 feet in length.

The assumptions for base case analysis include the following:

- Continued utilization of ATP-funded CPR in designing new TLP and SPAR platforms for a period of 20 years. This is a reasonable assumption in light of very long duration development and test cycles for new offshore riser designs.

Table 6: **Expected Number of Wells Completed with Composite Production Risers on New TLP and SPAR Platforms**

	TLP	TLP	SPR	TLP	TLP	SPR	TLP	TLP	SPR	TLP	TLP	SPR	TLP	TLP	SPR
2003															
2004															
2005															
2006															
2007	3														
2008	3	3													
2009	5	3	2												
2010	5	5	2	3											
2011	3	5	2	3	3										
2012	4	3	3	5	3	2									
2013	2	4		5	5	2	3								
2014		2		3	5	2	3	3							
2015				4	3	3	5	3	2						
2016				2	4		5	5	2	3					
2017					2		3	5	2	3	3				
2018							4	3	3	5	3	2			
2019							2	4		5	5	2	3		
2020								2		3	5	2	3	3	
2021										4	3	3	5	3	2
2022										2	4		5	5	2
2023											2		3	5	2
2024													4	3	3
2025													2	4	
2026														2	
Total	25	25	9	25	25	9	25	25	9	25	25	9	25	25	9

TLPs are tension leg platforms for offshore oil production.
SPARs are stationary floating platform for offshore oil production.

Composite production risers have been under development since the 1950s and are just now making their entry as commercially viable products.

- $1.05 million capital cost savings per production well relative to the cost of steel risers (Fischer 1995).
- Additional production of 10,000 bpd, or 3.5 million barrels per well per year, selling at $20 per bbl, each generating additional MMS royalty payments at 12.5 percent of crude selling price of $2.50 per bbl of raised crude. This is consistent with industry experience for Gulf of Mexico operations, where each production well is projected to produce crude oil at the above rate for an average of 10 years (Johnson 2003).

For a step-out scenario, capital cost savings are increased by 10 percent to $1.15 million per production well relative to steel risers, up from $1.10 in the base case. The 10 percent increase in capital cost savings is within accepted industry projections (Fischer 1995).

Pathway 3: CPR Use for Redeploying Out-of-Production TLP Platforms

Operational TLPs that gradually exhaust their underlying reservoirs can be moved to new, deeper reservoirs and refitted with lighter-weight risers to reach production wells in water depths twice or three times the original nameplate. This process is enabled by the availability of affordable and lighter-weight composite risers.

It is assumed that one operating TLP in the Gulf of Mexico will reach the end of its reservoir's economic life in 2007. The TLP will be disconnected from the current reservoir, relocated over a much deeper reservoir, and refitted with CPRs. For each relocation, the topside capital investment for hull and processing facilities is largely avoided. It is assumed this process is repeated every second year until 2023, by which time nine TLPs will have been redeployed in deeper water. The ATP-funded CPR technology is expected to capture one third of this market segment.

The base case analysis assumes that TLP redeployment in deeper water will result in $325 million capital cost savings, or 25 percent of a $1.3 billion new TLP. For the step-out scenario, capital cost savings are estimated at $390 million, or 30 percent of a $1.3 billion new TLP. The step-out scenario assumption remains a conservative estimate as capital costs of new platform hull and processing facility can be as much as 50 percent of total TLP capital costs (Lytal 2000).

ATP and Industrial Partner Investments

During the 1994 to 1999 period, ATP invested $2.39 million and its industry partners (Shell, BP Amoco, and ConocoPhillips) cost shared $2.42 million to develop high-risk CPR technology.

The ATP funding was exclusively used by Brunswick Corporation (the technology innovator) and its successor, Lincoln Composites, which acquired Brunswick, and by their technical and engineering subcontractors. Shell, BP Amoco, and ConocoPhillips fully funded their own project-related activities for CPR technical development, testing, and prototyping, and were funding sources for Lincoln Composites.

For purposes of cash flow analysis, the ATP investment was normalized to 2003 dollars and assumed to occur in 1997, the midpoint of the five-year investment period. The industry partner's investment costs were not included in the economic analysis, given the emphasis on measuring benefits to the nation relative to ATP's public investment.

Base Case Economic Analysis

Costs and expected values of benefit cash flows are indicated in Table 7. The net present value of ATP's investment is $510 million. Forty-seven percent of the NPV derives from CPR capital cost savings and 53 percent from additional MMS royalties.

Table 7: Cash Flows and Performance Metrics from CPR Deployment in Gulf of Mexico ($ Millions, in 2003 Dollars): Base Case

	Capital cost savings			MMS royalties			Total cash flows
	Path 2	Path 3	All Paths	Path 1	Path 2	All Paths	
1997			–1.37			–1.37	–2.74
2004				2.17		2.17	2.17
2005				6.50		6.50	6.50
2006				12.99		12.99	12.99
2007	0.78	80.44	81.22	19.49	0.97	20.47	101.68
2008	1.56	0.00	1.56	23.82	2.92	26.75	28.30
2009	2.60	80.44	83.04	25.99	6.17	32.16	115.20
2010	3.90	0.00	3.90	25.99	11.04	37.03	40.93
2011	4.16	80.44	84.60	25.99	16.24	42.23	126.83
2012	5.20	0.00	5.20	25.99	22.74	48.73	53.92
2013	5.46	80.44	85.89	25.99	29.56	55.55	141.44
2014	4.68	0.00	4.68	23.82	35.41	59.23	63.91
2015	5.20	80.44	85.64	19.49	41.90	61.40	147.03
2016	5.46	0.00	5.46	12.99	48.73	61.72	67.18
2017	4.68	80.44	85.12	6.50	53.60	60.10	145.21
2018	5.20	0.00	5.20	2.17	58.15	60.31	65.51
2019	5.46	80.44	85.89		61.72	61.72	147.62
2020	4.68	0.00	4.68		62.69	62.69	67.37
2021	5.20	80.44	85.64		63.99	63.99	149.63
2022	4.68	0.00	4.68		63.34	63.34	68.02
2023	3.12	80.44	83.56		60.42	60.42	143.98
2024	2.60	0.00	2.60		57.82	57.82	60.42
2025	1.56	80.44	82.00		53.27	53.27	135.27
2026	0.52		0.52		47.10	47.10	47.62
Net present value			$243 million			$267 million	$510 million
Benefit-to-cost ratio							187:1
Internal rate of return							58%

Note 1: A 1997 base year and an OMB-mandated 7 percent discount rate were used for analysis. Performance metrics were computed from time series assuming ATP investment in 1997 (project midpoint) and prospective cash flow benefits from 2004 to 2026.

Note 2: The NPV calculations for the Capital Cost Savings and Royalties benefit components assume investment costs divide equally across these benefit components.

The public benefit is $187 for every dollar invested, and the internal rate of return is estimated to be 58 percent.

Step-Out Scenario Economic Analysis

Table 8 indicates step-out scenario returns on ATP's investment in the CPR technology. The net present value of ATP's investment is estimated at $557 million. The public benefit is $204 for every dollar invested and the internal rate of return is 59 percent.

Private Benefits to ATP Industry Partners

Continued motivation to refine and commercially market the ATP-funded technology is a precondition for industrial-scale market impact envisioned by the ATP program for developing composites manufacturing technologies. Only with industrial-scale commercialization will the general public come to enjoy the associated economic and environmental benefits resulting from the ATP investment. Lincoln Composites' annual CPR sales, expressed in 2003 dollars, are expected to reach $7 million by 2008 and $10 million by 2011.

Industry collaborators will also realize substantial economic benefits from increased crude oil production and from TLP and SPAR capital cost savings. These economic benefits will be available to the entire offshore oil and gas industry, not only to JV members who participated in the consortium and have been net financial contributors to the ATP-funded CPR project.

Table 8: **Performance Metrics from CPR Deployment in Gulf of Mexico: Step-Out Scenario**

	Capital cost savings	MMS royalties	Total
Net present value	$288 million	$266 million	$557 million
Benefit-to-cost ratio			204:1
Internal rate of return			59%

Note 1: A 1997 base year and an OMB-mandated 7 percent discount rate were used for analysis. Performance metrics were computed from time series assuming ATP investment in 1997 (project midpoint) and prospective cash flow benefits from 2004 to 2026.

Note 2: The NPV calculations for the Capital Cost Savings and Royalties benefit components assume investment costs divide equally across these benefit components.

QUALITATIVE BENEFITS

Additional benefits from the ATP-funded CPR technology are expected to include the following:

- Additional domestic crude oil production of 7.5 million bbl in 2008, 77 million bbl in 2013, and 167 million bbl by 2020. Given the weight of steel risers, these incremental production levels and associated progress towards energy independence may not have been practical with currently available, state-of-the-art steel risers.
- Improved thermal protection from seawater temperatures and from corrosive saltwater environments as a result of composites' superior corrosion resistance characteristics compared with steel risers.

* * * * *

Prior to ATP funding, Lincoln Composites was unable to allocate financial resources to fund in full a high-risk program to develop composite production risers. In large part, the perception of unacceptable technical risk reflected prior failed industry efforts to develop composite risers.

In 1994, the ATP funded the proposed CPR project. In addition to cost sharing the high-risk technology development effort, ATP involvement provided the additional important benefit of "keeping the industry collaborators engaged and making it possible to jointly develop product performance specifications for composite risers" (Johnson 1999).

Technical and cost efficiency benefits from the CPR project would not have been realized without ATP funding and without ATP facilitation.

5. Additional Projects in the Cluster Study

This section discusses the technical challenges and accomplishments of two ATP-funded composites manufacturing projects for civil infrastructure applications and one composites manufacturing project for offshore oil and gas application. Together with the two case studies, these three projects comprise the cluster of five projects.

While the ATP-funded technical tasks of these three projects have been successfully completed, there has been less progress toward commercialization than for the two case study projects.

INNOVATIVE MANUFACTURING TECHNIQUES FOR LARGE COMPOSITE SHAPES:
Applications in Load-Bearing Beams for Short-Span Bridges

Federal Highway Administration studies indicate that nearly 30 percent of U.S. bridges are obsolete or structurally deficient and that bridge maintenance and repair are major ongoing expenses for many state and local transportation departments. In addition, road construction in metropolitan and urban areas significantly contributes to traffic congestion and to associated economic and environmental costs (Taylor 2002).

Load-bearing composite beams would be lighter than steel beams for bridge maintenance and repair, easier to transport, and faster to install. Composite beams would also be more durable and require less maintenance than steel. At the same time, composite beams are currently more expensive and can be difficult to fabricate into structures of appropriate shape and size, and with adequate stiffness.

Strongwell Corporation, working in conjunction with Georgia Institute of Technology, developed a proposal for addressing the design, fabrication, and cost challenges of composite beams for bridge maintenance and repair. In 1995, the ATP agreed to cost share the project with an investment of $2 million. Strongwell

Corporation provided a cost share of $1.138 million. The project was successfully completed in 1998.

Strongwell beams are made with glass and carbon fibers bound in polymer resin. Fabrication uses a pultrusion process that pulls fibers through a resin impregnation bath and a shaping die to form complex cross-sectional shapes. Technical accomplishments of the ATP-funded project include the following:

- Optimizing beam shape and developing design standards to increase beam stiffness, eliminate the need for braces, and reduce costs.
- Developing a manufacturing process to create 36 inch by 18 inch double-web I-beams from vinyl ester phenolic composites.
- Designing and fabricating a dual reciprocating hydraulic puller system, synchronized by a programmable linear controller, and developing a biofiltration process for emissions control.

The ATP-funded technology development effort led to a bridge demonstration project installed at Sugar Grove, VA, jointly funded by Strongwell Corporation, the Federal Highway Administration, and the Virginia Department of Transportation.

Future commercial use of the ATP-funded technology will lead to more efficient bridge maintenance, faster completion of construction tasks, and reduced congestion costs and environmental emissions. Realizing these benefits will depend on achieving further manufacturing improvements and cost reductions.

SYNCHRONOUS CNC MACHINING OF PULTRUDED LINEALS:
Application in Electric Transmission Towers

“While increasing amounts of electricity are flowing over the nation’s ‘wires’, America’s electric transmission infrastructure is aging. If new technologies and more capital are not utilized to relieve congestion, reliability will suffer. The economy will not grow, if it continues to rely on an inadequate transmission system” (Silverstein 2002).

Modernization of the nation’s electrical transmission system is inhibited, in part, by the traditional use of steel structures. Steel towers are expensive to manufacture, require large teams and heavy equipment to install, require anticorrosion treatments, and can weigh too much for helicopter transport into remote areas. Using lighter-weight and corrosion-resistant transmission towers made from composite materials could provide a number of benefits for modernizing the electric transmission infrastructure, including the following:

- Improved ease of transporting tower structures to remote sites (lighter weight).
- Faster installation and lower installation costs.
- Improved maintainability of corrosion-resistant transmission towers.

Ebert Composites Corporation submitted a proposal to the ATP to address the design, fabrication, and cost challenges of composite-based electric transmission towers. In 1994, the ATP agreed to cost share the project with an investment of $1.032 million. Ebert Composites Corporation provided a cost share of $0.303 million. The project was successfully completed in 1997.

Ebert designed and demonstrated an affordable manufacturing system, with significantly reduced production times, for composite towers. The system combines the pultrusion process with computer numerical control (CNC) machining. The ATP funding was used to design a CNC workstation with a five-axis machining head that performs intricate detailing on pultruded parts. Designs for different parts could now be stored in the computer and produced with high accuracy in any quantity and sequence without interrupting the pultrusion. The CNC machine significantly reduced labor costs and human error. Southern California Edison Co. (SCE) is currently testing several demonstration towers that Ebert made using the ATP-funded manufacturing process.

INNOVATIVE JOINING AND FITTING TECHNOLOGY FOR COMPOSITE PIPING SYSTEMS:
Applications in Offshore Oil and Gas Platforms

The weight of steel piping for cooling water, process water, fire suppression, and chemical systems on superstructures of floating oil and gas platforms is a significant capital cost in offshore platform design.

To realize capital cost savings, lighter-weight composite piping systems, able to reach operating pressures of 400 psi, could replace “topside” steel piping if cost-effective technologies were developed for joining composite pipes. This requires the development of reliable composite-to-composite and composite-to-metal joining technologies, to be produced with low-cost manufacturing processes that replace labor-intensive practices.

Specialty Plastics, Inc. makes composite pipes and components for the petrochemical and marine industries. To enable and stimulate the use of composite piping on offshore oil and gas platforms, the company proposed to develop an improved method for joining composite pipe segments and to develop more efficient, less costly processes for manufacturing pipe fittings. In 1995, ATP agreed to cost share the proposed project with an investment of $1.809 million. Specialty Plastics, Inc. provided a cost share of $0.773 million.

The project was completed in 1998. While many technical objectives were achieved, the extent of surface adhesion or chemical bonding between adhesives and composites could not be improved sufficiently to reach a targeted 400 psi operating pressure. As a result, the ATP-funded piping and fitting technology was limited to seawater cooling systems and other lower-pressure applications.

In 1998 Specialty Plastics was acquired by EDO Corporation. According to the manager of engineering for EDO Specialty Plastics, the successor company will make the ATP-funded technology available upon customer request. ATP-funded joining and fitting elements have been incorporated in some commercial sales of composite piping systems used for cooling water applications on offshore platform superstructures, as well as in some commercial sales for onshore composite piping systems. However, the successor company's business strategy and current plans do not include the active marketing of the composites joining and fitting technology.

6. Benefit-to-Cost Analysis for Cluster of Projects

The current cluster study uses a hybrid of traditional case-study approaches. The cluster study combines the advantages of overview case studies and detailed case studies for a richer assessment of empirical relationships between public investments and public benefits than would be possible with either of the two methods alone.

Detailed case studies are used to develop insights into market dynamics and technology commercialization pathways and to provide a credible basis for estimating benefit cash flows and associated probabilities. Cash flow estimates are then used to compute performance metrics to quantify the relationships of public investments and resultant public benefits.

Multiproject overviews are used to envision additional benefits, extend analysis beyond individual projects, and generate lower-bound performance estimates for a cluster of projects and an entire technology program.

PROJECT CLUSTER AND FOCUSED PROGRAM

The cluster of ATP-funded composites manufacturing technologies is composed of five projects. Two of these projects are at advanced stages of commercialization and have a high probability of generating public benefits: vapor-grown carbon fiber technology and the composite production riser technology. Detailed case studies for these two projects are discussed in Sections 3 and 4. The remaining three projects in the cluster discussed in Section 5 (composite bridge beam technology, composite joining and fitting technology, and machining technology for pultruded lineals) are at earlier stages of commercialization and can be associated with only speculative public benefits. At some point, these remaining technologies may also become commercialized and become associated with probable cash flow benefits. Given that remaining technologies may yield benefits in the future, developing performance metrics using cash flows from only two projects with near-term commercial impact leads to conservative, lower-bound performance estimates for the entire cluster.

Over the 1994–1998 period, the ATP funded 17 additional composites manufacturing technologies. Together with the five cluster projects, these 22 projects constitute the ATP focused program for manufacturing of advanced composite materials. While beyond the original scope of the cluster study, it seemed appropriate to extend analysis to include preliminary performance metrics for the focused program. Using the same approach as for the cluster analysis, cash flow benefits from the two case studies are compared to the combined cost of 22 projects of related technologies in the focused program. Given that at some future time additional projects in the program may become commercially successful and may yield benefits that are not yet determined and not yet included in the analysis, preliminary performance metrics for the program of 22 projects represent conservative, lower-bound estimates.

PUBLIC BENEFITS, PUBLIC INVESTMENTS, AND PERFORMANCE METRICS

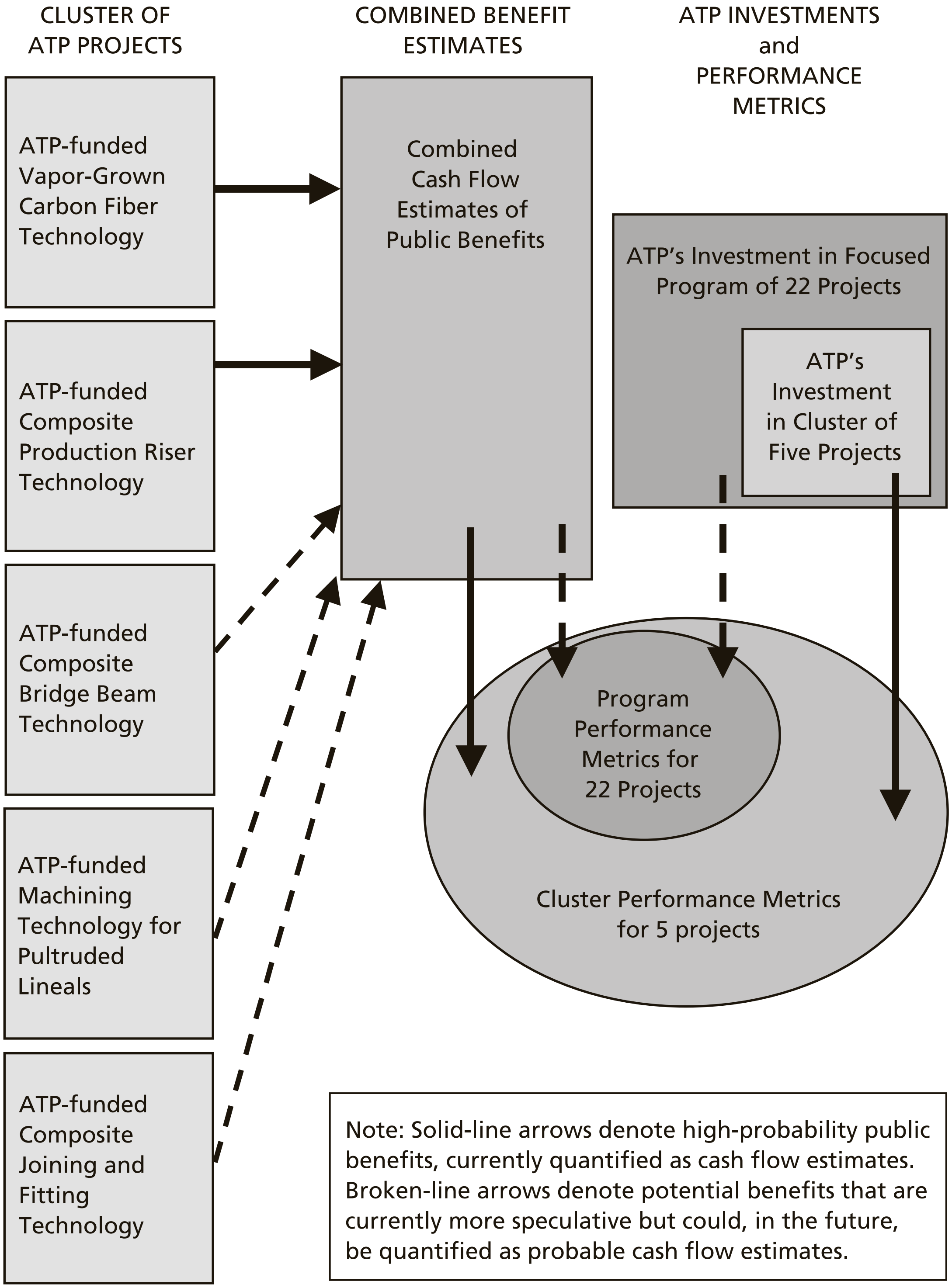
While ATP-funded composites manufacturing technologies, once fully commercialized, will generate both public and private benefits, the estimation of benefit cash flows and the computation of performance metrics were limited to public benefits, excluding private benefits to innovating firms. These public benefits will be realized by industrial users of new composite materials, by consumers of improved industrial products incorporating new composite materials, and by society at large, through enjoyment of reduced environmental emissions and increased energy availability.

Figure 11 illustrates the general flow of the cluster-study process. Public benefits from ATP-funded technologies and ATP-facilitated industry joint ventures are combined with public investment costs to yield economic measures of return. More specifically, two of the five projects in the cluster, analyzed in Sections 3 and 4 and associated with quantifiable, high-probability cash flow estimates from automotive and oil and gas applications, are connected with solid-line arrows to the "Combined Cash Flow Estimates" box in the middle of Figure 11. The remaining three projects with broken-line arrows to the "Combined Cash Flow Estimates" box do not represent current contributions. Rather, broken-line arrows denote possible future benefit cash flows, should currently speculative benefits from these three projects become more probable through ongoing commercialization efforts. While beyond the scope of the current study, cash flow estimates for these three remaining projects could be developed, when appropriate.

The "Combined Cash Flow Estimates" box in the middle of Figure 11 represents cash flows from automotive and from oil and gas applications, normalized for constant 2003 dollars. Normalized cash flows are added to yield a combined cash flow time series.

Boxes on the right side of Figure 11, "ATP Investment in 22 Projects" and "ATP Investment in Cluster of Five Projects," represent investment costs for the focused program and the cluster of projects, respectively.

Figure 11: Public Benefits, Investments, and Performance Metrics for Cluster of Related ATP Projects and, by Extension, Program of ATP Projects



Note: Solid-line arrows denote high-probability public benefits, currently quantified as cash flow estimates. Broken-line arrows denote potential benefits that are currently more speculative but could, in the future, be quantified as probable cash flow estimates.

The "Cluster Performance Metrics" circle represents the calculation of performance measures by comparing combined cash flow benefits to ATP's investment in the cluster of five projects. The metrics generated for the cluster, net present value (NPV), benefit-to-cost ratio, and internal rate of return (IRR), measure public returns against public investments.

Similarly, the "Program Performance Metrics" circle represents the calculation of performance measures by comparing combined cash flow benefits to ATP's investment in a program of 22 projects. The metrics generated for the program, NPV, benefit-to-cost ratio, and IRR measure public returns against public investments in the focused program. Given that program metrics are derived by comparing cash flow benefits from two projects to a much larger program investment, performance metrics for the focused program, while still at significant levels, have lower values than metrics for the cluster of five projects.

ECONOMIC ANALYSIS

The flow of benefits in Figure 11, from the two cases study projects and from the remaining three projects in the cluster, are directly attributable to the ATP.

Industry partners for the five cluster projects have indicated that, for various reasons specific to each high-risk technology project, development programs would not have been undertaken without ATP funding. In addition, industry partners for the two projects with currently quantifiable cash flow benefits stressed the value of ATP-facilitated industry joint ventures as essential ingredients for successful technical development and commercialization.

Base Case Analysis

The base case analysis represents a conservative set of assumptions regarding expected benefits from ATP-funded technology development.

On the benefit side, combined cash flows from the commercial utilization of two technologies for which quantifiable benefits are currently available (VGCF and CPR), covering the period of 2004 to 2026, are used to characterize both cluster and program performance, as summarized in Table 9. Combined cash flow estimates reflect the following assumptions:

- VGCF utilization in the automotive industry starting in 2006 and continuing for a period of 16 years until 2021 (estimates developed in Section 3).
- CPR utilization in Gulf of Mexico offshore oil platforms starting in 2004 and continuing for a period of 23 years until 2026 (estimates developed in Section 4).

On the cost side, ATP invested \$9.4 million and industry partners invested \$7.8 million in the cluster of five projects. To fund the 22-project focused program, the

Table 9: Combined Cash Flows of ATP Investments and Expected Benefits from VGCF and CPR Deployment ($ Millions, in 2003 Dollars): Base Case

Year	ATP cluster investments in five projects and combined cash flows from VGCF and CPR projects (see note below)	ATP program investments in 22 projects and combined cash flows from VGCF and CPR projects (see note below)
Investment years		
1995	–1.24	–6.92
1996	–2.34	–17.47
1997	–4.81	–23.55
1998	–2.51	–2.51
Benefit generation years		
2004	2.17	2.17
2005	6.50	6.50
2006	20.18	20.18
2007	116.06	116.06
2008	57.05	57.05
2009	172.69	172.69
2010	125.01	125.01
2011	222.27	222.27
2012	158.91	158.91
2013	256.93	256.93
2014	190.94	190.94
2015	286.76	286.76
2016	220.88	220.88
2017	314.29	314.29
2018	251.50	251.50
2019	352.20	352.20
2020	292.42	292.42
2021	397.18	397.18
2022	68.02	68.02
2023	143.98	143.98
2024	60.42	60.42
2025	135.27	135.27
2026	47.62	47.62

Note: Combined cash flows are computed from “Total cash flow” columns in Tables 2 and 7.

ATP invested $43.5 million and industry partners invested $39.0 million. Normalized to 2003 dollars, the ATP investment for the cluster was $10.90 and $50.45 million for the program.

In Table 9 column 2, normalized ATP cluster project investments are negative entries over the 1995 to 1998 investment period; combined VGCF and CPR cash flow benefits are positive entries during the 2004 to 2026 “benefit generation years.”

In Table 9, column 3, normalized ATP investments in the 22 projects of the focused program are negative entries over the 1995 to 1998 investment period and combined VGCF and CPR cash flow benefits are positive entries during the 2004 to 2026 "benefit generation years."

Base Case Performance Metrics

Cash flow time series over the 1995 to 2026 period, comprised of ATP investments and expected benefits (from Table 9, column 2), are used to compute performance metrics for the **cluster** of projects. These cluster performance metrics (NPV of $892 million, benefit-to-cost ratio of $83, and IRR of 44 percent) are indicated in Table 10, column 2.

Cash flow time series over the 1995 to 2026 period, comprised of ATP investments and expected benefits (from Table 9, column 3), are used to compute performance metrics for the **focused program**. These program performance metrics (NPV of $858 million, benefit-to-cost ratio of $18, and IRR of 29 percent) are indicated in Table 10, column 3.

Table 10 cluster and program performance metrics indicate excellent returns to taxpayers from ATP's investments in composites manufacturing technologies, as highlighted below:

- For every dollar of ATP's $9.4 million investment in the cluster of five projects, U.S. industry, U.S. consumers, and the nation will enjoy $83 of quantifiable benefits over the projected economic life of the VGCF and CPR technologies.
- For every dollar of ATP's $43.5 million investment in the program of 22 projects, U.S. industry, U.S. consumers, and the nation will enjoy $18 of quantifiable

Table 10: **Base Case Performance Metrics from Combined VGCF and CPR Cash Flows against ATP Cluster and ATP Program Investments (in 2003 Dollars)**

	Performance metrics cluster of five projects	Performance metrics program of 22 projects
Net present value	$892 million	$858 million
Benefit-to-cost ratio	83:1	18:1
Internal rate of return	44%	29%

Note: A 1995 base year and an OMB-mandated 7 percent discount rate were used for analysis. Performance metrics were computed from time series representing ATP investments over the 1995 to 1998 period and prospective cash flow benefits from 2004 to 2026.

benefits over the projected economic life of the VGCF and CPR technologies. Even though these results should be interpreted as preliminary and actual results could be stronger if more projects were analyzed in depth, the entire focused program investment yielded far greater benefits than its cost to taxpayers.

These measures reflect the estimated benefits to industry users and the general public relative to the ATP investment. Estimated benefits to direct recipients of ATP funding are excluded.

Most Significant Sources of Benefits

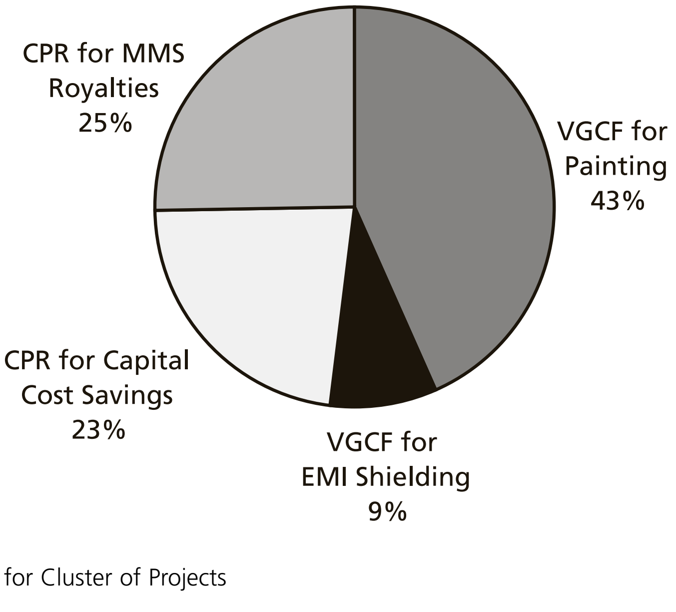
The results of a component analysis of the base case NPV for the cluster of five projects are presented in Figure 12. NPV contributions from VGCF deployment and CPR deployment are of similar magnitude at 49 and 52 percent, respectively. NPV contributions from CPR deployment are evenly split between capital cost savings and royalties to the U.S. Minerals Management Service, whereas contributions from VGCF for electrostatic painting dwarf the small (9 percent) contribution from VGCF use in EMI shielding.

Step-Out Scenario Analysis

The step-out scenario is based on more optimistic assumptions about expected benefits from ATP-funded technologies. Benefit estimates are somewhat higher and ATP investments are the same as for base case analysis.

Cash flow time series over the 1995 to 2026 period, comprised of ATP investments and expected benefits, are used to compute performance metrics for the **cluster** of

Figure 12: **Net Present Value Component Analysis: Base Case**



projects. These cluster performance metrics (NPV of $994 million, benefit-to-cost ratio of $92, and IRR of 46 percent) are indicated in Table 11, column 2.

Cash flow time series over the 1995 to 2026 period, comprised of ATP investments and expected benefits, are used to compute performance metrics for the **focused program**. These program performance metrics (NPV of $960 million, benefit-to-cost ratio of $20, and IRR of 30 percent) are indicated in Table 11, column 3.

FUTURE EXTENSION OF CASH FLOW BENEFITS

While some public benefits expected to be realized from the cluster of five projects could not be meaningfully quantified at this time, these potential benefits could become important for U.S. industry, consumers, and society at large in the future. Two examples are given below.

- A composite beam fabrication technology, developed by Strongwell Corporation for prefabricated structural components to repair short-span bridges in high-traffic metropolitan areas, could lead to reduced construction time and associated traffic congestion, as well as reduced gasoline consumption and auto emissions. Potential cash flow benefits could include cost savings from construction efficiencies and from automotive energy conservation.
- A CNC machining technology for pultruded composite lineals, developed by Ebert Corporation for applications in electric transmission towers, could be useful for the modernization of the nation's electric transmission grid. Potential cash flow benefits could include transportation efficiencies, moving lighter-weight tower structures to remote sites, more rapid installation of tower structures, and installation cost savings.

If the above technologies should progress toward successful commercialization, over time, the estimation of additional cash flow benefits could be warranted. This, in

Table 11: Step-Out Scenario Performance Metrics from Combined VGCF and CPR Cash Flows against ATP Cluster and ATP Program Investments (in 2003 Dollars)

	Performance metrics cluster of five projects	Performance metrics program of 22 projects
Net present value	$994 million	$960 million
Benefit-to-cost ratio	92:1	20:1
Internal rate of return	46%	30%

Note: A 1995 base year and an OMB-mandated 7 percent discount rate were used for analysis. Performance metrics were computed from time series representing ATP investments over the 1995 to 1998 period and prospective cash flow benefits from 2004 to 2026.

turn, would lead to an upward adjustment of performance metrics presented in the current study.

Given the potential for additional cash flow benefits from future analysis, it is clear that the levels of performance reported in this study (based on cash flow benefit streams from only two ATP-funded projects) provide conservative, lower-bound estimates of cluster performance and program performance.

7. Conclusions

The cluster-study approach of focusing on a few, targeted, ATP-funded projects is an efficient methodology for evaluating agency investment in high-risk composites manufacturing technologies.

Technology portfolios are complex, interdependent, and responsive to sudden changes in the research environment such as breakthroughs, new barriers, and collaboration patterns. Only a subset of agency-funded projects can be expected to succeed on a commercial basis. Hence, the relevant performance criterion for agency technology programs, as for privately funded venture capital portfolios, is not the average performance of all investments, but rather the performance of a subset of successful projects against agency program investment.

Starting in 1994, the Advanced Technology Program undertook a focused program of 22 composite manufacturing technology projects to develop these technologies and benefits:

- Rapid, high-volume, and low-cost composite manufacturing processes.
- Affordable, high-performance composites with high strength, lightweight, appropriate electrical conductivity, and corrosion resistance.
- Expanded use of composites in U.S. automotive, offshore oil production, and civil infrastructure industries.

To evaluate the expected performance of the focused program, a cluster of five projects spanning automotive, offshore oil production, and civil infrastructure applications were selected for analysis. Within this cluster, two projects were singled out as having the most probable near-term prospects for commercial deployment and for generating substantial economic benefits: the Vapor-Grown Carbon Fiber (VGCF) project for automotive applications and the Composite Production Riser (CPR) project for offshore oil platforms in the Gulf of Mexico. Detailed case studies were conducted for the VGCF and CPR projects and higher-level overview studies were conducted for the remaining three projects in the cluster.

Cluster analysis points to substantial public returns on ATP's investment. For every dollar of ATP's $9 million investment in the **cluster** of five projects, U.S. industry, consumers, and the nation will enjoy $83 of benefits. For every dollar of ATP's $43 million investment in the 22 projects of the **focused program**, U.S. industry, consumers, and the nation will enjoy $18 of benefits.

In addition to these quantitative performance metrics, cluster analysis also points to broad-based qualitative benefits including automotive body quality benefits, energy production benefits, reduced harmful environmental emissions, and reduced construction-related traffic congestion in metropolitan areas.

Based on extensive fact finding, the cluster study supports the following conclusions:

- Projected public returns and broad-based economic benefits to the U.S. automotive, offshore oil, and civic infrastructure industries have a strong probability of being realized.
- ATP's industry partners would not have developed these high-risk, low-cost composites manufacturing technologies without ATP support and without ATP facilitation of broad-based industrial joint ventures.

As the cluster analysis targeted only a few ATP-funded projects deemed to have the greatest current potential for commercialization and benefit generation, it is likely that additional ATP-funded composites manufacturing technologies will progress toward commercialization and benefit society over time. When appropriate, additional cash flow benefits from these remaining technologies can be estimated and the levels of performance metrics adjusted upward.

References

Advanced Technology Program, National Institute of Standards and Technology. 2002. *Manufacturing Composites Structures Program*. Online at: <www.atp.nist.gov/atp/focus/mcs.htm>

American Composites Manufacturing Association. 2002. *Technical Resources: Materials for Composites Manufacturing, Reinforcement Materials*. Online at: <http://www.cfa-hq.org/resources/>

ASI (Applied Sciences, Inc.). 2002. *Pyrograf-III Products: Frequently Asked Questions*. Online at: <www.apsci.com/ppi-faq.html>

———. 2002a. "Commercialization of Carbon Nanofibers" (December). Cedarville, OH.

Banholzer, W., and Adams, B. 2002. "Expanding Markets with Technology and Application Development." GE Plastics Technology Leadership Meeting.

Baud, R., et al. 2002. *Deepwater Gulf of Mexico 2002: America's Expanding Frontier.* Washington DC: Minerals Management Service, U.S. Department of Interior.

Broge, J.L. 2001. "Marketing Modular Plastics." SAE Automotive Engineering International Online (August). Online at: <http://www.sae.org/automag/material/08-2001/matinn2.htm>

BRG Townsend. 1998. *Automotive Bumper Systems*. Mt. Olive, NJ: BRG Townsend.

Brown, M. 2000. "Alternatives to Painting Automotive Plastic Parts: A Market Forecast for North America through 2004." Troy, MI: 3rd International Coatings and Plastics Symposium (June).

Brown, M., and M. Gregus. 2001. “A Market in Transition.” *Industrial Paint & Powder* (December).

Couch, H. 2003. (National Composites Center.) Interview.

CSM Worldwide. 2001. “Automotive Market Snapshots.” *Injection Molding* (November). Cannon Communications.

DeLuca, M. 2000. “Composites Shape Up for Risers.” *Offshore Engineer* (December 1).

Finegan, I, and G. Tibbetts. 2001 “Electrical Conductivity of Vapor-Grown Carbon Fiber/Thermoplastic Composites.” *Journal of Materials Research* 16(6):1668–1674.

Fischer, F.J. 1995. “Composite Production Risers for Deepwater Offshore Structures.” *Reveue de L’Institut Francais du Petrole* 50(1) (January).

General Motors. 2002. *Corporate Responsibility and Sustainability Report 2001–2002*. Detroit MI.

Gregus, M. 2001. “Painting Automotive Plastics Parts: A Market Forecast for North America through 2005.” Chicago, IL: SME Finishing Conference, June.

Hillegeist, P. 2001. “Global Deepwater Forecast on Floating Production.” *Alexander’s Oil & Gas Connections* 6(10).

Hughes, T.W. 2002. *Pyrograf-III Overview Polymer Applications*. Cedarville, OH: Applied Sciences Inc.

———. 2003. Correspondence “Review of Draft Technical Discussion.”

Jaffe, A. 1998. “The Importance of Spillover in the Policy Mission of the Advanced Technology Program.” *Journal of Technology Transfer* 23(2):11–19.

Johnson, D.B. 1999. “Rigid Composite Risers for Deepwater Oil Production.” Intertech Second International Conference on the Global Outlook for Carbon Fibers 1999. San Antonio, TX.

———. 2000. “Demand for Composites in Deepwater Oil Production.” International Conference on the Global Outlook for Carbon Fiber 2000, December. San Antonio TX.

———. 2003. (Lincoln Composites.) Interview.

KPMG. 2003. “In the Automotive Industry, Momentum.” *KPMG Survey Report* 3(1).

Krueger, S., et al. 2001. “New Challenges for Microsystem Technology in Automotive Applications.” *MST News* (January). Online at: <www.rgrace.com/Papers/leitartikel_klein%20(1).pdf>

Lake, M.L. 2002. “Production of Carbon Nanofiber from High Sulfur Coal.” National Coal Council Annual Meeting.

———. 2002a. *Carbon Nanofiber Production and Applications*. Cedarville, OH: Applied Sciences Inc.

Lake, M.L., et al. 2002. *Carbon Nanofiber Polymer Composites: Electrical and Mechanical Properties*. Cedarville, OH: Applied Sciences Inc.

Lytal, J. 2000. “Deepwater Projects.” El Paso Energy Partners. Presentation to Analysts.

Mansfield E., J. Rapoport, A. Romeo, S. Wagner, and G. Beardsley. 1977. “Social and Private Rates of Return from Industrial Innovation.” *Quarterly Journal of Economics* 91 (May):221–240.

Mazumdar, S.K. 2002. *Composites Manufacturing: Materials, Products, and Process Engineering*. New York: CRC Press.

McConnell, C., and S. Brue. 1996. *Microeconomics: Principles, Problems, and Policies*. Boston: McGraw-Hill Irwin.

MMS (Minerals Management Service), U.S. Department of Interior. 2003. “News Release” (February). Online at: <www.gomr.mms.gov>

———. 2001. “News Release” (April). Online at: <www.gomr.mms.gov>

Office of Automotive Affairs. 2002. *The Road Ahead for the Automotive Industry*. Washington, DC: International Trade Administration, U.S. Department of Commerce.

Readinger, T. 2003. “Role of Science and Technology in U.S. Energy Security.” *Annual Review and Forecast* 44(1).

RTP Engineering Plastics. 2000. “EMI Shielding: Cost Reductions for Electronic Device Protection” (January). Winona, MN.

Ruegg, R., and E. Feller. 2003. *A Toolkit for Evaluating Public R&D Investments: Models, Methods, and Findings from ATP's First Decade*. NIST GCR 03-857 U.S. Department of Commerce: Washington DC.

Salama, M. 2003. (ConocoPhillips). Interview.

Sawyer, C. 2001. "Speed to Market." *Automotive Design & Production* (July). Online at: <http://www.autofieldguide.com/>

———. n.d. "Full Metal Jacket."*Automotive Design and Production*. Online at: <http://www.autofieldguide.com/articles/060206.html>

Silverman, B. 1999."Drilling and Production Risers Business Poised to Grow." *Hart's E&P Net* (November). Online at: <http://www.eandpnet.com/ep/previous/nov99/lightweight.htm>

Silverstein, K. 2002. "Transmission Infrastructure Needs Critical Care." *Science Issue Alert* (August 16). Email at: IssueAlert@Sciencetech.com.

Strong, A.B. 1989. *Fundamentals of Composite Manufacturing: Materials, Methods, and Applications*. Dearborn, MI: Society of Mechanical Engineers.

Taylor, B.D. 2002 "Rethinking Traffic Congestion." *Access*. Institute of Transportation Studies. October 2002

University of Michigan, Office for the Study of Automotive Transportation. 2001. *Delphi X Forecast and Analysis of the North American Automotive Industry.* Ann Arbor, MI.

U.S. Energy Information Administration. 2003. *Annual Energy Outlook 2003*. Washington, DC.

Vasilash, G.S. 2001. "Body Building." *Automotive Design and Production* (March). Online at: <http://www.autofieldguide.com/>

Wu, H.F. 2002. "High Risk Composites Research Funded by the NIST Advanced Technology Program." Proceedings of the American Society for Composites 17th Technical Conference, Paper # 2060.

Appendix 1: ATP-Funded Projects for Composites Manufacturing Technologies

Project	Project title	Single or joint number venture	Single or joint venture lead company
Case studies & other cluster projects			
95-11-0024	Vapor-Grown Carbon Fibers for Automotive Applications	JV	Applied Sciences
94-02-0032	Composite Production Risers for Offshore Oil Production	JV	Lincoln Composites
94-02-0010	Innovative Joining/Fitting Systems for Composite Piping Systems	Single	EDO Specialty Plastics Inc.
95-11-0012	Innovative Manufacturing Techniques for Large Composite Shapes (Bridges)	Single	Strongwell Corp.
94-02-0025	CNC Machining of Pultruded Lineals	Single	Ebert Composites
Remaining projects in Focused Program			
94-02-0011	Structural Composites Manufacturing	Single	GenCorp, Inc.
94-02-0014	Low-Cost Automotive Manufacturing with Injection Molding PET Composites	Single	Allied Signal, Inc.
94-02-0027	Automotive Composite Structures	JV	General Motors Corp
94-02-0030	Polymer Matrix Composites Power Transmission Devices	JV	New Venture Gear
94-02-0033	High-Performance Composite Structures	JV	True North Company
94-02-0034	Thermoplastic Composites for Structural Applications	JV	DuPont Eng. Polymer
94-02-0038	Spoolable Composite Tubing	JV	Cullen Engineering
94-02-0039	Low-Cost Advanced Composites for Light Transit Vehicle Manufacturing	JV	Advance USA LLC
94-02-0040	Manufacturing Methods for Vehicle Composite Frames	Single	Budd Company
94-02-0041	Manufacturing Composite Flywheel Structures	Single	Dow-United Tech Composites Products
94-02-0043	Seismic Sensor Technologies for Bridges	JV	Composite Retrofit
94-02-0048	Composite Structures for Offshore Oil	JV	Northrop Grumman
95-11-0010	Composite Drill Pipes	JV	Cullen Engineering
95-11-0014	Intelligent Flexible Pipe Development	Single	Wellstream Corp.
95-11-0017	Thermoset Transfer/Injection Molding	Single	Budd Company
95-11-0018	Polymer Composites for Surface Transport	Single	Hexcel Corporation
95-11-0036	Integrated Agile Manufacturing for Composite Electric Vehicles	JV	Northeast Advance Vehicle Consortium

Source: ATP Awards Database.

Appendix 2: Actual ATP and Industry Investments in Composites Manufacturing Technologies ($ Millions)*

	Project number	Year funded	Project duration (years)	ATP funding	Industry funding	Total funding
Case studies & other cluster projects						
Case Study 1	95-11-0024	1995	5	2.229	3.162	5.391
Case Study 2	94-02-0032	1994	5	2.390	2.416	4.806
Other	94-02-0010	1994	3	2.000	1.138	3.138
Cluster	95-11-0012	1995	3	1.809	0.773	2.582
Projects	94-02-0025	1994	2	1.032	0.303	1.335
Remaining projects in Composites Portfolio						
	94-02-0011	1994	1	1.444	1.593	3.037
	94-02-0014	1994	1.5	0.588	0.707	1.295
	94-02-0027	1994	2	2.575	2.855	5.430
	94-02-0030	1994	5	2.397	2.399	4.796
	94-02-0033	1994	4	5.280	5.293	10.573
	94-02-0034	1994	3	2.272	2.379	4.651
	94-02-0038	1994	5	2.500	2.599	5.099
	94-02-0039	1994	5	4.171	4.483	8.654
	94-02-0040	1994	3	2.000	0.318	2.318
	94-02-0041	1994	1	0.099	0.155	0.254
	94-02-0043	1994	4	1.369	1.391	2.760
	94-02-0048	1994	5	2.382	2.607	4.989
	95-11-0010	1995	1	0.328	0.329	0.657
	95-11-0014	1995	1	0.694	0.112	0.806
	95-11-0017	1995	3	2.000	0.824	2.824
	95-11-0018	1995	2	0.977	0.188	1.165
	95-11-0036	1995	4	2.930	3.008	5.938

*Note: Actual ATP investments can be different from the awarded amounts.
Source: ATP Awards Database.

Appendix 3: Composite Materials for Engineered Products

Engineers can utilize over 50,000 materials for the design and manufacture of engineered products. These materials, depending on their mechanical and physical characteristics such as strength, stiffness, density, melting temperature, and conductivity, can be divided into four main categories: metals, plastics, ceramics, and composites.

While metals and plastics are currently the dominant materials for engineering applications, there has been an increasing utilization of composite materials, reflecting their superior performance characteristics. The key factor holding back additional increases in composite utilization has been the high cost of composites.

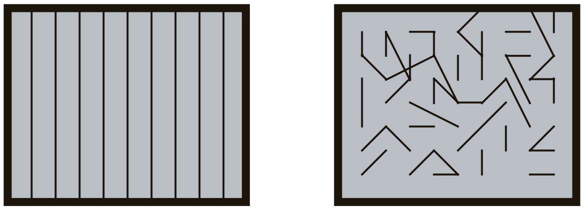
Composites are systems composed of at least two distinctly dissimilar materials, acting in concert. The properties of the polymeric composite system are not attainable by individual components acting alone. Engineered composites can be defined as systems of reinforcing fibrous materials in a polymer matrix binder.

The reinforcing fiber provides strength and stiffness to the composite. The matrix material binds the fibers together, provides form and rigidity, transfers the load to the fibers, and protects the load-bearing fiber from corrosion and wear. For composites in structural applications, continuous or long-fiber configurations are typical, whereas for nonstructural applications, short fibers can be used (Figure A3-1).

Common composite reinforcing fibers include glass fibers and carbon/graphite fibers. For specialized applications, boron and aramid (Kevlar) fibers can also be used. General fiber properties are described below:

- Kevlar fibers are organic fibers which have high strength and stiffness which is possible in fully aligned polymers. Kevlar fibers have a very low resistance to failure under axial compression.

Figure A3-1: Continuous-Fiber versus Short-Fiber Composites



- Glass fibers (fiberglass) have excellent electrical insulating properties, good chemical and moisture resistance, and low cost. Glass fibers come in several grades (higher performance S-glass with greater tensile strength and higher use temperatures versus lower performance E-glass) and are widely used in industrial composites.
- Carbon/graphite fibers are high-strength, high-modulus, lightweight fibers, used as reinforcement for high-performance applications.
- Mixed fiber structures use a combination of Kevlar, glass, carbon, or other fibers to fabricate hybrid composites to optimize composite properties and cost.

The matrix material (polymer resin and elastomer) surrounds and binds the fiber in the composite structure and has a lower modulus and greater elongation than the fiber reinforcement. The matrix determines the service operating temperature of a composite as well as processing parameters for parts manufacturing. Polymer matrix materials may come as thermoset and thermoplastic resins:

- During curing, thermoset resins form three-dimensional molecular chains (cross-linking chains) and, once cured, cannot be remelted and reformed. The higher degree of the cross-linking chains, the more rigid and thermally stable the composite material will be. The most common resin materials are epoxy, polyester, vinyl ester, phenolics, and cyanate esters.
- Thermoplastic resin molecules do not cross-link and thus remain flexible and reformable. They are, in general, more ductile and tougher than thermosets and are used in a wide variety of industrial (nonstructural) applications. At the same time, they have lower stiffness and strength values, which can be selectively improved by the appropriate choice of fiber reinforcement. Typical thermoplastic resins include nylon, polypropylene, polyetheretherketone (PEEK), polyester, and teflon.

Table A3-1 indicates representative physical properties of various composites, compared to common engineering materials. Composite materials have high specific strength (strength-to-density ratio) and high specific stiffness (modulus-to-density ratio).

Table A3-1: Typical Properties of Some Engineering Materials

	Density g/cc (ρ)	Tensile strength MPa (σ)	Tensile modulus GPa (E)	Specific strength (σ/ρ)	Specific modulus (E/ρ)	Max. service temp (°C)
Metals						
Steel, ASI 1045 HR	7.8	0.57	205	0.073	26.3	500–650
Aluminum 2024-T4	2.7	0.45	73	0.17	27.0	150-250
Polymer without reinforcement						
Nylon 6,6	1.15	0.082	2.9	0.071	2.52	75–100
Epoxy	1.25	0.069	3.5	0.055	2.80	80–215
Reinforced polymers with continuous fiber (% by weight)						
S-glass/epoxy (45%)	1.81	0.87	39.5	0.48	21.8	80–215
Carbon/epoxy (61%)	1.59	1.73	142	1.08	89.3	80–215
Reinforced polymer with short fiber (% by weight)						
Glass/epoxy (35%)	1.90	0.30	25	0.16	8.26	80–200
Glass/nylon (35%)	1.62	0.20	14.5	0.12	8.95	75–110

Source: Mazumdar 2002.

About the Advanced Technology Program

The Advanced Technology Program (ATP) is a partnership between government and private industry to conduct high-risk research to develop enabling technologies that promise significant commercial payoffs and widespread benefits for the economy. ATP provides a mechanism for industry to extend its technological reach and push the envelope beyond what it otherwise would attempt.

Promising future technologies are the domain of ATP:

- Enabling technologies that are essential to the development of future new and substantially improved projects, processes, and services across diverse application areas.
- Technologies for which there are challenging technical issues standing in the way of success.
- Technologies whose development often involves complex "systems" problems requiring a collaborative effort by multiple organizations.
- Technologies which will go undeveloped and/or proceed too slowly to be competitive in global markets without ATP.

ATP funds technical research, but it does not fund product development. That is the domain of the company partners. ATP is industry driven, and that keeps it grounded in real-world needs. For-profit companies conceive, propose, cofund, and execute all of the projects cost shared by ATP.

Smaller companies working on single-firm projects pay a minimum of all the indirect costs associated with the project. Large "Fortune 500" companies participating as a single firm pay at least 60 percent of total project costs. Joint ventures pay at least half of total project costs. Single-firm projects can last up to three years; joint ventures can last as long as five years. Companies of all sizes participate in ATP-funded projects. To date, two out of three ATP awards have gone to individual small businesses or to joint ventures led by a small business.

Each project has specific goals, funding allocations, and completion dates established at the outset. Projects are monitored and can be terminated for cause before completion. All projects are selected in rigorous competitions that are peer reviewed to identify those that score highest against technical and economic criteria. Contact the ATP for more information:

- On the World Wide Web: http://www.atp.nist.gov.
- By e-mail: atp@nist.gov.
- By phone: 1-800-ATP-FUND (1-800-287-3863).
- By writing: Advanced Technology Program, National Institute of Standards and Technology, 100 Bureau Drive, Stop 4701, Gaithersburg, MD 20899-4701.

About the Author

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