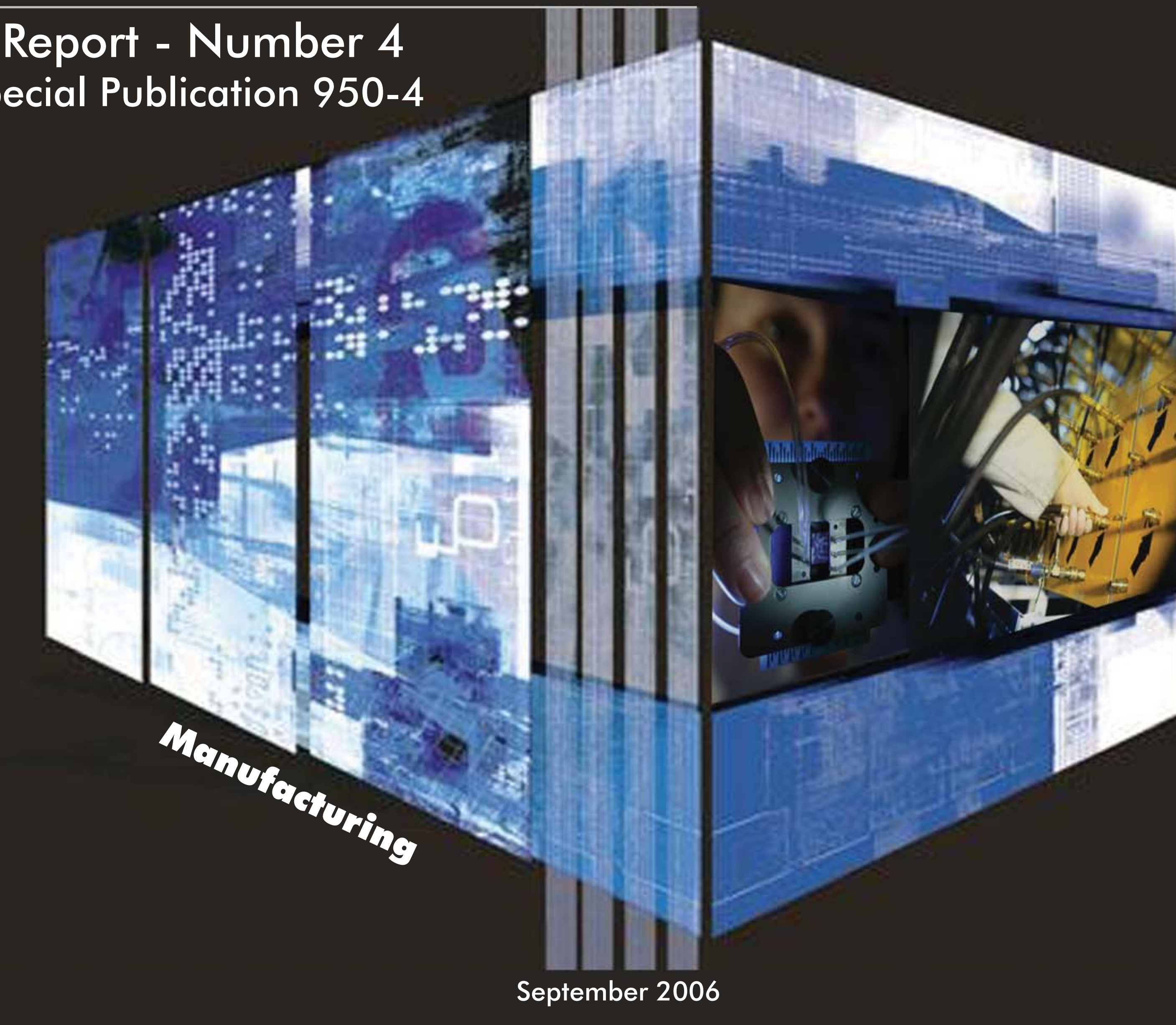
ADVANCED TECHNOLOGY PROGRAM

Performance of the Third 50 Completed ATP Projects

Status Report - Number 4

NIST Special Publication 950-4



September 2006

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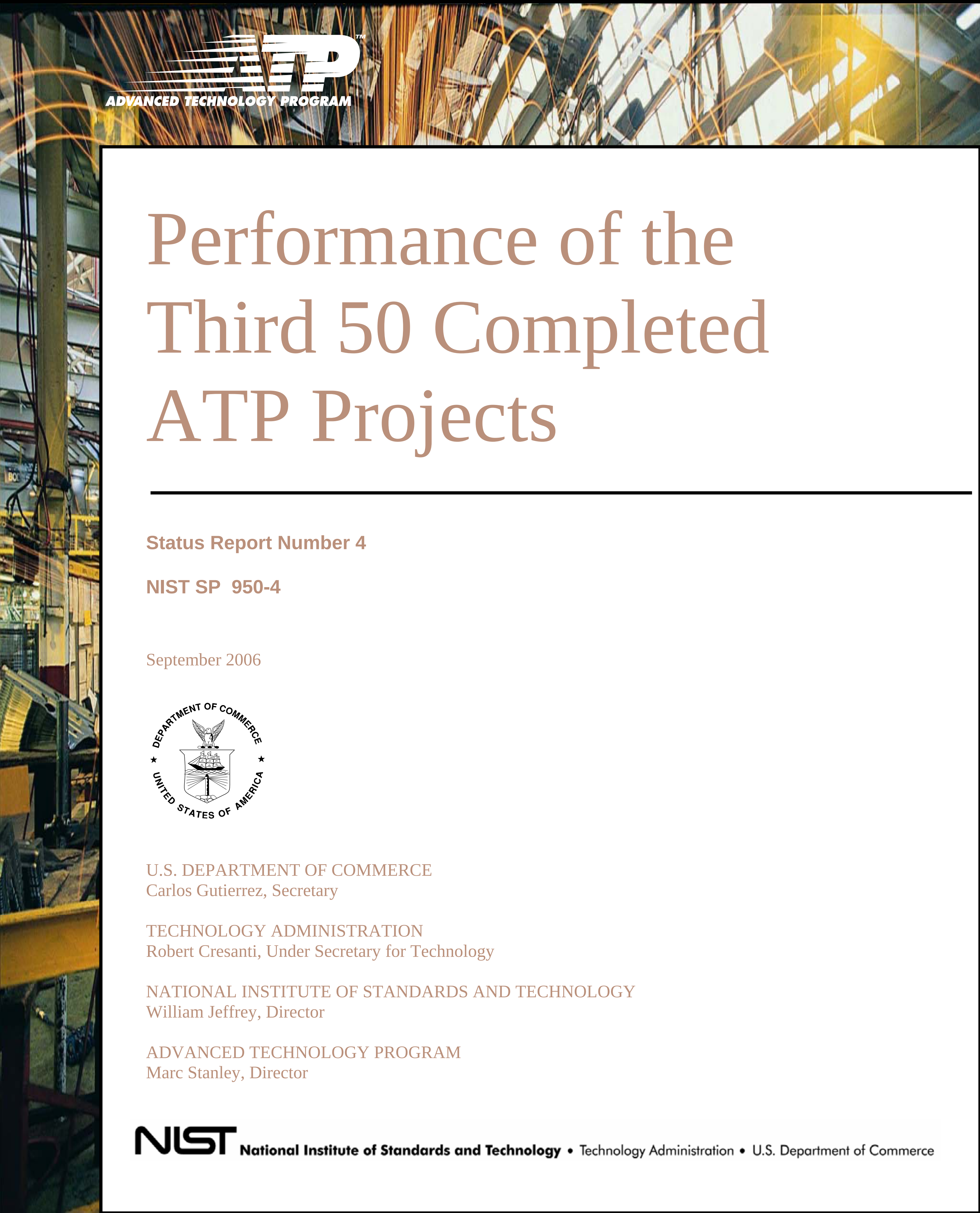

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U.S. DEPARTMENT OF COMMERCE
Carlos Gutierrez, Secretary

TECHNOLOGY ADMINISTRATION
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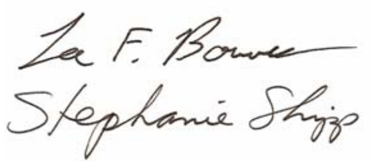
ACKNOWLEDGEMENTS

We are pleased to announce the completion of the next chapter in ATP's portfolio of status reports for completed projects. This compilation consists of the third batch of 50 "mini case studies" written to investigate the results and impacts of ATP's investment in innovative technologies. The goal of each status report is to provide the reader with a basic understanding of the technology, while also identifying any economic benefits that may have resulted from the ATP-funded project.

This process is a daunting one, requiring the efforts of many both inside and outside of ATP. The majority of the project was made possible by the former and current members of the status report team: Tony Colandrea, Stefanie Cox, Nashira Nicholson, Rick Rodman, Susan Stimpfle, and Virginia Wheaton. We would especially like to thank ATP Division Directors Michael Schen (Information Technology and Electronics Office) and Linda Beth Schilling (Chemistry and Life Sciences Office), and ATP Deputy Director Lorel Wisniewski, for their contributions to this project. Much appreciation also goes to the hard work of the others involved in preparing the status reports: project managers, reviewers, copy editors, and company representatives.

But these efforts aren't without rewards. As the portfolio of ATP status reports grows, we gain insight as to the role ATP plays in bridging the funding gap. We are confident this showcase of the third batch of 50 completed projects will help build on our understanding of ATP-funded innovations across many technology areas. We hope that you learn as much about the process of early-stage technology development, commercialization, and outcomes for the economy as we have in preparing these status reports.

Sincerely,



Lee Bowes, Economist
Stephanie Shipp, Director,
Economic Assessment Office
Advanced Technology Program

INTRODUCTION

Industry has proposed 6,924 projects to the ATP since 1990, of which 768, or 11 percent, have been selected by the ATP for funding. The number of participants for these funded projects totaled 1,511, with approximately an equal number of subcontractors. This study focuses on the third group of 50 projects that were completed and provides combined statistics for all 150 completed projects studied to date.

ATP: A Partnership with Industry

The ATP attracts challenging, visionary projects with the potential to develop the technological foundations of new and improved products, processes, and even industries. The ATP partners with industry on this research, fostering collaborative efforts and sharing costs to bring down high technical risks and accelerate technology development and application. These are projects that industry in many cases will not undertake without ATP support, or will not develop in a timely manner when timing is critical in the highly competitive global market. The program funds only research, not product development. The ATP is managed by the National Institute of Standards and Technology, an agency of the Commerce Department's Technology Administration.

ATP awards are made on the basis of a rigorous competitive review, which considers the scientific and technical merit of each proposal and its potential benefits to the U.S. economy. The ATP issues a proposal preparation kit that presents and explains the selection criteria to prospective applicants and provides guidance on preparing proposals.[1] U.S. businesses conceive, plan, propose, and lead the projects. Government scientists and engineers who are expert in the relevant technology fields review all proposals for their technical merit. Business, industry, and economic experts review the proposals to judge their potential to deliver broadly based economic benefits to the nation —including large benefits extending beyond the innovator (the award recipient).

The ATP delivers benefits to the nation along two pathways: 1) a direct path by which the U.S. award recipient or innovator directly pursues commercialization of the newly developed technologies; and 2) an indirect path which relies on knowledge transfer from the innovator to others who in turn may use the knowledge for economic benefit. Either path may yield spillover benefits. The ATP looks to the direct path as a way to accelerate application of the technology by U.S. businesses. It looks to the indirect path as a means of achieving additional benefits, or benefits even if the award recipient fails to continue. The ATP's two-path approach to realizing national benefits offers advantages: one path may provide an avenue for benefits when the other does not, and both paths together may yield larger, accelerated benefits as compared to having a single route to impact.

Project Evaluation

The ATP, like other federal programs, is required by law to report on its performance.[2] The ATP established its evaluation program soon after it began, even before evaluation was widely required by Congress. The Economic Assessment Office (EAO) of ATP plans and coordinates the evaluation of funded projects. It is assisted in this effort by leading university and consulting economists and others experienced in evaluation.

Performance is measured against the program's legislated mission. Emphasis is placed on attempting to measure benefits that accrue not only to the direct award recipients, but also to a broader population, i.e., spillover benefits. This emphasis reflects the fact the public funding covers part of the costs of these projects, and, therefore, a relevant question is how the broader public benefits from the expenditure.

This report constitutes one element of the EAO's multi-faceted evaluation plan: status reports. The purpose of status reports is to provide an interim assessment of the status of ATP-funded projects several years after they are completed. Although the ultimate success of the ATP depends on the long-run impacts of the entire portfolio of ATP projects, the performance-to-date of this partial portfolio provides some initial answers. This study contains an evaluation of 150 completed projects: the results of the 100 projects from the Status Report – Numbers 2 & 3, and the results and status reports of a third batch of 50 projects. These reports address the questions of what has the public investment of $321 million in the 150 projects produced several years after completion of the research, and what the outlook is for continued progress?

Study Approach

From the moment that ATP funded its first group of 11 projects in the 1990 competition, program administrators, the administration, Congress, technology policymakers, industry, and others in this country and abroad were keenly interested in the outcome. But technology development and commercialization are lengthy processes, and it takes time to produce results.

As more ATP-funded project are completed and move into the post-project period, sufficient time has elapsed for knowledge to be disseminated and progress to be made towards commercial goals. Thus, it is now possible to compile more complete aggregate portfolio statistics, and analyze these statistics with regard to implications for overall program success.

At the core of this study are 50 mini-case studies covering each of the completed projects. Each of these briefly tells the project story, recounting its goals and challenges, describing the innovators and their respective roles, and assessing progress to date and the future outlook. Photographs illustrate many of the projects.

Although the particulars vary for each project, certain types of data are systematically collected for all of them. Consistent with ATP's mission, the evaluation focuses on collecting data related to the following dimensions of performance:

- **Knowledge creation and dissemination**, which is assessed using the following criteria: recognition by other organizations of a project's technical accomplishments; numbers of patents filed and granted; citations of patents by others; publications and presentations; collaborative relationships; and knowledge embodied in and disseminated through new products and processes.
- **Commercialization progress**, which is gauged in terms of the attraction of additional capital for continued pursuit of project goals, including resources provided by collaborative partners; entry into the market with products and services; employment changes at the small companies leading projects and other indicators of their growth; awards bestowed by other organizations for business accomplishments of project leaders; and the analyst's assessment of future outlook for the technology based on all the other information.

The approach is to provide, in an overview chapter, the aggregate statistics of interest across a set of 150 projects, such as the total number of patents and the percentage of projects whose technologies have been commercialized. In addition, the aggregate statistics are combined to produce composite project metrics for overall performance. The composite performance scores allow one to see at a glance the robustness of a project's progress towards its goals. Underlying the simple scores is a wealth of data.

Sources of Information

Data for the projects were collected from many sources: ATP project records; telephone interviews with company representatives; interviews with ATP project managers; company websites; the U.S. Patent and Trademark Office; in-depth project studies conducted by other analysts; academic, trade and business literature; news reports; filings at the Securities and Exchange Commission; and business research services, such as Dun and Bradstreet, Hoover's Online, Industry Network, and CorpTech. Each one of the individual project write-ups was reviewed for accuracy by the project's lead company and ATP staff.

Study Limitations and Future Directions

Since developments continue to unfold for most of these projects, the output measures for the cases may have changed significantly since the data were collected. The cases provide a snapshot of progress several years after the completion of the ATP-funded projects.

Although undertaken at different calendar dates, the reports are written within about the same interval of time after ATP funding ended. Yet, different points in each technology's life cycle may be captured, depending on the technology area. Information technology projects, for example, may be expected to be further along than advanced materials and chemical projects. Examined at a later time, there may be less (or more) difference in the accomplishments among projects in different technology areas.

This study tracks outputs leading to knowledge dissemination but it does not assess the actual commercialization efforts by others who acquire the knowledge. The tracking of commercialization efforts is limited to the direct path of impact (i.e., commercialization by the award recipients or innovators).

"Completed" and "Terminated" Projects Defined

Projects do not necessarily finish in the order funded. For one thing, they have different lengths, ranging from approximately two years to no more than five years. For another, they are required to file a final report with the ATP and have financial and other paperwork completed before project closeout. The financial closeout is done through the National Institute for Standards and Technology (NIST) Grants Office, which notifies the ATP that it considers the project completed. This study assesses the first 150 projects the Grants Office declared "completed."

Not all ATP projects reach completion; some are stopped short and are classified as "terminated." Some of these were announced as award winners but never officially started. Other projects got off the ground but were closed for various reasons with a substantial amount of the technical work still unfinished. These terminated projects are assessed according to the principal reasons they stopped before completion. They are treated in Appendix B. While the terminated projects are generally regarded as unsuccessful, some produced potentially useful outputs.

Report Organization

The report has been divided into separate technology area "editions" in order to provide a smaller, more targeted compilation. However, the overview still provides a summary overview of the performance of the 150 completed projects as a group. It identifies some major outputs that appear useful as indicators of the degree of project success, and it uses these outputs in a prototype project performance rating system. A preview also notes some of the broad-based benefits that this portfolio of projects is producing and likely to produce. For additional background, the make-up of the portfolio of projects in terms of technologies, organizational structure, company size, and other features is provided.

The individual project reports, within the particular technology area, follow the overview. The reports highlight major accomplishments and the outlook for continued progress. A detailed account of the project under review is given, with attention to technical and commercial goals and achievements, information about technology diffusion, and views about the role played by ATP funding. A performance rating is assigned to each project based on a four-star scoring system. The rating depends on the accomplishments of the project in creating and disseminating new scientific and technical knowledge and in making progress toward generating commercial benefits, as well as the outlook for continued progress.

Three appendices provide supporting information. Appendix A provides a listing of technical and commercial achievements of each completed project. Appendix B provides a discussion of the terminated projects throughout ATP's existence. Appendix C provides a list of the first 150 completed projects and the respective composite performance ratings. The listed is sorted in descending order of performance rating, then by company name.

1. The current edition of the kit and other program materials may be obtained on ATP's website (www.atp.nist.gov), by e-mail (atp@nist.gov), by phone (1-800-ATP-Fund or 1-800-287-3863), or by mail (ATP, NIST, 100 Bureau Drive, Stop 4701, Gaithersburg, MD 20899-4701).
2. The Government Performance and Results Act (GPRA) is a legislative framework for requiring federal agencies to set strategic goals, measure performance, and report on the degree to which goals are met. An overview of the GPRA is provided in Appendix 1 of the General Accounting Office Executive Guide, Effectively Implementing the Government Performance and Results Act, GAO, Washington, D.C., GGD-96-118, 1996

Overview of Completed Projects

PART 1

Project Characteristics

This report provides an overview of the first 150 ATP-funded projects to reach completion. These projects reflect an investment of more than $621 million that was shared about equally by ATP and industry.

Of the initial 150 projects, 75 were led by small businesses that submitted single-company-applicant proposals to ATP. Eighty-seven percent involved collaborative relationships with other firms, universities, or both. Sixty-seven percent were funded in ATP's General Competitions.

In terms of classification by type, 25 percent of the projects were "Electronics, Computer Hardware, or Communications", while "Advanced Materials and Chemicals" accounted for 23 percent. "Manufacturing", "Information Technology", and "Biotechnology" each constituted about 17 percent of the remaining projects.

(The 150 completed status reports discussed in this chapter can be found on-line at http://www.atp.nist.gov/ under funded projects.)

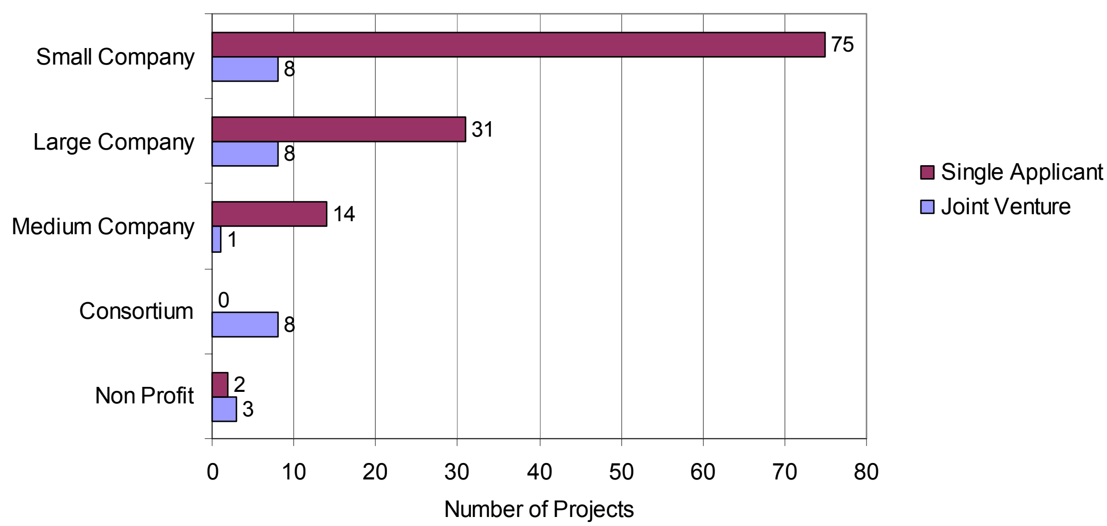
Single Applicants and Joint Ventures

"Single-applicant projects," make up 81 percent of the first 150 ATP-funded projects; these projects were subject to an upper limit on ATP funding of $2 million and a time limit of 3 years. Nineteen percent of the 150 projects were joint ventures. Each of these projects had a minimum of two for-profit companies sharing research and costs for up to 5 years. Typically, the joint-venture membership included other for-profit companies, universities, and nonprofit laboratories. These projects, free of the funding constraint, tended to take on larger problems for longer periods of time.

Project Leaders

Figure 1-1 illustrates how project leadership of single-applicant and joint-venture projects was distributed among the various types of organizations. Small companies led most of the projects—75 of the 122 single-applicant projects and 8 of the 28 joint-venture projects. "Small" follows the Small Business Administration's definition and includes companies with fewer than 500 employees. Large companies—defined as Fortune 500 or equivalent firms—led 31 of the single-applicant projects, or 25 percent, and eight of the joint ventures, or 29 percent. Medium-sized companies led only 14 single-applicant projects and one joint venture. Consortia led eight of the joint venture projects. Nonprofit institutions led two of the single-applicant projects[1], and three joint ventures.

Figure 1-1
Number of Single-Applicant and Joint-Venture Projects by Type of Leadership



Source: Advanced Technology Program First 150 Status Reports

A Variety of Technologies

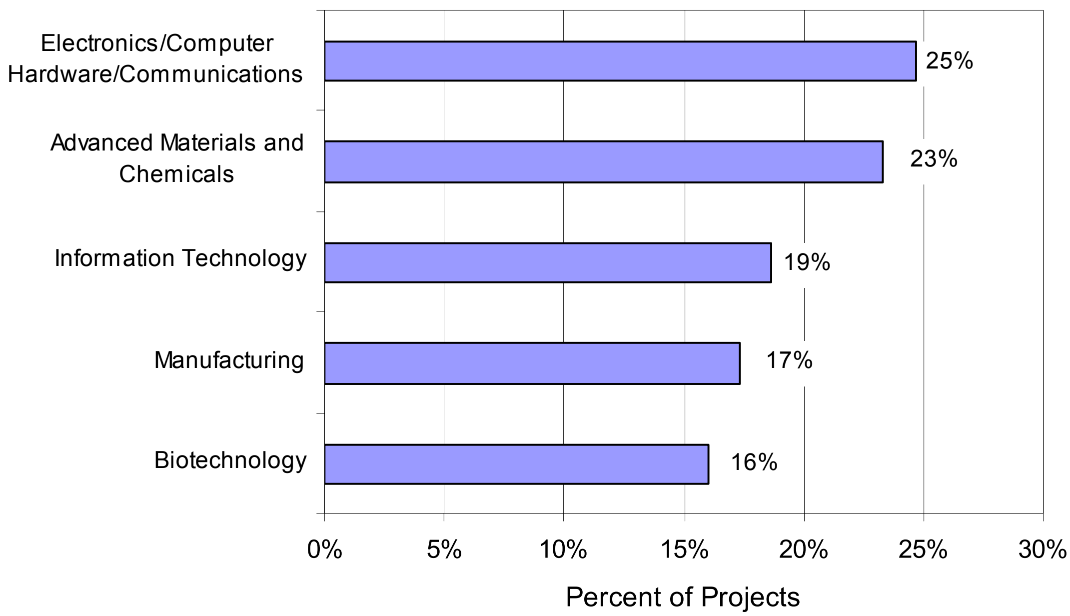
The 150 completed projects fall into the five technology areas used by ATP for classification purposes. Figure 1-2 shows the percentages of completed projects by technology area. The highest concentration, accounting for 25 percent of the total, is in "Electronics, Computer Hardware, or Communications." This category includes microelectromechanical technology, microelectronic fabrication technology, optics and photonics, and other electronics projects.

"Advanced Materials and Chemicals" account for 23 percent of the projects. "Information Technology," "Manufacturing," and "Biotechnology" account for, 19, 17 and 16 percent respectively of the 150 projects. The Manufacturing category includes areas such as energy conversion and energy generation and distribution, in addition to machine tools, materials handling, intelligent control, and other discrete manufacturing. The Advanced Materials and Chemicals category includes the subcategories of energy resources/petroleum, energy storage/fuel cell, battery, environmental technologies, separation technology, catalysis/biocatalysis, and other continuous manufacturing technologies, as well as metals and alloys, polymers, building/construction materials, and

[1] From the 1991 competition, when nonprofits were eligible to lead ATP projects.

other materials. The category of Biotechnology includes areas such as bioinformatics, diagnostic and therapeutic, and animal and plant biotechnology.

Figure 1-2
Distribution of Projects by Technology Area



Source: Advanced Technology Program First 150 Status Reports

The technology make-up of these 150 projects differs from that of the larger ATP portfolio of projects in part because the composition of ATP applicants and awardees over time changes. Of the first 150 completed projects, 67 percent come from ATP's General Competitions that were open to all technologies, while 33 percent come from ATP's focused program competitions, which were held from 1994 through 1998. These competitions funded technologies in selected areas of focus, such as in Motor Vehicle Manufacturing Technology and Digital Video in Information Networks.

It should be noted that while the five major technology areas are used to classify the projects, most of them are not easy to classify. Most ATP projects involve a mix of technologies and interdisciplinary know-how.

Collaborative Activity

Although only 19 percent of the 150 projects were joint ventures, 87 percent of all projects had collaborative arrangements. As shown in Table 1-1, 49 percent of the projects involved close research and development (R&D) ties with universities. Sixty-one percent reported collaborating on R&D with companies or other nonuniversity organizations. Slightly less than half the projects formed collaborative relationships with other organizations for commercial pursuit of their ATP-funded technologies. Thirty-five percent of projects had collaborative relationships with both universities and nonuniversities for either R&D or commercial purposes.

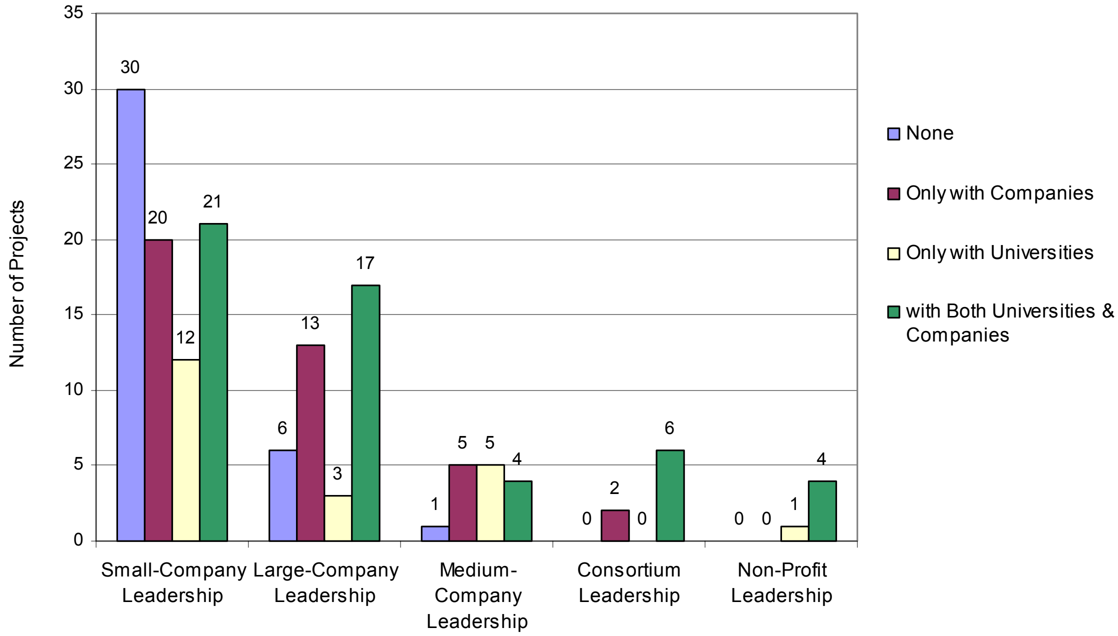
Table 1-1
Collaborative Activity

	Type of Collaboration	Percentage
A)	Collaborating on R&D with other companies or nonuniversity organizations	61%
B)	Close R&D ties with universities	49%
	Collaborating on R&D with other companies or nonuniversity organizations OR close R&D ties with universities (A or B)	75%
	Collaborating with both universities and non-university organizations (A and B)	35%
C)	Collaborating on commercialization with other organizations	46%
	Collaborating in one or more of the above ways	87%
Note: This assessment of collaborative relationships likely understates the numbers because it focused on the project's lead organization and probably missed some of the informal collaborative relationships of other participants.		

Source: Advanced Technology Program First 150 Status Reports

For more detail, Figure 1-3 illustrates the types of collaboration undertaken by projects with different forms of project leadership. It highlights the fact that under all forms of project leadership, projects were highly likely to involve collaboration with other companies. About 43 percent of the projects led by small and large companies involved university collaboration, while the share rose to 60 percent for projects led by medium-sized companies, and 75 percent for consortium-led projects.

Figure 1-3
Number of Projects with R&D Collaborations by Type of Collaboration and Type of Project Leadership



Source: Advanced Technology Program First 150 Status Reports

Costs of the Projects

As shown in Table 1-2, ATP and industry together invested in excess of $621 million on the 150 projects. They shared almost equally in project costs, with ATP providing a slightly larger share. ATP spent an average of $1.72 million per single-applicant project and an average of $3.97 million per joint-venture project. Across the 150 projects, the average total cost (ATP plus industry) per project was $4.14 million. Estimated benefits attributed to ATP from just a few of the 150 projects for which quantitative economic benefits have been provided exceed ATP's funding for all of the 150 projects. In addition, there is considerable evidence of large project benefits that have not yet been quantified.

Approximately 45 percent of single-applicant projects had total research costs under $3 million. These projects had an ATP share that ranged from a little more than $.5 million to $2 million. Slightly less than 50 percent had total research costs greater than $5 million, and one project had total research costs greater than $30 million. ATP's share of these costs were $2 million or more for 50 percent of the projects and were $5 million or higher for 36 percent. For one of the projects, ATP's share exceeded $10 million. Joint ventures, which made up only 19 percent of the total number of projects, accounted for 35 percent of total ATP funding.

Table 1-2
ATP Funding, Industry Cost Share, and Total Costs of 150 Completed Projects

	Single Applicant Projects	Joint Venture Projects	Total Projects
ATP Funding ($ Millions)	210.1	111.1	321.2
Industry Cost Share ($ Millions)	184.6	115.2	299.8
Total Project Costs ($ Millions)	394.7	226.3	621.0
ATP Share of Costs	53%	49%	52%
Industry Share of Costs	47%	51%	48%
Average Project Funding Provided by ATP ($ Millions)	1.72	3.97	2.14
Average Project Cost-Share Provided by Industry ($ Millions)	1.51	4.11	2.00
Average Project Funding Provided by Overall ($ Millions)	3.24	8.08	4.14

Source: Advanced Technology Program First 150 Status Reports

P A R T 2

Gains in Technical Knowledge

One of ATP's major goals is to build the nation's scientific and technical knowledge base. Each of the 150 completed ATP projects targeted a number of specific technical goals designed to achieve a new or better way of doing things. The knowledge created by each project is the source of its future economic benefit, both for the innovator and for others who acquire the knowledge. It is a good starting place for assessing completed projects.

(The 150 completed status reports discussed in this chapter can be found on-line at http://www.atp.nist.gov/ under funded projects.)

New Technologies and Knowledge Gains

Knowledge gains by the projects are diverse and encompass the five major technology areas. The technologies developed in the 150 projects are listed in column C in Tables A-1–A-5 in Appendix A. The set of tables provides the reader with a convenient, quick reference to the entire range of technologies. The entries are arranged alphabetically, by project lead company using the five technology areas. As was mentioned earlier, most of these projects are interdisciplinary, involving a mixture of technologies and generating knowledge in multiple fields.

Even those projects that were not fully successful in achieving all of their research goals, or those that have not been followed by strong progress in commercialization, have achieved knowledge gains. Moreover, some of the projects carried out by companies that have since ceased operations or stopped work in the technology area yielded knowledge, as indicated primarily by the presence of publications and patents. In these cases the direct market routes of diffusion of knowledge gains through commercialization by the innovators are likely lost. However, the indirect routes—whereby others acquire and use the knowledge—remain.

Of What Significance Are the Technical Advances?

Measuring the significance of technical advances is challenging. One factor that challenges measurement is the length of elapsed time that typically separates an R&D investment and its resulting long-term outcomes. In the interim period, various short-run metrics may serve as indicators that project results appear to be on track toward achieving long-term goals. One metric that has been used to signal the significance of a project's technical achievements is formal recognition in the form of an award from a third-party organization.

Thirty awards for technical accomplishments were made to participants for achievements related to ATP-funded projects. Participants in 19 of the 150 projects received awards for their technical achievements. Participants in seven of the projects received multiple technical awards. Table 2-1 lists the awards made to these projects by third-party organizations in recognition of their technical accomplishments.

Table 2-1
Outside Recognition of Technical Achievements of the First 150 Completed Projects

Project Awardee	Year	Awarding Organization	Award
American Superconductor	1996	*Industry Week* Magazine	Technology of the Year award
American Superconductor	1996	*R&D* Magazine	One of the 100 most important innovations of the year
Automotive Composites Consortium (a Partnership of DaimlerChrysler [formerly Chrysler], Ford and General Motors)	1999	*Popular Science* Magazine	Best of What's New for the Chevrolet Silverado composite truck box, "a breakthrough in the use of structural composites"
Cincinnati Lamb, UNOVA (Lamb Technicon)	1999	*Industry Week* Magazine	Top 25 Technology and Innovation Award
Communication Intelligence #1	1997	Arthritis Foundation	"Ease-of-Use Seal of Commendation" for the development of natural handwriting technology, for use by disabled people who have trouble with keyboard entry
DuPont	1993	*Microwave & Rf* Magazine	One of the Top Products of 1993, for high-temperature superconductivity component technology
Ebert Composites	1999	Civil Engineering Research Foundation	Charles Pankow Award for Innovation in Civil Engineering
Engineering Animation	1994	*Computerworld* Magazine	Smithsonian Award, for the use of information technology in the field of medicine
Engineering Animation	1995	Association of Medical Illustrators	Association of Medical Illustrators Award of Excellence in Animation
Engineering Animation	1995	International ANNIE Awards	Finalist, received together with Walt Disney, for best animations in the film industry
Engineering Animation	1996	*Industry Week* Magazine	One of the 25 Technologies of the Year, for interactive 3D visualization and dynamics software used for product development
GM Thermoplastic Engineering Design (Engineering Design with Thermoplastics)	2001	Internal GM R&D Award	Campbell Award for "Process Modeling and Performance Predictions of Injection-Molded Polymers"
GM Thermoplastic Engineering Design (Engineering Design with Thermoplastics)	2001	Society of Plastics Engineers	Best Paper Award from the Product Design and Development Division

Project Awardee	Year	Awarding Organization	Award
HelpMate Robotics	1996	*Discover* Magazine	One of 36 finalists for Technology of the Year, for the HelpMate robot used in hospitals
HelpMate Robotics	1997	Science Technology Foundation of Japan	Japan Prize, to CEO Joseph Engelberger, for "systems engineering for an artifactual environment"
Illinois Superconductor	1996	*Microwave & Rf* Magazine	One of the Top Products of 1996, for cellular phone site filters and superconducting ceramics
Illinois Superconductor	1997	American Ceramic Society	Corporate Technical Achievement Award
Integra Life Sciences**	1999	New Jersey Research and Development Council	Thomas Alvin Edison Award
Kopin Corporation	1998	*Electronic Products* Magazine	"Product of the Year" Award for expanding functionality of portable devices including PDAs, cell phones, and pagers
Kopin Corporation	1998	*IndustryWeek* Magazine	"25 Technologies of the Year" Award
Kopin Corporation	1999	*Photonics Spectra* Magazine	"25 Most Technically Innovative Products" Award for the CyberDisplay 320C
Kopin Corporation	2003	Consumer Electronics Show 2003	"Best Innovation" Award for the 44-inch LCoS HDTV
Molecular Simulations	1996	Computerworld Magazine	Finalist for Smithsonian Award, the 1996 Innovator Medal
NCMS	1994	Institute for Interconnecting & Packaging Electronics Circuits	Best Paper of Conference Awards
Perceptron (formerly Autospect, Inc.)	1998	International Body Engineering Conference	Best Paper Award
Strongwell Corporation	1998	Composite Fabricators Association Conference	Best of Show Award
The Dow Chemical Company	2004	Department of Commerce, NIST/Brookhaven	Gold Medal for Scientific/ Engineering Achievement for Dr. Daniel Fischer's work on "a unique national measurement facility for soft X-ray absorption spectroscopy enabling breakthrough materials advances"
Xerox Palo Alto Research Center	2003	*JavaWorld*	Editors' Choice Award for the Most Innovative Java Product or Technology
X-Ray Optical Systems (XOS)	1995	*R&D* Magazine	R&D top 100
X-Ray Optical Systems (XOS)	1996	*Photonics Spectra* Magazine	Photonics Circle of Excellence Award

Source: Advanced Technology Program First 150 Status Reports

**The award went to Dr. Kohn of Rutgers University for his collaborative work with Integra on the project.

Examples of Projects with Knowledge Gains

Xerox Palo Alto Research Center: Xerox Palo Alto Research Center (PARC) expanded its research on modularity with a cost-shared award for $1.7 million from ATP's Component-Based Software Focus Program. The project began in 1995, and the researchers developed two prototype applications that extracted system-wide concerns into separate modules with their own code. They called this approach aspect-oriented programming (AOP).

As ATP funding ended, PARC began working with the Defense Advanced Research Projects Agency to create a general-purpose language and tool, which PARC patented and called AspectJ. This product:

- Is freely available through IBM's eclipse.org web site
- Has six trade books devoted to it
- Won the JavaWorld Editors' Choice Award for the Most Innovative Product or Technology in 2003
- Is used aggressively by IBM in developing new software products

AOP is well recognized in the computer industry and has eight patents associated with it. More than a dozen universities in North America and in the United Kingdom include it in their curricula. Although the average computer user does not know or care about aspects, programmers' use of AOP in designing web sites will bring speed, reliability, greater customization, and savings. End users receive better services, delivered more quickly, at a lower cost.

Orchid BioSciences (formerly Molecular Tool, Inc. Alpha Center): A small company, Molecular Tool, applied for and was awarded $1.9 million under the ATP Tools for DNA Diagnostics focused program in 1995, in order to compress most of the functions of SNP analysis that were being done in the 20-foot by 15-foot biotechnology laboratory onto a 1-square-inch glass chip..

Molecular Tool successfully developed a patented prototype SNP analysis tool in 1998 and gained the attention of the biotechnology industry. Orchid BioComputer (later renamed Orchid BioSciences) purchased Molecular Tool in 1998 to acquire the ATP-funded equipment and the company's project-related knowledge.

In 2000, Orchid BioSciences was performing DNA analyses using a single nucleotide polymorphism (SNP) analysis tool, which performed more than 800,000 DNA analyses per day. Orchid's SNP scoring tool, called SNPstream, analyzes up to 100,000 data points for increased accuracy. Furthermore, a typical result showed one in several billions statistical probability, increased from one in a million. SNP technology has had high-profile applications:

- Used to attempt to identify the remains of some New York City World Trade Center victims of 2001, which could not be identified by conventional DNA analysis due to sample degradation.

- Used in assisting major metropolitan police departments in forensics, including Los Angeles, Houston, and England's Scotland Yard. Also developed advanced forensic applications to identify individuals from unsolved crimes using degraded DNA samples for the Federal Bureau of Investigation. Orchid's express DNA service provides forensic DNA analyses in five business days compared with the standard four to five weeks.

- Used for the United Kingdom's scrapie genotyping program to help sheep farmers use selective breeding to eliminate the disease scrapie from their flocks. The company has genotyped over 1 million sheep to date.

The societal benefits of SNP analyses are growing. Typical DNA analysis cost has been reduced by approximately 70 percent, and the time it takes to perform DNA analysis has been reduced by approximately 75 percent, such that DNA analysis can now provide results in about a week (reduced from 4 weeks). Police departments are able to solve cold cases, because SNPstream is able to analyze DNA from degraded samples. It is hoped that pharmacogenetic applications (studying genetic variations related to the onset of disease, and pharmaceuticals) will improve medical treatment.

SciComp: ATP provided in cost-shared funds to $1.9 million to SciComp to develop a software synthesis technology that would simplify the process of mathematical modeling.

SciComp, Inc successfully incorporated simplified mathematical modeling (representing a mathematical device or process) into software for the derivative securities industry. Called SciFinance, this solution includes tools that can automate the pricing of complex derivative securities, organize libraries of pricing codes, and provide risk-management analysis.

As of 2004, SciFinance includes six financial products, four of which incorporate the ATP-funded synthesis technology and two that enhance the other products.

SciComp's software synthesis technology improved the productivity of mathematical modelers by tenfold. SciComp has been awarded two patents based on ATP-funded technology development, and the company has shared knowledge through nine published papers and made several presentations at conferences.

As of 2004, the volume of derivative securities trading has continued to grow, resulting in increased demand for software tools to assist in the pricing of complex derivative structures. SciComp is one of only a few companies that provide these tools.

PART 3

Dissemination of Knowledge

If knowledge from the projects is disseminated—either through products and processes commercialized by the innovators or through publications, patents, and other modes of knowledge transfer—it may benefit other producers in the economy and, subsequently, consumers. The resulting national benefits may go far beyond the returns to the innovating firms and the benefits to their customers.

(The 150 completed status reports discussed in this chapter can be found on-line at http://www.atp.nist.gov/ under funded projects.)

Multiple Ways of Disseminating Knowledge

New knowledge developed in a project can be diffused in a variety of ways. This section discusses two principal means: through patents filed and granted by the U.S. Patent and Trademark Office (USPTO) and cited by others, and through preparation of technical papers that are published or are presented at conferences. Collaborative activity among research and commercial partners, treated in Part 1, is another way by which knowledge is disseminated. Another way is through the observation and reverse engineering of the new goods or services produced directly by the innovators and their partners, discussed in Part 4. Among the other important ways—not explicitly covered here—in which knowledge developed in a project can be diffused are informal interactions among researchers, suppliers, customers, and others; movement of project staff to other organizations; distribution of nonproprietary project descriptions by government funding agencies; and project-related workshops and meetings.

Pathways of knowledge dissemination allow others to obtain the benefits of R&D without having to pay its full cost. When the technology is particularly enabling—in the sense of providing radically new ways of doing things, improving the technical bases for entire industry sectors, or being useful in many diverse areas of application—the spillover benefits to others are likely to be particularly large. The generation of spillover benefits, or positive externalities, from technological advancement is an important argument for public support of enabling technologies.

Balancing Intellectual Property Protection and Knowledge Dissemination

ATP encourages broad dissemination of knowledge produced in ATP-funded projects because it increases the number of potential users of the knowledge and, therefore, may increase national benefits. At the same time, ATP does not force innovating companies to compromise their ability and willingness to pursue early commercial applications of the technology by giving away all of their intellectual property. After all, these companies, which contribute a substantial share of the costs, have agreed to tackle difficult research barriers and to take the technology to the marketplace as rapidly as possible.

Thus, it is not surprising that the amount of knowledge dissemination varies among the projects. Most of the projects pursue some forms of deliberate knowledge dissemination, such as publishing scientific papers, giving presentations, and forming collaborative relationships. Most projects also engage in considerable unintended knowledge dissemination; for example, as a company's scientists move and work among other companies and universities; as myriad formal and informal discussions occur; as others reverse-engineer their products; and through mergers and acquisitions of the innovating companies.

Public Disclosure of Patent Filing Information

When applying for a patent to protect intellectual property, an inventor must explicitly describe the invention. Because patent law requires that the invention is both novel and useful, the inventor must demonstrate that the invention is essentially different from any other invention and must describe how it can be used. When the USPTO grants a patent, the full application text describing how the invention may be used and how it is related to other technologies is put into the public record and becomes a medium through which knowledge is transferred to others. Hence, patents serve to disseminate knowledge.

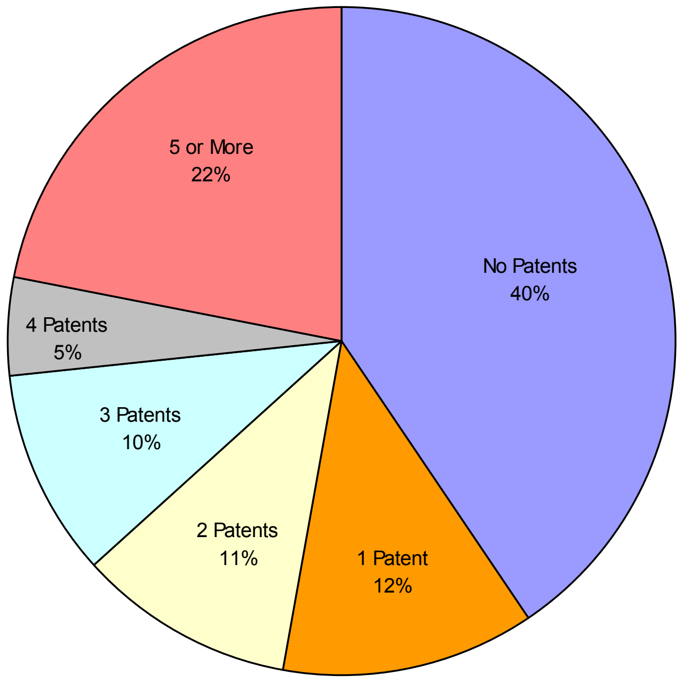
At the same time, patent data are not perfect signals of knowledge creation and dissemination. The decision to seek patent protection for intellectual property is influenced by many factors, including the ease with which others can copy the property's intellectual content and the difficulty of defending the patent position from infringement. Some companies may decide that patent protection is not worth its expense or that a strategy of trade secrets and speed-to-market is more effective. Conversely, patents may be filed as the basic ideas are forming, and trade secrets used in later stages. Furthermore, the importance of patents as a strategy varies among technology areas; for example, patents figure more strongly in electronics and manufacturing than in computer software. The absence of a patent does not mean that intellectual property was not created. But the presence of a patent is a signal that it was created. Despite the limitations, patent statistics serve as useful indicators of knowledge creation and dissemination, and they are widely used by researchers.

Of the 150 completed projects, 89 had filed 500 patents at the time the study data were collected.[2] Eighty-one of the projects had among them a total of 347 patents granted, or 70 percent of the total filed. Thirty-two of the projects had filed a total of 153 patents for which a final decision on granting was still pending.

[2] Patents filed and not yet granted are included here, in addition to those filed and granted, despite the fact that there is no public disclosure until patents are actually granted. The reason for including patents filed and not yet granted is to help offset the problem that there are substantial differences across industries in the lag time between patent filing and granting.

Figure 3-1 displays the distribution of the 150 projects by the number of patents filed, whether granted or not yet granted. More than half the projects have filed one or more patents. Participants in 12 percent of projects had filed a single patent, 26 percent had filed 2 to 4 patents each, and 22 percent had filed 5 or more patents. Forty percent of the projects had not filed a patent.

Figure 3-1
Distribution of Projects by Number of Patents Filed



Source: Advanced Technology Program First 150 Status Reports

Knowledge Disseminated by Patents as Revealed by Patent Trees

Each published patent contains a list of previous patents and scholarly papers that establish the prior art as it relates to the invention. The citations provide a way to track the spread of technical knowledge through patents granted to ATP-funded projects. By following the trail of the patent referenced, it is possible to construct what looks much like a horizontal genealogy tree.

Once the pool of ATP-related patents was identified, computerized tools made available by the USPTO were used to track subsequent patents that refer to each of the ATP-related patents as prior art and the links recorded.[3] The process is then repeated in turn for each of these patents, until the chain of references is complete. Next, the information is

[3] The references to prior patents contained in a published patent are based on information supplied by the applicant and on research by USPTO researchers. There is no way to distinguish between the two sources and no indication that one tends to dominate the other. (USPTO telephone interview with ATP staff, February 11, 2000.)

converted into a graphic format that illustrates the diffusion of knowledge along the path from ATP project patents in the tree.

With the passage of additional time, new branches may emerge as outgrowths of earlier patents. To the extent that later patents are dependent on the earlier ones, the patents in the tree represent developments in knowledge that would not have occurred, or at least not in the same timeframe, had ATP not stimulated the creation and dissemination of that platform knowledge.

Patent Tree Illustrating Knowledge Dissemination

The patent tree in Figure 3-2 shows citations of a patent that came out of an ATP-funded project led by **Texas Instruments, Inc.** during which the company developed a special insulating material, known as aerogel, to overcome problems with interconnect delays as a result of the continuing trend toward miniaturization. The company overcame impediments to aerogel processing early in the project, but in 1997, an industry competitor announced that it would begin using copper interconnect wiring in future integrated circuit designs. After the ATP-funded project Texas Instruments shifted focus away from aerogels for aluminum and began to develop copper interconnects.

The patent tree illustrates how an ATP-funded project whose direct path appears to have slowed or has come to a standstill nevertheless has the potential to remain influential along an indirect path of knowledge utilized and cited in subsequent patents. As the patent tree illustrates, a number of other companies are referencing the Texas Instrument patent, and the potential for beneficial impact from the research continues.

Figure 3-2
Patent Tree for Texas Instruments, Inc. - Patent 5,894,173
Project Impact After Innovator Reduced Activity

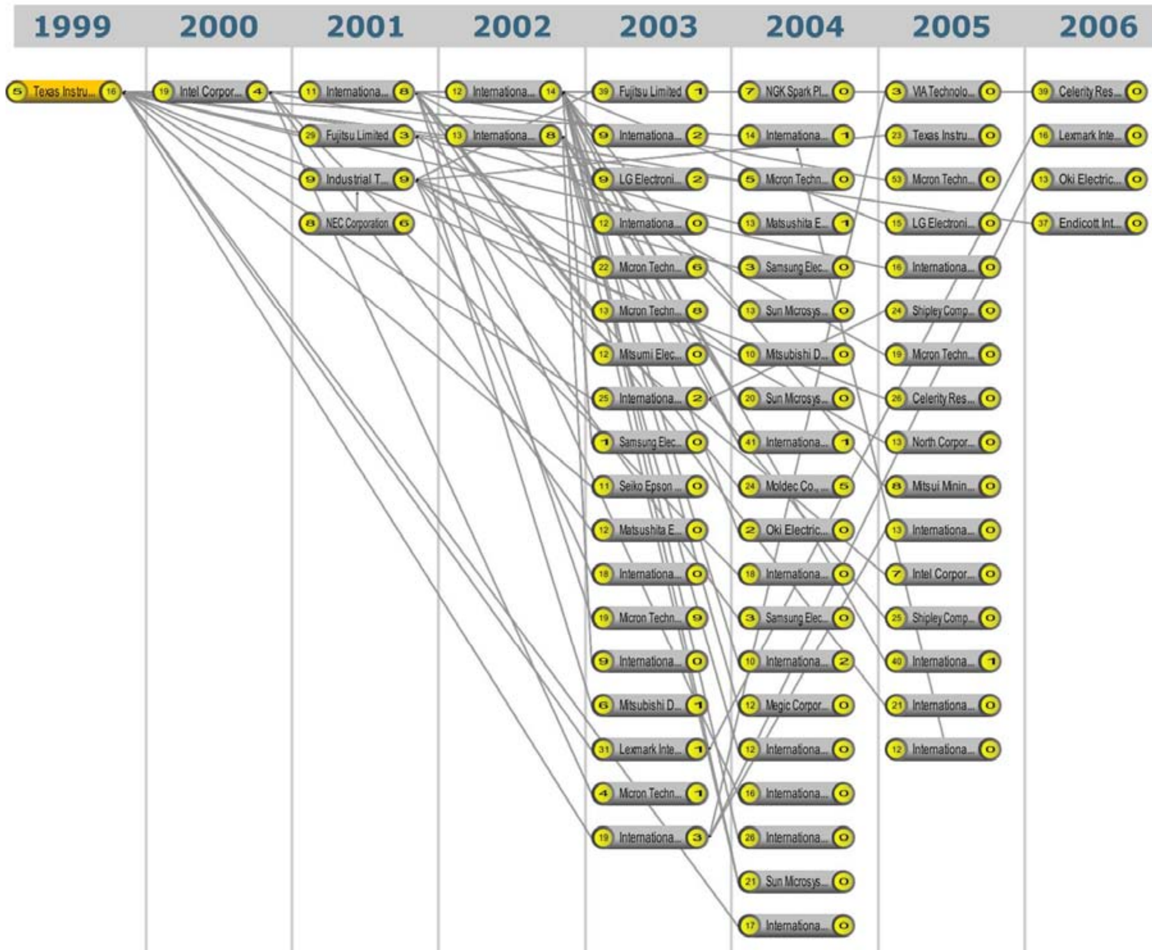


Figure 3-3
Patent Tree for Large Scale Biology Corporation - Patent 5,993,627
Project Impact Where Innovator Went Bankrupt

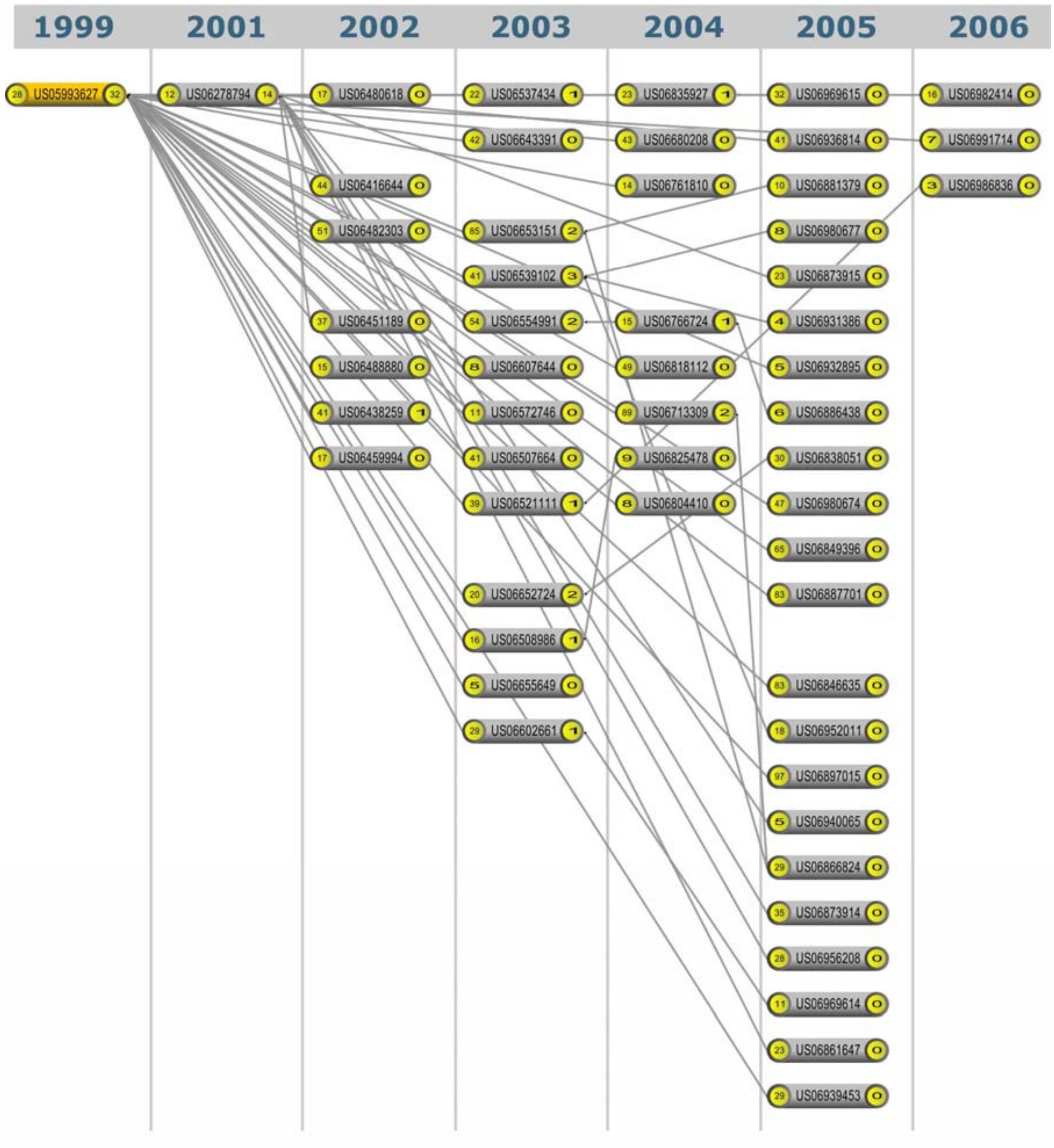


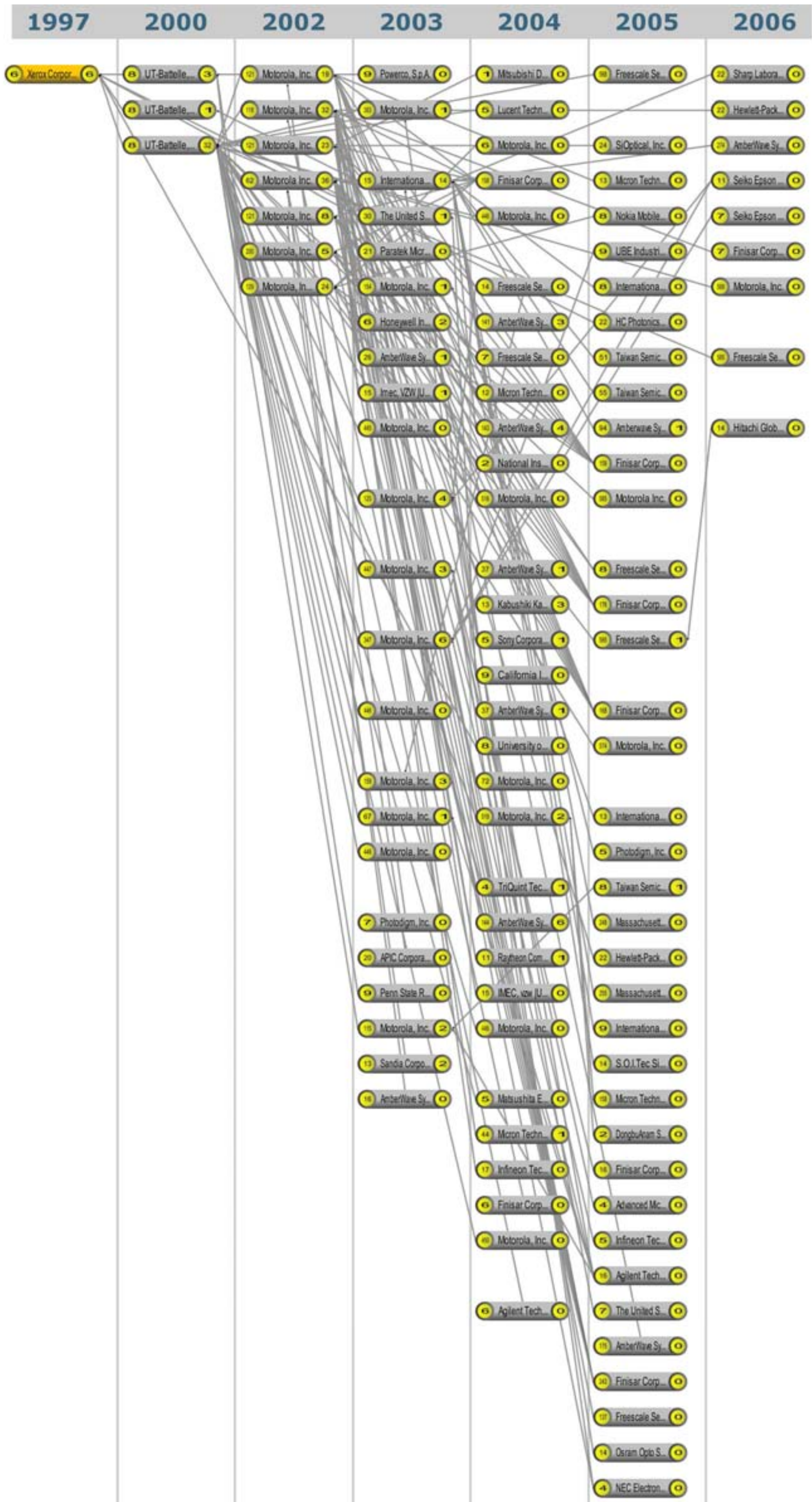
Figure 3-3 shows citations of a patent resulting from a project led by **Large Scale Biology Corporation**. Though the company went bankrupt, the patent tree illustrates how knowledge can outlive its creator and continue to be disseminated. An observer who equates business success of the innovator, one-to-one, with ATP project success may be mistaken, because the indirect path may nevertheless produce important benefits.

Patent Tree Illustrating Extensive Knowledge Flows

Figure 3-4 illustrates just how complex knowledge dissemination through patent citations can become. The path shown is for a patent resulting from an ATP-funded project led by **JDS Uniphase (formerly SDL, Inc.)** and **Xerox Corporation**. With the ATP award, the research team successfully developed high-performance, multibeam red laser diodes; two alternative methods for monolithic integrations of red, infrared, and blue emitters; and several valuable intermediary technologies. From these successes, the ATP-funded project built a strong U.S. technology base for multiple laser applications. Eighty-four inventions from this project have been commercialized into numerous products. This single Xerox patent resulted in approximately 110 citations.

For projects that have received a patent or patents, access to patent trees is available through the individual status reports on the NIST ATP website (http://statusreports-atp.nist.gov/basic_form.asp). Although representing only one aspect of knowledge dissemination, the patent trees extend awareness of the influence of the new knowledge.

Figure 3-4
Patent Tree for Xerox Corporation - Patent 5,963,447
Example of Extensive Knowledge Flows

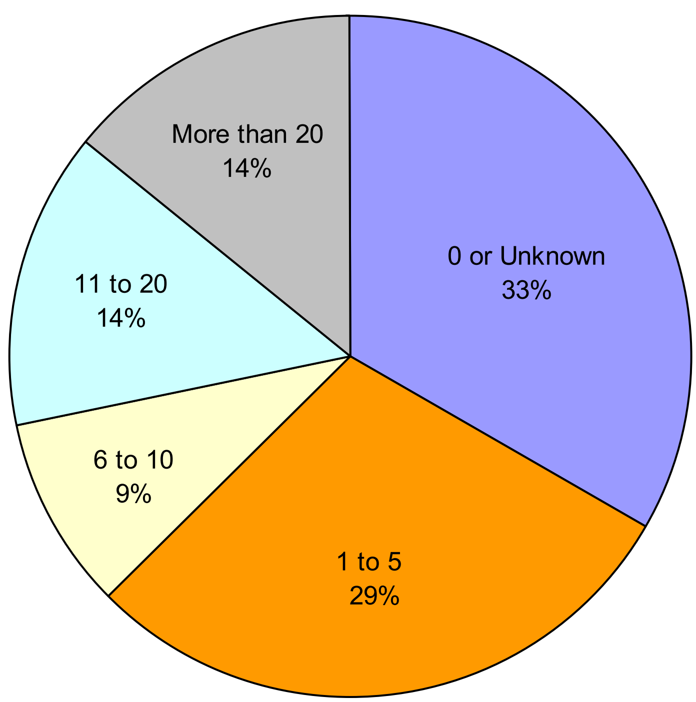


Knowledge Dissemination through Publications and Presentations

Participants in almost 66 percent of the 150 projects had published or had presented papers in technical and professional journals or in public forums. Participants in more than half of all projects had published, and the number of publications totaled at least 831 papers. Participants in nearly 47 percent of the projects had given project-related presentations, and the number of presentations totaled at least 739. Overall, publications and presentations for these 150 projects equaled or exceeded 1570.

Figure 3-5 gives the distribution of projects by their numbers of publications and presentations. Twenty-nine percent of the projects each had between one and five papers published or presented. Nine percent had between 6 and 10 papers published or presented, and another 14 percent had between 11 and 20. At the high end, 14 percent of projects each had more than 20 papers published or presented. Thirty-three percent had no known presentations or publications.

Figure 3-5
Distribution of Projects by Number of Publications and Presentations



Source: Advanced Technology Program First 150 Status Reports

Knowledge Dissemination through Other Means

Aside from publishing, presenting, and patenting, ATP-funded projects have a high rate of collaborative activities. Eighty-seven percent of the projects showed some type of collaboration (see Table 1-1). With so many partners, collaborators, and subcontractors involved, it would be difficult to secure the information. The involvement of so many participants in the projects provides rich avenues of further interaction, and those interactions in turn may increase knowledge flows through personal and professional contacts.

When the government enters into an agreement with an organization, certain information about the agreement is generally made public. Such is the case with ATP and company cost-sharing partnerships. Nonproprietary information has been disclosed to the public for each of the 768 projects funded by ATP in 44 competitions held from 1990 through September 2004 (project information is available on the ATP website[4]). Further, new nonproprietary project descriptions are added to the site as new awards are made. Evaluation reports, such as this one, are also available at ATP's website and provide information to the public.

[4] http://jazz.nist.gov/atpcf/prjbriefs/listmaker.cfm or http://atp.nist.gov (go to Funded Projects Database).

PART 4

Commercialization of the New Technology

New technical knowledge must be used if economic benefits are going to accrue to the nation. This generally means that a new product or process is introduced into the market by the innovating firm, its collaborators, or other companies that acquire the knowledge. In competitive markets, the producer is typically unable to capture all the benefits of a new product or process, and the consumer reaps part of the benefits. The higher up the supply chain the innovation occurs, the more value-added steps there are before final consumption, and the more intermediate firms in the supply chain may benefit, in addition to the final consumer.[5]

(The 150 completed status reports discussed in this chapter can be found on-line at http://www.atp.nist.gov/ under funded projects.)

Commercialization of Products and Processes—A Critical Step Toward National Benefits

When a product or service incorporating new technology reaches the marketplace, a buyer can learn a great deal about the technology. The mere functioning of a new product reveals some information. Intentional investigation, including reverse engineering, reveals even more. More than 60 percent of the 150 projects reviewed for this study had some commercial products or processes based on ATP-funded technology already on the market. Therefore, product use and examination are providing others with information about the new technologies.

Ninety-one of the projects had already spawned or expected to bring to market 222 new products or processes when the data for this report were collected. Companies in 18 additional projects expected to achieve their first commercialized results shortly[6], and

[5] For a detailed treatment of the relationship between spillover benefits (knowledge, market, and network spillovers) and commercialization, see Adam B. Jaffe, *Economic Analyses of Research Spillovers: Implications for the Advanced Technology Program*, GCR 96-708, (Gaithersburg, MD: National Institute of Standards and Technology, December 1996). He notes: "Market spillovers will not be realized unless the innovation is commercialized successfully. Market spillovers accrue to the customers that use the innovative product; they will not come to pass if a technically successful effort does not lead to successful commercialization" (p. 12). In commenting on spillovers that occur because new knowledge is disseminated to others outside the inventing firm, he observes: "Note that even in the case of knowledge spillovers, the social return is created by the commercial use of a new process or product, and the profits and consumer benefits thereby created" (p. 15).

[6] "Shortly" refers to the time when the question is asked. Since Status Reports are written about 5 years after ATP funding ends, the perspective is the same for all status reports. So, when a company answers that

companies in 17 projects that had already commercialized their technology expected to add new products and processes soon. Thus, 73 percent of the projects had spawned one or more products or processes in the market or were expected to do so shortly, for a total of 245 products or processes either on the market or expected shortly after the time the data were collected. Table 4-1 summarizes the commercialization results.

Table 4-1
Progress of Participating Companies in Commercializing the New Technologies

Degree of Progress	Number of Projects	Number of Products/Processes
Project has resulted in at least one Product/Process on the market AND additional Products/Processes are expected soon	17	63
Project has resulted in at least one Product/Process on the market, but no additional Products/Processes are expected soon	74	159
Project is expected to result in a Product/Process on the market soon, but no Product/Process is currently on the market.	18	23
Total Projects that have resulted in Products/Processes on the market OR are expecting to have Products/Processes on the Market soon.	109	245

Source: Advanced Technology Program First 150 Status Reports

A number of additional years have passed since the data for the first 150 projects were collected. Since that time, further developments have doubtless occurred with these projects, which have changed their commercialization results. This overview reports commercial progress of the first 150 projects, all at approximately comparable times following their completion.

A Quick Glance at the New Products

A variety of new products and processes resulted from the projects. For a convenient, quick reference, brief descriptions of the new products or processes for each project are listed in column D in Tables A-1–A-5 in Appendix A. For each new product or process, the new technology on which it is based is also listed in the tables, in column C.

they expect a product or process on the market soon or shortly, they are referring to new product commercialization in the next 3 to 12 months.

Commercialization: A Critical Step, but Not the Final Word

Commercializing a technology is necessary to achieve economic benefit, but it does not ensure that the project is a full success from the perspective of either the company or ATP. Widespread diffusion of the technology may or may not ultimately follow the initial commercialization. Nevertheless, it is significant that these products and processes are actually on the market.

Rapidly Growing Companies

Rapid growth often signals that a small innovating company is on the path to taking its technology into the market, and one dimension of company growth typically is its employment gains.[7]

Figure 4-1 shows employment changes for the 75 small-company, single-applicant ATP award recipients.[8] Twenty-seven percent of these companies experienced job growth in excess of 500 percent from the beginning of the project until several years after the project had completed. Thirty-two percent —the largest share— experienced job growth in excess of 100 percent, ranging up to 500 percent. Mergers and acquisitions accounted for 20 percent, or nine of the 45 projects that experienced substantial job growth (substantial job growth being in excess of 100 percent).

Not all the small companies grew. A little more than one-quarter of them experienced no change or a decrease in staff. Several of the companies that were small when they applied to ATP grew so rapidly they moved out of the small-size category. As a group, of the 75 small single-applicant companies, 45 companies at least doubled in size; 14 of them grew more than 1,000 percent. ATP helped these companies develop advanced capabilities, which they subsequently leveraged into major business endeavors.

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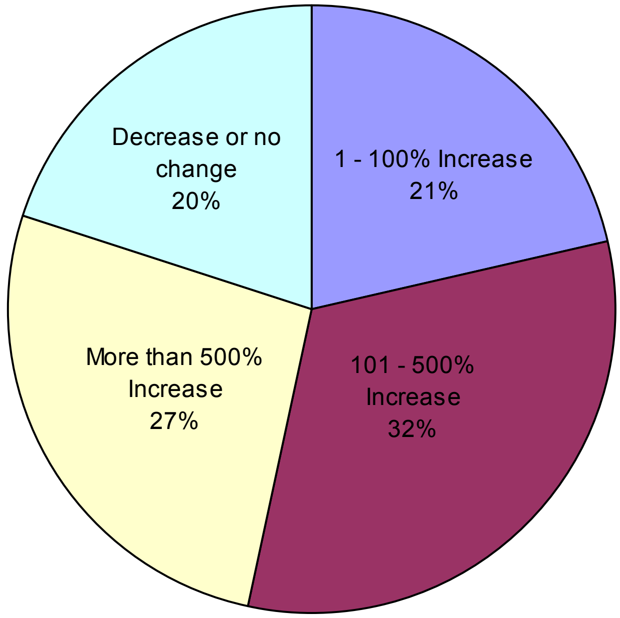
[7] Employment within the small companies is considered as an indicator of commercial progress. Assessing macroeconomic employment gains from the technological progress stimulated by the 150 projects is beyond the scope of this report.

[8] Employment changes in joint ventures, larger companies, and nonprofit organizations are less closely tied to the success of individual research projects, and, therefore, are not included in the employment data in Figure 4-1.

Figure 4-1
Employment Change at Small Companies that Received a Single-Applicant Award



Source: Advanced Technology Program First 150 Status Reports

The following examples illustrate the potential impact of ATP funding on the employment growth of funded companies.

Incyte Corporation grew from 4 to 215 employees due to the development of flexible techniques for manufacturing chem-jet-based microarrays. The technique synthesizes large arrays of specific DNA fragments suitable for medical diagnosis, microbial detection and DNA sequencing, and for creating supplies of detachable oligonucleotides for subsequent use. (Project number 94-05-0019)

Nanophase Technology increased employment from 2 employees at the start of the ATP project to 61 employees at the time the status report was written. The employment is a result of Nanophase's development of a technology that enabled a 25,000-fold increase in the development of nanoscale materials and a 20,000-fold reduction in cost. (Project number 91-01-0041)

Capital Attraction

Attraction of additional capital is another signal that a company is positioned to make further progress. Of the 150 projects, 104 had attracted additional capital to further pursue development of their technologies. Additional funding came variously from collaborative partners, venture capitalists, public offerings of stock, other governmental departments including state government programs, and other sources.

Members of the **Genosensor Consortium** attracted additional internal funding after successfully developing a technology for automated DNA sequence analysis during the ATP-funded project. (Project number 92-01-0044)

eMagin Corporation received a $3 million grant from the U.S. Air Force after successfully developing microdisplays that have been integrated into hundreds of medical, commercial, and military applications. (Project number 93-01-0154)

ABB Lummus attracted additional internal capital after the ATP project as a result of the company's successful development of a new, environmentally superior process to manufacture alkylate using solid-acid catalysts. (Project number 95-05-0034)

The Dow Chemical Company also attracted additional capital due to the methodologies developed during the ATP project to create a direct, economical, single-product oxidation process incorporating a silver-based catalyst for conversion of propylene to propylene oxide. (Project number 95-05-0002)

P A R T 5

Overall Project Performance

The individual performance of the 150 completed projects has varied, as, measured by the creation and dissemination of knowledge and the accelerated use of that knowledge for commercial purposes. Some of the award-recipient companies grew by leaps and bounds as they translated their knowledge gains from ATP-funded research into profitable and beneficial products, services, and production processes. Some continued to strive toward hard-to-achieve goals, while others showed little outward signs of further progress. A few that achieved impressive research accomplishments later failed in the commercialization phase. However, the achievements of the more successful projects, with their impressive new performance capabilities resulting in lower costs and higher quality products and processes, appear to have much more than compensated for the less successful projects. There is considerable evidence that the benefits attributable to ATP from the 150 completed projects substantially exceed their costs.

(The 150 completed status reports discussed in this chapter can be found on-line at http://www.atp.nist.gov/ under funded projects.)

Composite Performance Scores

During the intermediate period covered by this analysis—after project completion but before long-term benefits have had time to be realized—ATP uses a Composite Performance Rating System (CPRS) to help gain a sense of how projects in the portfolio have performed overall thus far against ATP's mission-driven multiple goals.[9] In this intermediate period of project life cycles, the focus is on progress toward the goals of 1) knowledge creation, 2) knowledge dissemination, and 3) commercialization. The CPRS uses a weighted composite of output data systematically collected for each of the 150 projects—some of which have been presented in aggregate form in the preceding sections of this overview—to assess overall performance of the portfolio of completed projects in this intermediate period.

The output data serve as indicator metrics of progress toward achieving goals. Examples of available indicator metrics signaling progress toward the creation and dissemination of knowledge are a) awards for technical excellence bestowed by third-party organizations,

[9] For an in-depth treatment of the CPRS, which was developed in prototype for ATP's use, see Rosalie Ruegg, *Bridging from Project Case Study to Portfolio Analysis in a Public R&D Program*, NIST GCR 03-851 (Gaithersburg, MD: National Institute of Standards and Technology, 2003).

b) patent filings, c) publications and presentations, d) knowledge dissemination from potential reverse engineering of new and improved products/processes on the market or expected soon, and e) collaborative activity. Available indicator metrics signaling progress toward commercialization of the new technology include a) attraction of additional capital, b) employment gains, c) project-related company awards for business success, d) moving products and processes into the market, and e) analysts' outlooks for future progress by the award-recipient companies.

Weights are assigned to the indicator data, which are combined to produce a composite numerical score that is then converted to a zero- to four-star rating for each project. A score of one star or less signals poor overall performance; two stars, moderate performance; three stars, strong performance; and four stars, outstanding performance. The distribution of CPRS scores computed for each project in a portfolio of projects is then examined, and the results taken as indicative of overall portfolio performance.

The resulting CPRS ratings provide an easy-to-grasp highlighting of portfolio performance in the intermediate period. They call out those projects that have exhibited outstanding or strong outward signs of progress towards long-run program goals during the years covered and those that have exhibited moderate or few signs of progress. However, the ratings are imperfect and should be viewed as only roughly indicative of overall performance.

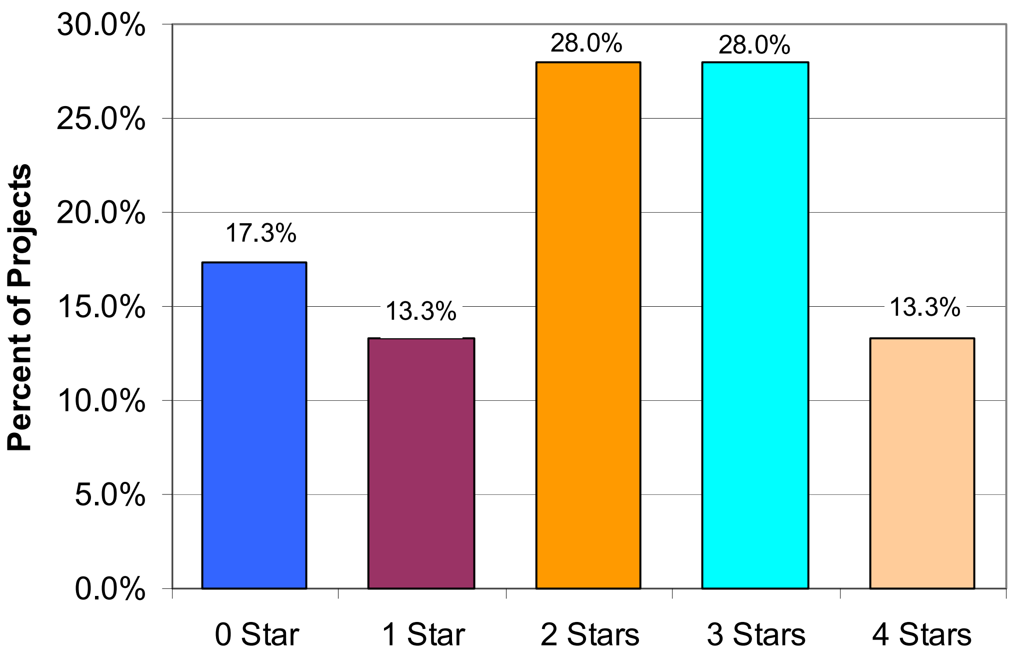
The performance metrics are consistent with the view of varying degrees of success—with knowledge creation and dissemination constituting partial success, and a continuation into commercialization constituting a fuller degree of success in terms of project progress. Some companies carried out their proposed research with a degree of success during the time of ATP funding, but then did not continue pursuit of their project's larger goals after ATP funding ended. At this stage of evaluation, ATP considers such projects only partial successes, because the direct path for achieving project goals is truncated. Such projects are not among the higher scorers in this report. It is possible, however, that developments along the indirect path (diffusion of knowledge from the project through publications, presentations, patents, and licensing) may nevertheless occur—particularly if a project produced effective knowledge transmitters, such as patents and publications. It is also possible that a company may work in secrecy for a long period of time with no visible outputs and then suddenly explode on the scene with a single output that will yield large societal benefits.

Limiting factors include the extent to which not all relevant effects are captured; moreover, the use of indicator metrics is constrained by data availability, the development of the weighting system is empirically driven rather than theoretically based, and the ratings do not directly measure national benefits. The degree of correlation between a project's performance score and its long-run societal benefits is impossible to know at this time. Projects with the same scores are not necessarily equal in their potential benefits. They are, however, somewhat comparable in terms of the robustness of their progress to date.

Scoring the First 150 Completed Projects

The distribution of CPRS scores for ATP's first 150 completed projects is shown in Figure 5-1. Combining the two and three-star categories shows 56 percent of projects performed at a moderate level. Thirteen percent of the projects performed at a high (four-star) level and approximately 30 percent of the projects scored one star or less, perhaps not surprising for companies taking on difficult goals.

Figure 5-1
Distribution of Projects by Star Rating



Source: Advanced Technology Program First 150 Status Reports

The 20 four-star projects overall include 16 single-applicant projects led by small companies and four joint ventures, two led by a consortium and two led by small companies. Leaders of these top-scoring projects are listed in Table 5-1.

Table 5-1
List of Four-star Projects

Aastrom Biosciences, Inc.	Nanophase Technologies Corporation
American Superconductor Corp.	National Center for Manufacturing Sciences (NCMS)
Automotive Composites Consortium (a Partnership of DaimlerChrysler [formerly Chrysler], Ford and General Motors)	Orchid BioSciences (formerly Molecular Tool, Inc. Alpha Center)
Cerner Corporation (formerly DataMedic - Clinical Information Advantages, Inc.)	SciComp, Inc.
ColorLink, Inc.	SDL, Inc. and Xerox Corporation
Cree Research, Inc.	Third Wave Technologies, Inc.
Engineering Animation, Inc.	Tissue Engineering, Inc.
Integra LifeSciences	Torrent Systems, Inc. (formerly Applied Parallel Technologies, Inc.)
Kopin Corporation	Xerox Palo Alto Research Center
Large Scale Biology Corporation (formerly Large Scale Proteomics Corporation)	X-Ray Optical Systems (XOS), Inc.

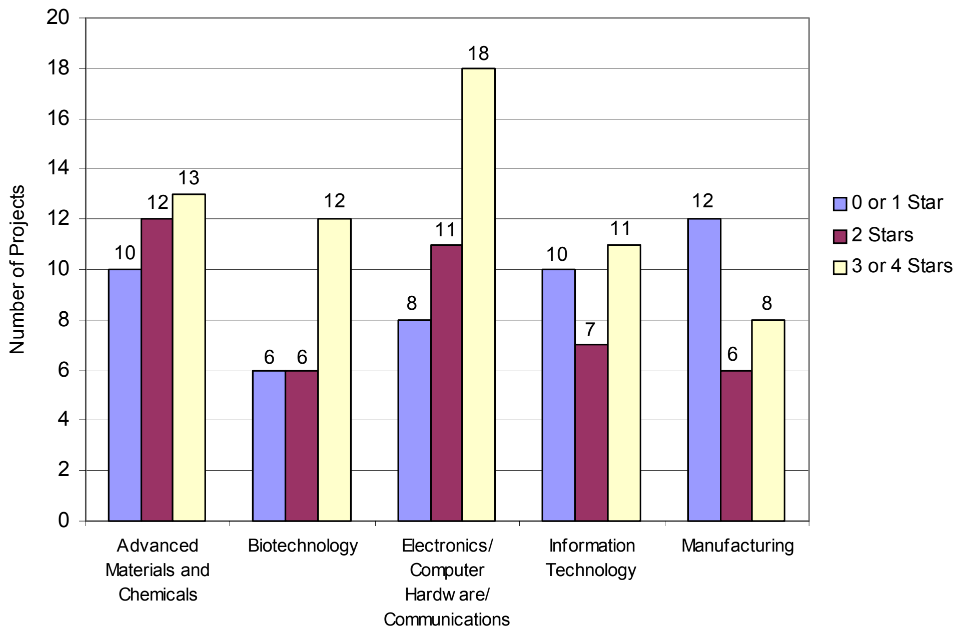
The three-star projects included 35 single-applicant projects and 7 joint-venture projects. Of the single-applicant projects, 25 were led by small companies, two by medium companies, and eight by large companies. Of the joint ventures, two were led by small companies, two by an industry consortium, two by a large company, and one by a nonprofit organization.

A few projects with low CPRS ratings had impressive technical achievements as indicated by the receipt of a third-party technical award, though most of the technical awards went to those with the highest overall ratings. In contrast, all of the awards for business acumen went to the projects with CPRS ratings of three or four stars

Performance by Technology Areas

Overall project performance in the intermediate period covered by the study varied by technology area, as illustrated in Figure 5-2. Of the 24 Biotechnology projects, 12 were three- or four-star projects. Of the 37 Electronics projects, half scored high. Of the 26 Manufacturing projects, close to third scored high, but 46 percent scored low. The 35 projects in the Advanced Materials and Chemical group were more evenly divided into high, low, and moderate scorers. The 28 Information Technology projects had 11 projects that were high-scoring projects, 7 moderate-scoring, and 10 low-scoring projects. Differences in life cycles among the technology areas may account for part of the performance differences, but the relatively small number of projects in each category does not support the drawing of robust conclusions about how projects in the different technology areas will perform.

Figure 5-2
Number of Composite Scores by Technology Area



Source: Advanced Technology Program First 150 Status Reports

Project Performance Translated into Economic and National Security Benefits

Photonics

ATP has provided cost-sharing funding to more than 120 photonics projects since 1991[10]. To access the economic benefits from a portion of these projects, the author adopted a cluster study approach to combine the methodological advantages of detailed case studies and of higher level overview studies. The following five projects were selected for analysis: Capillary Optics for X-Ray focusing and Collimating; MEMS-Based Infrared Micro-Sensor for Gas Detection; Infrared Cavity Ring-Down Spectroscopy; Optical Maximum Entropy Verification; and Integrated Micro-Optical Systems.

Findings from the study indicate that U.S. industry and consumers, and the nation, will enjoy at least $33 of benefits for every dollar of ATP's $7.47 million investment in the cluster of five projects. ATP technology translates into $1.90 already realized benefits generated for every dollar of ATP's investment in the five projects.

Component-Based Software (CBS)

Developing the capacity to build large software systems from assemblies of smaller, reusable, independent components is an important strategy to reduce software system

[10] Pelsoci, Thomas, M., *Photonics Technologies: Applications in Petroleum Refining, Building Controls, Emergency Medicine, and Industrial Materials Analysis*. NIST GCR 05-879 (Gaithersburg, MD: National Institute of Standards and Technology, September 2005).

costs, increase system reliability, and enable lower cost upgrades. Three projects included among the first 150 Status Reports were part of a portfolio of 24 projects that was included in an in-depth economic case study conducted by RTI.[11] These projects were led by **Reasoning Inc.**, **TopicalNet, Inc. (formerly Continuum Software)**, and **HyBrithms (formerly Hynomics Corp.)**.

Across the entire CBS portfolio, RTI's economic study estimated $840 million in net-present-value benefits and a benefit-to-cost ratio at 10.5, suggesting that the investment in the portfolio of projects as a whole was worthwhile. The net-benefits estimate is based on the cost of all 24 projects, but the benefits of only 8 were the subject of the detailed case study. In addition, the study found other benefits that were presented qualitatively, namely, enhancing the credibility of the mostly small software firms that were funded and assisting firms in strengthening their planning and management functions.

Reasoning Inc., TopicalNet Inc. (formerly Continuum Software), and Hynomics Corp. (formerly HyBrithms) had commercialization activities underway when RTI conducted its study. Their costs, but not their benefits, were included in RTI's aggregate portfolio net-benefit measure, because they were not among the eight projects selected by RTI for the portfolio benefits assessment. Thus, the RTI study results, at best, suggest that the three projects are part of a portfolio of projects found to be valuable. Of the three projects, two are rated as three-star performers, and one is a two-star performer.

It is also informative to look at how some of the other projects that were rated as top performers have progressed since the original data were compiled and the CPRS ratings calculated. Additional projects are profiled below.

Scalable Parallel Programming

One of the top-performing projects among the first 50 completed projects, originally profiled in Volume 1, was a project led by **Torrent Systems, Inc.** Although Torrent had fewer knowledge-dissemination outputs than the other top-performing projects, its exceptional commercialization efforts boosted it into the four-star group. The project developed a component software system that insulates programmers from the complexities of parallel programming while allowing them to use it productively in scalable applications. Torrent delivered this new capability in its software product, Orchestrate™. An early user of the new software, United Airlines, was able to increase its revenue by $100 million per year as a direct result of using Orchestrate™.[12]

When revisited in Status Reports, Volume 2, Torrent's technology was reported to be enabling e-businesses and other companies to process and analyze unlimited volumes of data. Torrent was listed in *Computerworld's* "100 Hot Emerging Companies" in 1998 and received a number of other awards recognizing both its software technology and business acumen.

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[11] White and Gallaher, November 2002.

[12] Information from Hoover's Online company search and Torrent's website, current August 31, 2000.

Since that time, Torrent, which had only two employees when it received its ATP award, has been acquired for a purchase price of $46 million by Ascential Software Corp., a global company with a market capitalization of $1.1 billion, headquartered in Westboro, Massachusetts.[13] According to Ascential's Chairman and CEO, Peter Gyenes, "Torrent's patented and proven parallel processing technology is a perfect complement to the rich feature set within our data integration solution, DataStage."[14] According to additional public statements by the company, Ascential has integrated Orchestrate™ into its DataStage XE product family, with the result that customers will be able to integrate data of virtually any volume and complexity, with infinite scalability, and turn growing amounts of data into valuable information assets.

United Airlines, first a Torrent customer and then an Ascential customer, is using Orchestrate™ and an IBM parallel-processing computer to design a system for managing airplane seat assignments. A statement by Bob Bongirno, managing director of applications development for United Airlines, which is posted at the Ascential Software Corp. website provides a user's perspective of the importance of the product:

> *"At United, we analyze 'astronomical' amounts of data every day through our Orion system to determine the optimum seat availability and price across tens of millions of passenger itineraries," he said. "For Orion and our other data-intensive applications, we demand a parallel processing technology that is robust and reliable enough to process massive data volumes on very large systems and will provide a state-of-the-art data integration foundation that helps us manage all our disparate data sources and accelerates the development of new applications. The combination of technologies from Torrent and Ascential holds great promise for meeting the data processing needs of customer-centric organizations like United."*

Thus the commercialization path has grown more complex for this ATP-funded technology as the technology has been combined with other software elements. At the same time, the impact potential of the technology appears strong. According to Doug Laney, META Group Vice President, the worldwide market for data integration was projected to grow from $900 million in 2001 to $1.3 billion in 2004,[15] and the technology platform funded in part by ATP appears well positioned to play a role in serving this growing market. Those projections were well-founded. Ascential grew rapidly in 2004, with a 46 percent increase in total revenue. In March 2005, Ascential agreed to be acquired by IBM for approximately $1.1 billion, strengthening IBM's fast-growing information integration business.[16] (Project number 94-06-0024)

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[13] Standard and Poor's stock report on Ascential Software Corp.

[14] Press Release, November 28, 2001, available on-line at www.ascentialsoftware.com, Press Center.

[15] Ibid.

[16] Company press release, "IBM to Acquire Ascential Software." March 14, 2005. (http://ibm.ascential.com/news/pr.html/view/1107)

High-Temperature Superconducting (HTS) Wire

The project led by **American Superconductor Corporation (AMSC)** is another of the top-rated 100 completed projects profiled originally in Status Report Volume 1. At the time Volume 1 was being written, the company was beginning to launch its commercialization effort. Since then, the company has reportedly continued making impressive advances, building the world's first high-volume HTS wire manufacturing plant with a capacity to manufacture 20,000 kilometers of wire per year when it is fully equipped. This new manufacturing capacity is said to give potential customers the ability to accelerate their schedules for launching commercial products incorporating HTS wire by making the product available to them in commercial quantities, at commercial prices.[17] AMSC's products and services listing now shows a vertically integrated portfolio that includes HTS wire, motors, generators, synchronous condensers, industrial power quality solutions, power conversion, and transmission grid solutions.

A press release issued October 1, 2003, announced that AMSC had received additional funding from the Department of Defense (DOD) and Department of Energy (DOE) to support further manufacturing scale-up for second-generation HTS wire. According to Dr. Paul Barnes, U.S. Air Force Superconductivity Team Leader, ensuring that the United States will have a reliable supply of the second-generation HTS wire is expected to be central to the development of many future military systems, including lightweight high-power generators and advanced weapon systems. According to James Daley, manager of the Superconductivity program at DOE, the technology is also expected to play an important future role in upgrading the nation's power grid.[18] (Project number 91-01-0146)

Visualization Software

As in the preceding examples, **Engineering Animation, Inc. (EAI)**, leader of another of the top-performing projects and originally profiled in Status Report Volume 1, continued to aggressively and successfully pursue applications of its award-winning imaging software capabilities developed in the ATP-funded project. Founded by two professors and two graduate students in 1990, EAI had 20 employees at the time ATP made the award. According to company officials, the ATP award allowed it to significantly extend its capabilities in computer visualization and computations dynamics and to form important collaborative relationships that enabled it to leverage the technology in many different directions. The company used its ATP-funded technology to improve the training of doctors as well as to guide medical procedures. Furthermore, patients reportedly had better outcomes when the visualization software was used during their surgical procedures.

In 1999, the company employed approximately 1,000 staff members and had sales of $71 million. At that time, EAI had extended and deployed its award-winning visualization

[17] Information provided by the company at its website, www.amsuper.com.

[18] Company press release, October 1, 2003.

capabilities to develop a virtual factory technology implemented at Ford Motor Company. This application of the software enabled faster design and analysis of factory models.

On October 23, 2000, EAI was acquired by Unigraphics Solutions Inc. for $178 million. Subsequently, through acquisition and merger, Unigraphics and another software services company, SDRC, became a combined subsidiary of Electronic Data Systems Corporation (EDS), the world's largest information technology outsourcing services company, which has a worldwide infrastructure and 138,000 employees.[19] Unigraphics and SDRC were combined to form EDS's fifth line of business, Product Lifecycle Management (PLM) Solutions. This union provided, through Unigraphics NX software, a unified approach to extended enterprise collaborations enabling the modeling and validation of products and their production processes digitally from initial concept to finished parts. Thus, EAI followed the business model for growth of merging with a much larger company.[20] An online search revealed that previously developed EAI products and books remain on the market. (Project number 91-01-0184)

Examples of strong projects from among the three and four -star group are described below. These, too, appear to be delivering important economic benefits.

Improving Software Efficiency through Reusable Components

An example is a four-star project led by **Xerox Parc** which is credited with developing aspect-oriented programming (AOP) and later developed products that incorporated its principles. After the ATP funded project ended Xerox developed AspectJ, an open-source language based on AOP. Aspect J extends Java; and is being further developed and used in IBM's software applications and by many others. Eight patents emerged from this ATP-funded project and more than 3,250 articles or books have been written about AOP. In June 2003, AspectJ won the JavaWorld Editors' Choice Award for the Most Innovative Product or Technology Using Java. (Project number 94-06-0036)

Miniature LCSs Enhance High-Definition Displays

Another four-star project with continued strong commercialization was led by **Kopin Corporation**. Kopin formed a joint venture with Philips, and together with their subcontractor, Massachusetts Institute of Technology facilitated a paradigm shift in high-definition display technology. During the ATP funded project, Kopin and Philips combined existing monochrome liquid crystal displays (LCDs), with color, signal processing, and high-definition technology. Independently, Philips successfully commercialized high-resolution projection HDTVs using the ATP-funded technology. Kopin also successfully applied the ATP-funded enabling technology in numerous applications including miniaturized display applications for use in viewfinders for camcorders and digital cameras, wearable computers, virtual reality games, and military

[19] Prior to the acquisition of Unigraphics, EDS was the major company stockholder. Information found at www.eds.com.

[20] Ibid.

applications. LCD projection display technology is a key product differentiator in U.S. electronics manufacturing. (Project number 94-01-0304)

Structural Composites for Large Automotive Parts
As a result of the ATP funded project the **Automotive Composites Consortium-ACC**, (A partnership of DaimlerChrysler [formerly Chrysler], Ford and General Motors) successfully produced a prototype box for a pickup truck that is stronger and more durable than steel, does not rust, is visually attractive, requires no bed liner, and improves fuel efficiency through its light weight (36 pounds, or 33 percent, lighter than steel). This pickup truck box gave the ACC member companies (General Motors [GM], Ford, and Chrysler, which later became DaimlerChrysler) the knowledge and tools to develop commercial products and to continue innovative research, based on this initial success. Applications of this successful ATP-funded technology include strong, lightweight components for aircraft, firefighter helmets, and marine motor covers. Project researchers shared their developments through one granted patent and several articles and presentations. As public acceptance of tough, durable composites increases, applications are expected to broaden. (Project number 92-01-0040)

To these examples, other promising technologies may be added—technologies that improve productivity, facilitate better weather forecasts, improve communications, enable new drug discovery, reduce energy costs, and improve health and safety.

What Difference Did ATP Make?

ATP aims to improve the international competitiveness of U.S. firms by funding projects that would not take place in the same timeframe, on the same scale, or with the same goals without ATP's support. A project may be successful in terms of achieving its goals, but if the same accomplishments would have occurred in the same timeframe without ATP, then the program has not had the intended effect. For this reason, evaluation studies of ATP—as well as other government programs—should apply the principle of "additionality" to correctly distinguish between benefits that would likely have occurred anyway and those benefits that are reasonably attributable to ATP.

In preparing the 150 individual mini-case studies, analysts asked project leaders about the role ATP funding played in their projects. Throughout the project selection process, beginning with the application, ATP presses the questions of why the project requires ATP funding, why funding is appropriate, what will happen if ATP funding is not provided, and how the expected outcome will differ with and without ATP involvement. During the evaluation process, these questions are again pursued retrospectively, i.e., what happened that was different as a result of ATP? Applied prospectively, the results are hypothetical. In evaluation studies, the results may be based on counterfactual survey and interview questions, such as those posed in the status report case studies. Evaluation studies have also used control group techniques, which provide more reliable evidence of the additional impacts of ATP.[21]

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[21] See *Survey of Applicants 2002*, NIST GCR 05-876, (Gaithersburg, MD: National Institute of Standards and Technology, June 2005).

Forty-six percent of the respondents indicated their projects would not have happened at all without ATP funding. Indeed, some participants said their companies would have gone out of business had the ATP award not been made.

Thirty-eight percent of the respondents said they would have attempted the project at some later date or at a slower pace and that ATP funding enabled them to accelerate the technology. Table 5-1 shows the project time savings attributed to ATP for those projects that reported they would have proceeded without ATP funding. With ATP, the projects avoided delays ranging from six months to five years and more. The acceleration of some of the projects may seem short; however, the value of even a small acceleration can be substantial. Speed in developing and commercializing a technology can also mean increased global market share for U.S. producers.

Table 5-2
Effect of ATP Funding on Expected Timing of Research

Effect on Project			Number of Projects
Would not have conducted Project without ATP funding			69
Would have proceeded without ATP funding, but with a delay*:			57
	Length of Delay		
	6 months	*1*	
	12 months	*3*	
	18 months	*7*	
	21 months	*3*	
	24 months or more	*10*	
	More than 5 years	*11*	
	Delay, but time unspecified	*22*	
No Response			24
Total			150

Source: Advanced Technology Program First 150 Status Reports

*Another factor potentially influenced by ATP funding (the scope and scale of the project) was not explicitly covered.

**The Printed Wiring Board Joint Venture project had a split response: half the tasks would not have been done at all and half would have been delayed by at least a year. This result is recorded conservatively in Table 5-1 as a two-year delay.

A number of companies also reported other effects of their ATP awards. Some reported that receiving their award enhanced their ability to raise additional capital. Some reported that their award helped them form collaborative relationships for research and commercial activities. Others reported that receipt of their ATP award had enabled them to gain in international competitiveness.

What Constitutes Success and Failure for ATP?

Because individual project failure must be allowed and tolerated in a program that focuses on overcoming challenging technical barriers to innovation, it is essential to take a portfolio approach to assessing ATP. Moreover, success should be assessed against the legislated mission of the program.

Four general tests, and several additional specific tests—all derived from ATP's mission—if applied after sufficient passage of time, should reveal the extent to which ATP has successfully met its mission, as described below.

Test 1: Has the portfolio of ATP-funded projects overall produced large net social benefits for the nation?

Test 2: Has a substantial share of net social benefits accrued to citizens and organizations beyond ATP direct award recipients?

Test 3: Did ATP make a substantial positive difference in the size and timing of the benefits?

Test 4: Has the portfolio of ATP-funded projects enhanced United States' economic and technological competitiveness?

Additional specific tests of success include the following: Did the projects produce new scientific and technical knowledge? Did ATP increase collaboration? Were small businesses able to participate? Were manufacturing capabilities improved?

While the ultimate answers to these success "test questions" depend on the long-run impacts of the entire portfolio of ATP projects, the performance-to-date of the sub-portfolio of 150 projects provides emerging answers.

There is mounting evidence that the tests for program success are being met. First, there is strong evidence that social benefits of the portfolio are large and exceed program costs. Second, there are benefits extending well beyond those captured by the direct award recipients: there is substantial evidence of knowledge and market spillovers as others cite the project patents and use the products. Third, there is evidence that ATP has made a significant difference in the amount and timing of benefits, as well as having other beneficial impacts on the companies. Fourth, there is some evidence of improvements in the competitiveness of U.S. companies.

The performance ratings show that the majority of the projects continued to make progress in the several years after ATP funding ended. Moreover, the portfolio has been shown to contain a core group of highly active and productive projects that are successfully accomplishing their high-risk project goals.

ATP awarded a total of $621 million to the 150 completed projects. Questions of keen interest are what is the public investment producing in the way of benefits, and are the tests for program success being met? Estimated benefits attributed to ATP from just a few of the 150 projects for which quantitative economic benefits have been provided exceed ATP's funding for all of the 150 projects. In addition, there is considerable evidence of large project benefits that have not yet been quantified.

This completes the portfolio view of ATP. Appendix A that follows provides an overview of the 150 individual projects that make up the portfolio. Appendix B describes reasons that some ATP-funded projects did not proceed to completion. Appendix C lists the first 150 completed projects along with their CPRS star ratings.

Abrasive Technology Aerospace, Inc

CAD/CAM Technology Advances Superabrasive Grinding

In 1995, a highly efficient grinding process called superabrasive grinding was beginning to be used by manufacturers in the automotive and industrial sectors. Superabrasive grinding, which uses tools such as the electroplated superabrasive grinding wheel, removes material faster and achieves more exacting dimensional tolerances than traditional grinding. The grinding wheel that is used is a metal hub with a single layer of superabrasive material, such as diamond, plated to a machine rim. Although it was underutilized in the United States, especially when compared with Europe or Japan, its use was expected to grow as manufacturers increasingly adopted difficult-to-machine materials, such as ceramics and superalloys. However, the initial cost of developing the wheels used in the process was high, turnaround time was slow, and producing the wheels was labor intensive.

Abrasive Technology Aerospace, Inc., the world's largest U.S.-owned manufacturer of cubic-boron-nitride-plated and diamond-plated tools, proposed to develop an integrated computer-aided design/computer-aided manufacturing (CAD/CAM) approach to apply superabrasive coatings to the complex surfaces of electroplated superabrasive grinding wheels. This was a high-risk endeavor, as it involved computer-based predictive design, which was a new concept at the time. However, the company also anticipated that a CAD/CAM approach would result in a 90-percent reduction in order turnaround time and a significant reduction in cost. In 1995, after unsuccessful attempts to secure funding from the private sector and other government sources, Abrasive Technology applied for cost-shared funding through the Advanced Technology Program's (ATP) focused program, “Motor Vehicle Manufacturing Technology”.

By the end of the ATP project in 1998, Abrasive Technology had successfully reached its goal of developing an advanced high-precision grinding wheel technology and had reduced turnaround time from several weeks to three days. Since 1998, the company has continued to manufacture more complex, higher tolerance grinding wheels and has increased its sales of the wheels to a variety of industries, including automotive and aerospace.

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

Research and data for Status Report 95-02-0053 were collected during January 2003.

NCMS Recommends Development of Superabrasive Grinding

Grinding is a major material-removal process in manufacturing. In 1994, the National Center for Manufacturing Sciences (NCMS) completed a study on the importance of grinding in the United States, "US Grinding Partnership - 2000." The study recommended the development of high-speed grinding using grinding wheels plated with superabrasive cubic boron nitride (CBN) or diamond, which were the two hardest known materials.

Superabrasive grinding combines grinding at high wheel speeds with deep-cut, creep-feed grinding (a process in which a formed grinding wheel is plunged into the workpiece, slowly producing a finished part in a single pass). With superabrasive grinding, it is possible to achieve both high dimensional tolerances and high surface-finish tolerances at less cost and in less time than through conventional grinding.

By 1995, superabrasive grinding was an emerging yet underutilized technology in the United States. The initial application development cost of plated wheels was high, turnaround time for the product was slow, and the process to produce the wheels was labor intensive. Also, U.S. manufacturers had little knowledge of the high-speed grinding process, and wheel builders did not have significant experience building low-cost plated wheels for this process.

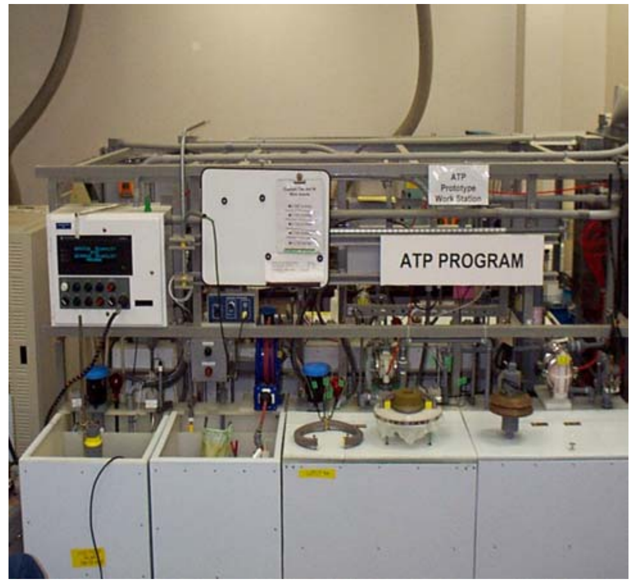
Abrasive Technology Proposes CAD/CAM System

Abrasive Technology Aerospace, Inc. agreed with the conclusions of the NCMS study. The company's goal was to develop an innovative computer-aided design and computer-aided manufacturing (CAD/CAM) system for the rapid design and manufacturing of plated superabrasive grinding wheels. This new system would reduce the time it took to design, fabricate, and electroplate a new wheel design from three to eight weeks to three days, as well as significantly reduce the cost. If successful, Abrasive Technology would establish a new standard for the rapid, low-cost manufacture of high-precision plated superabrasive grinding wheels.

By 1995, superabrasive grinding was an emerging yet underutilized technology in the United States.

The CAD/CAM technology would consist of a predictive design system, based on existing software, as the technology engine for an electrodeposition CAD station; a CAM station for the electrodeposition of plated grinding wheels; and the integration and validation of the resulting software and hardware into a working prototype system. The technology would enable the full integration of a grinding tool request, from the time an order was entered until it was tested and shipped.

Abrasive Technology realized that the development of the CAD/CAM technology was a high-risk endeavor. This was because the concept of a computer-modeling tool that could accurately predict the best



A prototype of a CAM plating workstation incorporates features that could be refined and specified from the CAD system.

manufacturing conditions to produce acceptable thickness distributions on a plated part was new. At the time, only one software package, Cell Design, was capable of simulating an existing plating process at the request of a user. This two-dimensional software, which was owned by L-Chem, Inc., a subcontractor to the project, had no predictive design capabilities. However, the anticipated benefits encouraged Abrasive Technology to pursue this project. At the time, funds for research and development were limited, and Abrasive Technology estimated it would take 10 years to complete the project. By that time, business would have shifted to foreign suppliers. Abrasive Technology predicted that with ATP support, it could complete the project in three years, and so, in 1995, the company submitted a proposal to ATP for funding within the “Motor Vehicle Manufacturing Technology” focused program.

Broad-Based Benefits Could Expand Nation's Competitive Position

Abrasive Technology believed that using an integrated CAD/CAM technology to design, fabricate, and electroplate new wheel designs would significantly increase the rate at which plated complex-form wheels were produced, resulting in substantial cost savings. Manufacturing advances in applying close-tolerance superabrasive coatings to complex surfaces that used 100-percent electrodeposition technology would improve the quality and reliability of the wheels.

The company anticipated a 50-percent increase in plated form wheel usage. Because of the significant cost savings that would accrue in producing wheels for superabrasive grinding, manufacturers using more traditional grinding methods would be able to cost-effectively convert to this more efficient grinding process. Using this new process would provide immediate benefits: the manufacturers could remove material faster, use fewer steps to form various complex parts made from new materials to final dimension, and reach finished tolerances more quickly and at less cost.

New CAD/CAM System Is Successfully Developed

Abrasive Technology began its development of the CAD/CAM technology by conducting short focused studies of the entrapment of superabrasives in the plating process. Although electroplating and electroless plating had been studied in the past, these processes had not been associated with the bonding of precision conformal coatings of abrasive particles over complex part geometries. Much of the work in studying this relationship was performed at Case Western Reserve University.

Abrasive Technology would establish a new standard for the rapid, low-cost manufacture of high-precision plated superabrasive grinding wheels.

One of the major challenges that Abrasive Technology faced was how to improve the CAD process so that the company could rapidly analyze the manufacturing process parameters of a customer's request. It could then determine the feasibility of the parameters in terms of coating placement, thickness, abrasive concentration, and allowable process variation. To successfully apply plated diamond and CBN to abrasive-coated parts and tooling, several computer-based modeling techniques for feasibility assessment, process design, process operation, and process prediction had to be developed. The new software had to be integrated into drafting software similar to AutoCAD. A portion of this CAD modeling development work, which involved modifying Cell Design, was performed by L-Chem, Inc..

Next, Abrasive Technology began to develop a prototype of a CAM plating workstation, which incorporated features that could be refined and specified from the CAD system. The workstation was designed to permit fabrication to close tolerances specified by a mathematical model. The central part of the prototype plating station, a high-precision plating-cell fixture, was then engineered and constructed according to the features and specifications generated from the CAD system.

The new software has been used to produce grinding wheels for a variety of industries, including automotive and aerospace.

Abrasive Technology attempted to automate the process for applying abrasive to plated complex-form wheels. The company believed that automating this process was necessary to achieve consistency, reduce manual labor, and minimize bare spot fill during plating. With the new system, a metering device would dispense the abrasive on the area to be coated. Automation of the abrasive application, however, turned out to be very difficult to implement, so this activity was abandoned in the first year of the project.

Abrasive Technology also developed a test prototype control system. This control system was central to automating the routine manual steps in the plating process. Data from the research and modeling phases of the project were used to predict optimal control parameters for applied current, voltage, and time to minimize plating time and produce the highest quality plated product. Simultaneous monitoring and control of applied current and voltage were expected to produce a good part the first time. The major features of the control system were:

- Control for process actuators and pumps
- Control for process chemistry (pH, temperature, and concentration)
- Data logging for test, evaluation, and quality control

Finally, the integrity between the output from the computer-based manufacturing tools and the prototype plating workstation was validated to test modeling and plating station performance across a variety of complex forms. The goal was to demonstrate an actual physical plating station that would perform according to the predictive model and produce a product correctly the first time.

Prototype Is Constructed and Tested

By the end of the project, Abrasive Technology had collected experimental data on plating solution chemistries, and kinetic parameters had been successfully quantified. The software that was integrated with the AutoCAD interface was working well, resulting in a faster and more efficient design process. However, extension of the software to incorporate three-dimensional surface solutions (for nontraditional machining) was only partially achieved. Overall, though, the functionality of Cell Design was greatly improved over the 1995 MS-DOS demonstration model.

The prototype CAM plating workstation was successfully constructed and testing of it continued. Development of the high-precision plating-cell fixture, the central part of the plating workstation, proved to be a great success. Abrasive Technology was able to cost effectively apply the new design/engineering technology to increasingly more difficult and high-precision wheel geometries. The prototype control system was also completed and testing was expected to continue for at least two years.

Abrasive Technology then integrated the CAD system with a new technology database and the manufacturing process workstation. (The database was created to join together critical parts of the CAD/CAM system.) The systems integration and testing proved successful. Afterward, an integration team at the company used the new technology on a trial basis. Abrasive Technology produced parts while receiving prototype production orders for field testing and customer acceptance evaluations. At the same time, a cross-company integration team for "rapid technology transfer" met on a regular basis.

Superabrasive Grinding Wheel Market Increases

In 1998, at the end of the ATP project, Abrasive Technology began to look into superabrasive grinding wheels for gas turbines as a potential market for the CAD/CAM technology. The new technology could be used to create automobile parts, stationary power generators, and turbo chargers. Also, the automotive industry had shown strong interest in using superabrasive grinding wheels for the production of parts for co-generation power plants, facilities that burn fossil fuel to produce both steam and electricity. Another potential opportunity was through the Department of Energy, which was expected to use superabrasive grinding tools in a major initiative for a ceramic turbine engine hybrid power plant within the automotive industry. Abrasive Technology also participated in exploratory meetings with the University of Massachusetts at Amherst and the University of Toledo to discuss the longer range application of high-precision ceramics grinding.

Between 2000 and 2001, Abrasive Technology earned $600,000 from the sale of complex, close-tolerance electroplated superabrasive grinding wheels and anticipated that revenue from these products would exceed $1 million by 2003. In response to interview questions in 2003, the company stated that, as a result of the ATP-funded project, it is now producing more complex, higher tolerance grinding wheels with increased repeatability. Moreover, since the project ended, sales of the wheels have increased. The new software has been used to produce grinding wheels for a variety of industries, including automotive and aerospace.

The newer grinding wheels allow designers in the automotive industry to specify parts with closer tolerances and finer surface finishes that are made from a greater variety of materials. In the aerospace industry, use of the wheels for superabrasive grinding has resulted in increased productivity and significant reductions in engine production costs, enabling companies to remain competitive with overseas manufacturers.

According to Loyal Peterman, the President of Abrasive Technology, "The computer-aided design and manufacturing process is now part of our technology base for wheel production."

Conclusion

By the end of the ATP-funded project, Abrasive Technology had successfully reached its goal of developing an advanced high-precision grinding wheel technology through an integrated computer-aided design/computer-aided manufacturing (CAD/CAM) approach involving predictive design. The new technology reduced order turnaround time from several weeks to three days. Since 1998, the company has consistently manufactured more complex, higher tolerance grinding wheels and has increased its sales of the wheels. It has used the new CAD/CAM technology to produce grinding wheels for a variety of industries.

PROJECT HIGHLIGHTS
Abrasive Technology Aerospace, Inc.

Project Title: CAD/CAM Technology Advances Superabrasive Grinding (Advanced Computer-Aided Design and Manufacturing Technology for Rapid Fabrication of Superabrasive Grinding Tools)

Project: To develop innovative computer-aided design/computer-aided manufacturing (CAD/CAM) technology for the rapid design and precision manufacturing of electroplated superabrasive grinding wheels.

Duration: 9/15/1995-9/14/1998
ATP Number: 95-02-0053

Funding (in thousands):

ATP Final Cost	$ 1,996	66%
Participant Final Cost	1,038	34%
Total	$3,034	

Accomplishments: During this three-year project, Abrasive Technology successfully developed an integrated CAD/CAM approach to applying superabrasive coatings to complex surfaces of electroplated superabrasive grinding wheels. The company achieved the following:

- Developed advanced computer-aided design software and product prediction simulation
- Developed production workstation hardware and modeling techniques

In October 1997, Abrasive Technology presented the following paper at the Advanced Technology Program Motor Vehicle Manufacturing Technology Public Workshop:

- "Computerized Modeling of Electrodeposition Between Conducting Boundaries Having Variable Geometries."

Commercialization Status: In 2000, Abrasive Technology began to market and sell electroplated superabrasive grinding wheels using the CAD/CAM technology it developed during the ATP-funded project, and still continues to do so. The company has used the new technology to produce grinding wheels for a variety of industries, including automotive and aerospace.

Outlook: Since the ATP-funded project ended in 1998, Abrasive Technology has consistently manufactured grinding wheels that are more complex and have a higher tolerance than those it manufactured prior to the project. The company has also increased its sales of the wheels.

Composite Performance Score: * *

Focused Program: Motor Vehicle Manufacturing Technology, 1995

Company:
Abrasive Technology Aerospace, Inc.
8400 Green Meadows Drive
Lewis Center, OH 43035

Contact: Loyal Peterman, President
Phone: (740) 548-4100

Subcontractors:

- Case Western Reserve University
  10900 Euclid Avenue
  Cleveland, OH 44106
- L-Chem, Inc.
  13909 Larchmere Blvd.
  Shaker Heights, OH 44120

Research and data for Status Report 95-02-0053 were collected during January 2003.

Cincinnati Lamb, a Division of UNOVA Industrial Automation Systems
(formerly Lamb Technicon)

Boring with Optimal Accuracy

Engine block bores for camshafts and crankshafts, as well as gearbox bearing houses, require precise cylindrical holes up to 30 inches long. In 1995, all line-boring operations to ensure precision specifications on these cylindrical holes were performed by a machine tool that was dedicated to a specific engine model. Lamb Technicon and its research partner, the University of Michigan's College of Engineering, proposed to develop an agile, flexible precision line-boring machine tool for engine manufacturing. This single machine tool, called Boring with Optimal Accuracy (BOA), would provide line-boring operations for six or more different engine models. The project involved developing a complex piece of equipment that must be able to manufacture accurate parts and operate reliably for 16 hours a day. If successful, the precision advancements could potentially reduce auto production costs by up to $750 million annually, based on the domestic production of 15 million vehicles.

The Advanced Technology Program (ATP) awarded Lamb Technicon cost-shared funding in 1995 as part of the focused program, "Motor Vehicle Manufacturing Technology." By the ATP-funded project's conclusion in 1998, the BOA team had successfully developed an award-winning prototype machine, had received three patents, and had published its project results. They succeeded in incorporating innovative laser measurement, software control methods, and sophisticated hardware to achieve quick changeovers between engine models, while improving the required ultra-high precision. These innovations gave Lamb Technicon considerable recognition as a leader among U.S. machine tool manufacturers. However, in recent years auto manufacturers have developed new processes using standard flexible machining centers and have decided not to purchase the more specialized BOA.

Soon after the conclusion of the ATP-funded project, manufacturers of large-scale engines (such as heavy diesel and tractor engines) expressed interest in the technology; however, it was too costly to scale up BOA's dimensions compared with using new standard machining centers and new processing techniques. The BOA technology (e.g., software control and laser measurement methods) is being applied in new engineering developments at the University of Michigan's Engineering Research Center. In 2003, Lamb's parent company, UNOVA Industrial Automation Systems, merged Lamb's operations with Cincinnati Machine and renamed the combined organization Cincinnati Lamb. This merger has enhanced Lamb Technicon's ability to supply standard flexible machining center systems, which incorporate some of the knowledge gained from BOA.

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

Research and data for Status Report 95-02-0019 were collected during November 2003.

Existing Dedicated Boring Machines Were Precise but Inflexible

Line boring, a critical and expensive operation in industrial engine production, involves first drilling a hole in a metal part. Then a boring tool smoothes the inside a boring bar (like blades on a fan) to ensure a smooth finish and to meet precise diameter and concentricity (roundness) tolerances (see illustration below). A number of products (e.g., engine block camshaft and crankshaft bores and gearbox bearing houses) require narrow holes up to 30 inches long.

In 1995, boring had to be performed by machine tools and stations on the assembly line that were dedicated to one engine model. This situation prevented the engine manufacturing industry from achieving the economic benefits that accrue with fully flexible, agile systems. A typical boring station is part of a factory assembly line that has dozens of machine tools lined up sequentially to perform many specific operations, such as milling surfaces flat, drilling holes, and cutting cylinder bores. The boring blades move horizontally along the cylindrical opening. The conventional method for boring in high-volume production was to make multiple passes to produce a finished bore. At the time, the engine manufacturing industry was producing 400,000 to 500,000 components per year, and the machine tools had to work quickly and achieve precise tolerances.

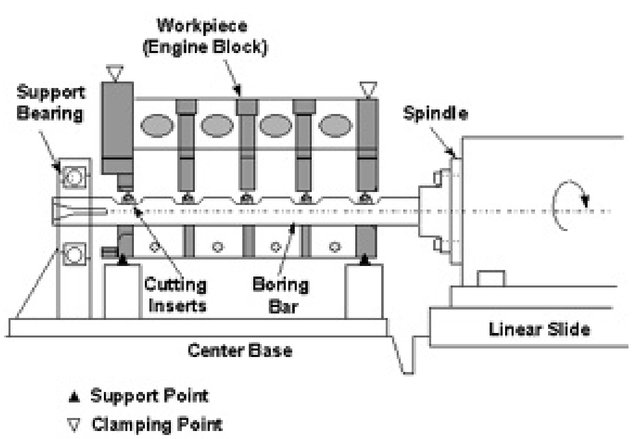


Diagram of a conventional boring tool of 1995, placed to the right of a workpiece (engine block). The boring bar enters the engine block from the right and is supported by a bearing at the left. The boring bar, with many cutting inserts, is attached to the spindle and machines that bore through the entire length of the engine casting. It requires multiple passes to complete the boring process.

Dedicated machine tools, such as boring tools, can produce high volumes of precision parts, but are limited to performing a specific repeated task on a particular engine model. This constrains the introduction of flexible manufacturing systems that are necessary in order to compete in the automobile market. High-precision machining of long bores for automobile engine crankshafts and camshafts ranked among the most inflexible processes of all. Increasing flexibility, so that one machine could bore holes in blocks for multiple engine models, resulted in less accuracy and precision. To enable quick changes of boring bars, for example, the end support bearing could be eliminated. However, then the bar would be subjected to excessive vibrations and cutting insert deflections (droop at the end of the bar), which would decrease the precision.

ATP Funding Stimulates Research

Lamb Technicon Machining Systems was a leading U.S. manufacturer of machine tools for the worldwide automotive, truck, and off-road vehicle industries. Prior to 1995, the University of Michigan's College of Engineering had conducted conceptual and exploratory research into auto manufacturing technology and solution concepts with the "Big 3" U.S. auto manufacturers (Chrysler [later DaimlerChrysler], Ford, and General Motors). Their research results showed that line boring was the least flexible process in the production system and should be redesigned.

Together, Lamb Technicon and the University of Michigan approached ATP for funding under ATP's focused program, "Motor Vehicle Manufacturing Technology," which aimed to stimulate manufacturing innovations and develop more versatile equipment with greater operational flexibility. They proposed to pioneer an agile (truly flexible) line-boring system with intelligent tooling and controls that would correct for known causes of inaccuracy and would quickly identify errors. Those capabilities would eliminate the need for support bushings and, along with innovative machine and tooling designs, would enable quick changeovers from one engine design to another. The team called the machine tool concept Boring with Optimal Accuracy (BOA). The BOA machine tool would bore distinct parts with varying sizes and locations for at least six different engine models without the need for changeover or retooling. The primary risk lay in embedding intelligence in the control electronics and in the mechanical components to achieve ultra-high precision. ATP awarded funding to Lamb Technicon for three years, beginning in 1995.

In 1995, boring had to be performed by machine tools and stations on the assembly line that were dedicated to one engine model.

Boring flexibility would enhance auto manufacturers' ability to participate in the manufacturing trend toward mass customization and would accelerate the made-to-order process. Existing technology required at least six dedicated boring machines to bore the different sizes and locations of six different engine models. A flexible line-boring station would enable high-level capacity utilization, thereby providing the potential to trim U.S. automotive production costs by up to $750 million annually using BOA (based on the domestic production of 15 million vehicles). Chrysler, Ford, and General Motors initially stated that they would cooperate on the work. In 1995, it was estimated that by 2005 domestic car companies alone would invest several billion dollars in new engine-machining systems, with each system costing more than $50 million. Machine tool technology that enabled both flexibility and high precision in boring would provide speed and agility to U.S. automotive manufacturers. In addition, spillover applications would include other manufacturing needs for precision-bored and aligned holes, such as heavy diesel and aircraft manufacturing.

Lamb Technicon Develops Challenging Milestones

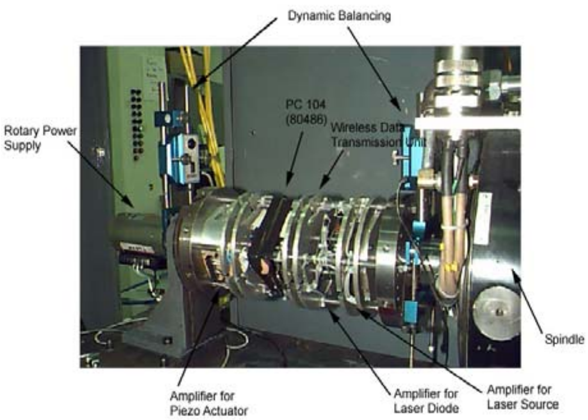
The team's primary challenge was, "How do we add precision to the line-boring process without sacrificing rigidity?" Their research plan was organized into six tasks:

1. **Process and tool modeling.** Design rigid tools without supports to enhance precision; design smart cutting tools to improve process performance and reduce downtime by 50 percent. The goal was to increase accuracy and precision of the boring process by compensating for boring bar deflections (droop at the end of the bar), vibrations, and thermal distortions, which were caused by components heating and expanding at different rates.
   Results: The team developed algorithms to accurately predict the tool deflection (droop) and allow compensation. They built two prototype cutting tools that take into account tool rotation and optimize the stiffness and frequency of the boring bar in order to increase the precision of the process. The cutting tools allow bores with lengths up to 30 inches and diameters of 1 to 3 inches to be machined in various locations.

2. **Machine Design.** Design mechanical hardware to enable precision machining of at least six different engine block models on the same machine tool station with short changeover time (less than 10 seconds, which is the time necessary to unload/load an engine block).
   Results: Rather than use solid metal for the body of the machine, the team arranged the metal in layers that resembled a honeycomb to increase strength without adding substantial mass. They designed a unique machine that provides both flexibility and precision in the line-boring process. The team was able to move the boring bar's location and allow for quickly changing the horizontal, 30-inch-long tool for different size bores (less than 10-second changeover time for 6 or more different engine models).

3. **Smart tool development.** Develop a personal computer (PC)-based control and laser-positioning sensor to allow early detection of process failures (to enhance reliability) and to identify the engine being processed (to store the information). The goal was to gain active control of the precision line-boring process, isolating vibration and disturbance. The housing for the instrumentation was designed to work with multiple boring bars, allowing for fast changes. Adding precision was the aspect of the project that had the highest risk.
   Results: The team met all of the objectives: early corrective action eliminated failures and engine specifications were stored to speed changeovers. The team developed a "smart tool" a PC-based control, and achieved precision levels of about 0.1 micrometer (μm), a hundredfold improvement. They increased the precision of the boring process by adding sensors and actuators inside the boring bar to allow nearly instant, minute adjustments (see

illustration below). BOA responded to operator position adjustments in about 0.6 milliseconds. Ultimately, the laser tracking and navigation system was able to adjust the cutting insert location 1,000 times per second, approximately 30 times per revolution.



Lamb Technicon's prototype "Smart Tool" Signal Processor and Controller. Laser sensors and piezo (pressure) actuators (to compensate for errors) are located inside the boring bar to make adjustments. Results are transmitted to the operator's PC at a rate of 1,000 results per second, or 30 times per revolution. This allows for virtually instant recognition and correction of a potential problem. Patented electronics compensate for droop during the boring operation.

4. **Intelligent control and compensation.** Add a predictive controller to (a) shorten the time to change over to a new engine model and maintain precision despite environmental changes; and (b) enhance both precision and production speed by monitoring process and tool performance. Thermal effects (distortion caused by ambient temperature changes and heat created during operation) needed to be incorporated into the compensation predictions. Error compensation must allow the boring bar to maintain an entering angle that was perpendicular to the workpiece.
   Results: The team developed non-proprietary software (called open-architecture control) that uses 18 error components as major input parameters in order to compensate for the geometric error at the tool tip. Sensors and actuators account for geometric and thermal compensation. A machine controller accepts input from machine sensors and computes axis offsets for added precision.

5. **Integration into experimental prototypes.** Integrate the four previous tasks into one machine.
   Results: The tool was still under construction when the ATP-funded project concluded in September 1998, but all engineering for the system, including all subsystems to accomplish agile and precise line boring, was complete.

6. **Evaluation of experimental prototypes.** Build and test the final lab prototype.
   Results: This was 75-percent complete upon project conclusion. The target completion date was January 1999, and the team planned to start testing immediately following completion of the prototype.

BOA Achieves Technical Success

After ATP funding ended, the BOA team completed testing of the prototype with very favorable results. Lamb Technicon used internal funds to continue the project. The BOA machine tool design is more flexible and cost effective than previous conventional dedicated designs. It allows small-batch processing of multiple parts that would otherwise need to be produced on separate boring machine tools. Compared with dedicated boring stations, manufacturers would save time and money and would gain increased precision and accuracy using the computer-controlled Smart Tool System.

They proposed to pioneer an agile (truly flexible) line-boring system with intelligent tooling and controls.

The BOA machine tool achieved significant technical advances: the spindle and feed axis allows the bore size to be changed quickly (less than 10 seconds) and ranges from 1 to 3 inches in diameter and up to 30 inches in length; the rotation speed and bore depth are programmable; and the Smart Tool contains patented electronics to compensate for droop during the boring operation (maintaining precision, while increasing flexibility).

Even today, the University of Michigan's Engineering Research Center continues to develop the BOA project technology. "The technology advancements represent a quantum leap over the technology of the time," said Professor Zbigniew Pasek. The business partnership established during this project also became a model for the university's further collaboration with industry. Ongoing research from the BOA project in 2003 included open architecture (non-proprietary software, so that additional applications can use the system), smart tool concepts, laser measurement techniques, miniaturized electronics, and improvements in stiffness. The university is monitoring machine tool performance online by connecting with machines over the Internet. These research results are being applied to improve the life of machine tooling.

Product Fails to Reach Commercialization

While the BOA machine tool was intended to improve the auto engine manufacturing process at an anticipated price of $700,000 to $800,000, auto manufacturers developed a new process that would allow the use of standard flexible machining centers. They found that they could perform half of a boring operation and then rotate the engine block to complete the task. Precision and flexibility are somewhat lower with this process, but still meet specifications. This allows manufacturers to use less expensive machine tools (priced at $400,000 to $500,000) to meet their needs. Therefore, Lamb Technicon has been unable to find a manufacturer to buy and implement its technically successful ATP-funded specialized BOA machine. Soon after the project was completed, several large-scale diesel manufacturers expressed interest in using the BOA technology; however, the tool would need to be twice as big. Further development to scale up would be difficult and expensive. The machine tool industry has been hit hard by the transfer of manufacturing jobs overseas and by the downturn in the U.S. manufacturing economy. Manufacturers must limit capital investments and keep costs down.

The BOA machine tool achieved significant technical advances.

The BOA technology received three patents and won a "Top 25 Technology and Innovation Award" from *Industry Week* magazine in 1999, the first ever for a machine tool. The researchers published their findings in trade journals. The success of the BOA project's process innovations led Lamb Technicon to increase its research and development group and earned it a reputation as an innovative leader among U.S. machine tool manufacturers. Much of the processing knowledge from BOA was incorporated into Cincinnati Lamb's new process techniques in standard flexible machining centers.

In 2003, Lamb Technicon's parent company, UNOVA Industrial Automation Systems, merged its Cincinnati Machine operations, a machine tool manufacturer that served the aerospace, heavy equipment, and defense industries with the business operations of Lamb Technicon to form Cincinnati Lamb. This organization is now the largest machine tool maker in the United States and one of the largest in the world.

Conclusion

Lamb Technicon and the University of Michigan proposed the Boring with Optimal Accuracy (BOA) project in response to an automotive industry need for increased agility in manufacturing. An industry survey determined that line boring of long, cylindrical holes (e.g., for camshafts) was the single most inflexible operation performed in the factory assembly line. The BOA team achieved all of its technical goals and developed a prototype flexible boring machine. However, Lamb Technicon was unable to commercialize the BOA tool, because other flexible less expensive standard flexible machining centers and manufacturing processes were developed during the same time period. Technology advancements, such as open architecture, laser-guided measurements, and smart tool concepts, from the BOA project continue to be developed and applied in machine tool and precision manufacturing.

PROJECT HIGHLIGHTS
Cincinnati Lamb, a division of UNOVA Industrial Automation Systems (formerly Lamb Technicon)

Project Title: Boring with Optimal Accuracy (Agile Precision Line Boring)

Project: To develop an experimental prototype of a flexible line-boring station with intelligent tooling and controls.

Duration: 9/15/1995 – 9/14/1998
ATP Number: 95-02-0019

Funding (in thousands):

ATP Final Cost	$1,997	82%
Participant Final Cost	448	18%
Total	$2,455	

Accomplishments: The success of this project helped elevate Lamb Technicon to the forefront of U.S. machine tool manufacturing. Lamb and the University of Michigan met or exceeded all of their technical goals. They successfully constructed a prototype Boring with Optimal Accuracy (BOA) machine tool with all of the desired qualities:

- Innovative laser measurement
- Open-architecture control methods (using non-proprietary software)
- Sophisticated hardware to allow quick (10-second) changeovers between engine models (for bores with lengths up to 30 inches and diameters of 1 to 3 inches), while maintaining the required ultra-high precision
- Smart tool concept, which allows compensation for errors
- Electronic rather than mechanical control
- Improved stiffness
- Improved cutting-tool process

Lamb Technicon received three patents for technology developed during the BOA project:

- “Precision positioner for a cutting tool insert” (No. 6,062,778: filed August 7, 1998; granted May 16, 2000)
- “Machine and method for flexible line boring” (No. 6,149,561: filed March 16, 1999; granted November 21, 2000)
- “Method of error compensation for angular errors in machining (droop compensation)” (No. 6,325,578: filed August 17, 1999; granted December 4, 2001)

Lamb Techicon won an innovation award for the BOA project, the first ever for a machine tool:

- “Top 25 Technology and Innovation Award,” from Industry Week magazine, 1999

Commercialization Status: The BOA technology was not commercialized because auto manufacturers found less expensive machine tools to meet their specifications.

Outlook: The outlook for the BOA product is uncertain. The BOA technology advances established the company as an innovator among U.S. manufacturers. Machine tool productivity continues to rise at approximately 12 percent annually, while machine tool prices continue to drop. However, the BOA technology has not been commercialized. Some aspects of the technology such as open architecture (non-proprietary software) control, droop compensation, and laser-precision measurements, are still being developed and applied to multiple forms of research at Cincinnati Lamb and the University of Michigan’s Engineering Research Center. Cincinnati Lamb is expanding its offerings in flexible machining center systems.

Composite Performance Score: * *

Focused Program: Motor Vehicle Manufacturing Technology, 1995

Company:
Cincinnati Lamb
5663 E. Nine Mile Road
Warren, MI 48091

Contact: Richard Curless
Phone: (800) 521-0166

Subcontractor:
University of Michigan
College of Engineering
Ann Arbor, MI

Publications and Presentations:
The team’s publications include the following:

- Li, C.-J. and A.G. Ulsoy. “High-precision measurement of tool-tip displacement using strain gauges in precision flexible line boring.” Mechanical Systems and Signal Processing, vol. 13, no. 4, pp. 531-546, July 1999.

PROJECT HIGHLIGHTS
Cincinnati Lamb, a division of UNOVA Industrial Automation Systems (formerly Lamb Technicon)

- Koren, Y., Z. Pasek, and P. Szuba. “Design of a Precision, Agile Line Boring Station.” Annals of the CIRP, 48/1, pp. 313-316, 1999.
- Li, C.-J. and A.G. Ulsoy. “Precision measurement of tool-tip displacement using strain gages in precision flexible line boring.” American Society of Mechanical Engineers, Dynamic Systems and Control Division, DSC, vol. 67, pp. 743-751, 1999.
- O'Neal, G., B.-K. Min, Z.J. Pasek, and Y. Koren. “Integrated Structure/Control Design of Micro-Positioner for Boring Bar Tool Insert.” Journal of Smart Material Systems and Structures, vol. 12, no. 9, pp. 617-628, 2001
- O'Neal, G., B.-K. Min, Z. J. Pasek, and Y. Koren. “Cutting Process Diagnostics Utilizing a Smart Cutting Tool.” Mechanical System and Signal Processing, vol. 16, no. 2-3, p. 475-486, 2002.
- Min, B.-K., G. O’Neal, Y. Koren, and Z. Pasek. “A Smart Boring Tool for Process Control.” Mechatronics, vol. 12, pp. 1097-1114, 2002.
- Mehrabi, M. G., P. Szuba, G. O'Neal, B. Min, Z. Pasek, and Y. Koren. “Geometric Error Compensation in Line Boring Process.” Journal of Intelligent Manufacturing, 13/5, pp. 379-389, 2002.
- Li, C.-J., W. Endres, and A.G. Ulsoy. “The effect of flexible-tool rotation on regenerative instability in machining.” Journal of Manufacturing Science and Engineering, Transactions of the American Society of Mechanical Engineers (ASME), vol. 125, no. 1, pp. 39-47, February 2003.

Four Ph.D. dissertations resulted from this project:

- Szuba, P. Improving Part Accuracy in Machining Operations that Employ Cantilevered Boring Tools. Ph.D. Thesis, Oakland University, Auburn Hills, MI, 1998.
- Li, C.-J. Tool-Tip Displacement Measurement, Process Modeling, and Chatter Avoidance in Agile Precision Line Boring. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, 1999.
- Min, B.-K. Modular Diagnostics of Computer-Controlled Machine Tools and Mechatronic Systems. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, 1999.
- O’Neal, G. An Analytical Approach to Integrated Structural and Control Design. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, 2001.

The team shared the project’s technology advances through numerous presentations

- O’Neal, G., B.-K. Min, Z. J. Pasek, Y. Koren, and P. Szuba. “The Development of a Precision Piezoelectric Micro-Positioner for Line Boring Bar Tool Insert.” ATP Motor Vehicle Manufacturing Technology (MVMT) Public Workshop, Ann Arbor, MI, Oct. 1997.
- Pasek, Z. J. and P. Szuba. “Development of a ‘Smart’ Tool and Machine for Precision, Agile Line Boring.” AC ’98 V Intl. Conference on Monitoring and Automatic Supervision in Manufacturing, Warsaw, Poland, Aug. 20–21, 1998.
- Pasek, Z. J. and P. Szuba. “Intelligent Agile Line Boring Station.” Proceedings of Dynamic Systems and Control Division, ASME International Mechanical Engineering Congress and Exposition, DSC, Vol. 64, pp. 439-446, Anaheim, CA, 1998.
- O’Neal, G., B.-K. Min, C.-J. Li, Z.J. Pasek, Y. Koren, and P. Szuba. “Precision Piezoelectric Micro-Positioner for Line Boring Bar Tool Insert.” Symposium on Active Control of Vibration and Noise, ASME IMECE, DE-Vol. 97/DCS-Vol. 65, pp. 99-106, 1998.
- O’Neal G., Z. Pasek, B.-K. Min, and Y. Koren. “Integrated Structure/Control Design of Micro-Positioner for Boring Bar Tool Insert.” Proceedings of SPIE’s 7th International Symposium on Smart Structures and Materials, Conference on Smart Structures and Integrated Systems, Atlanta, GA, 2000.
- Pasek, Z. J., B.-K. Min, Y. Koren, A.G. Ulsoy, and P. Szuba. “Strategies to Enhance Agility and Machining Accuracy in Line Boring.” 2nd IFAC Conference on Mechatronic Systems, pp. 601-606, Berkeley, CA, Dec. 9–11, 2002.
- Li, C.-J., W. Endres, and A.G. Ulsoy. “The effect of flexible-tool rotation on regenerative chatter in line boring.” ASME IMECE Symposium on Dynamics Acoustics and Simulations, DE-98, pp. 235-243, 2003.

Research and data for Status Report 95-02-0019 were collected during November 2003.

General Electric (GE) Global Research

Increased Fuel Efficiency and Decreased Emissions Through TBCs

The ability to achieve high fuel efficiency gives turbine manufacturers one way to gain a competitive advantage in the electricity marketplace. In particular, efficiency is an important factor in increasing the generating capacity of power plants. The maximum efficiency for a General Electric (GE) gas turbine engine in 1995 was 54.5 percent. In order to improve efficiency and reduce operating costs for its turbines, GE wanted to raise the firing temperature of its gas-fired turbine engines. By applying thermal barrier coatings (TBCs) onto hot-path turbine engine components, turbines could operate at higher temperatures, thereby increasing efficiency without reducing component life. However, GE researchers could not be certain that high-performance TBCs could be produced reliably with the durability required to withstand harsh operating conditions. GE submitted a proposal to receive funding from the Advanced Technology Program (ATP) because the technology development project was beyond the scope of research and development efforts funded by other Federal research programs and GE's internal research and development budget.

In 1995, GE was awarded funding for the project as part of the ATP focused program, "Materials Processing for Heavy Manufacturing." GE's successful project fostered a scientific, integrated, structured approach to the development of thermal spray technology, which could also be used by the steel, automotive, aircraft, biomedical, and paper industries. Project researchers developed thermal spray technologies used to produce high-performance TBCs that contributed to an upgraded version of GE's 1996 F-series power plant model, raising its 54.5-percent efficiency to 56 percent. TBCs made a critical contribution to the development of the next-generation H-series gas turbine engine, which can achieve 60-percent efficiency (the first commercial model was delivered in 2000). As a result of these advancements, power plants consumed less fuel and reduced their emissions, and GE became a market leader in worldwide gas turbine production.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

* * *

Research and data for Status Report 95-07-0018 were collected during April - June 2003.

Higher Temperature Increases Efficiency

The greatest barrier to using high temperatures in gas turbine engines is the rotating turbine blades' lack of durability. These and other components can be damaged when exposed directly to excessively hot gases. If engineers could attain higher temperatures, the engines would consume less fuel to generate electricity and would produce lower carbon dioxide (CO_2) emissions. In 1995, the state-of-the-art turbine engine was developed by General Electric (GE) and was based on jet engine technology. It allowed firing temperatures of up to 1300 °C, for a thermal efficiency of 54.5 percent. While GE did have a market-leading position, global competition was stiff, and GE needed to continue to make advances to protect its market share as well as U.S. jobs and U.S. economic growth.

TBCs Allow Higher Firing Temperatures

GE aimed to achieve higher firing temperatures and higher efficiency by protecting heat-sensitive components with an insulating "armor," called thermal barrier coatings (TBCs). TBCs are thin ceramic layers applied to component surfaces to insulate the surface alloy from hot gases, allowing engineers to design engines capable of operating at higher temperatures. TBCs help to increase efficiency and reduce emissions, without increasing downtime or maintenance costs.

Air-plasma-sprayed TBCs had been used on some gas turbine parts for more than a decade, but the industry lacked a reliable manufacturing process for applying these high-performance coatings onto high-temperature parts. The plasma spray process involves spraying a protective material, such as refractory ceramics (e.g., zirconia), in molten form onto a surface (substrate) to provide a protective, insulating TBC. The materials are injected as powders into a very-high-temperature plasma flame. The hot material impacts on the substrate and rapidly cools to form a coating that is approximately 0.1 to 2 mm thick.

Existing plasma-coating technology did not monitor all of the critical process conditions or TBC specifications (e.g., spray particle temperature and coating thickness) during spraying. Coating results could be inconsistent due to online disturbances, wear of spray gun parts, and spattering. Existing control systems monitored and regulated only the directly controllable, preset process variables. These variables, which were based on an operator's or a coater's experience, included gun current, gas flow rates, powder feed rates, gun speeds, spray distances, and spray angles. The control systems provided no objective, real-time feedback on the process and coating conditions.

GE requested funding from the ATP "Materials Processing for Heavy Manufacturing" focused program in order to apply rigorous scientific methods to measure and advance plasma-coating methods for the entire thermal spray industry. The company had a clear focus on a major manufacturing need: using TBCs to increase efficiency in power plants. However, it could take years to see any return on investment. Moreover, GE researchers could not be sure that high-performance TBCs could be deposited reliably on high-temperature components to meet the required lifetimes.

In this ATP-funded project, GE planned to develop an Intelligent Processing of Materials (IPM) technology for consistently applying high-quality TBCs using plasma coating. The IPM thermal spray technology has five elements: new plasma spray sensors, an empirical process-properties database, physics-based models, control algorithms, and process controllers. The sensors would provide feedback for developing and controlling thermal spray processes. The database and models would produce the quantitative link between the control parameters and the TBC properties. Control algorithms and the hardware for process control would enable real-time adjustments to the plasma spray process.

GE Developed an Aggressive Technical Plan

GE identified several technical risks in its proposal to ATP. Could multiple sensors on the spray equipment operate effectively together in a high-temperature environment? Could the data from the sensors be understood and analyzed efficiently? Could the control indicators be effectively identified and quantifiably mapped to results? Would an IPM control strategy be cost effective? Would IPM substantially improve coating performance?

To develop the IPM technology for high-performance TBCs, the project team worked on five tasks. These tasks and their results are described below:

1. ***Task***: Learn more about the plasma spray process by working with the National Research Council of Canada (NRC), a subcontractor, to consider and apply a robust set of control sensors to monitor numerous parameters. NRC is a leading expert in control sensor development for the plasma spray process.
   Result: The team selected and developed two sensors to measure component surface temperature and coating particle temperature. This impacted two critical TBC properties, elastic modulus and tensile strength.

2. ***Task***: Develop and populate an empirical database with data points from the sensors.
   Result: The team used the database results to generate a set of models for flat-plate substrates to connect process parameters with TBC properties.

3. ***Task***: Work with the University of Minnesota, a subcontractor, to develop a physics-based process model and useful control algorithms. GE had worked with this group before; they are leading experts in modeling the plasma process. The

plasma-particle interaction model would provide rules for the system controller to update the spray process parameters on-the-fly and to ensure that the coatings would meet specifications.
Result: The team developed and verified plasma, substrate-heating, and particle-heating models with production parameters.

4. ***Task***: Develop a process control model based on the results from Tasks 2 and 3. The system controller would use online feedback from the sensors to maintain quality control, reduce the process variations, and produce improved TBC properties.
Result: The team developed a control design toolbox to control the particle state and substrate temperature. This toolbox can be adapted to include newer process models and additional control modes.

5. ***Task***: Work with Sulzer Metco, a subcontractor, to provide the controller hardware and Ethernet communications to establish an interface between the sensors, controllers, and operators and to demonstrate the system.
Result: The team developed and demonstrated an integrated, expandable infrastructure for the IPM controller that accessed the process sensors and plasma controller via Ethernet communications. This included monitoring the particle state and the substrate temperatures recorded by the sensors in Task 1.

As a result of the ATP-funded project, GE and its subcontractors, University of Minnesota, Sulzer Metco, and the NRC, developed a method to improve the process for applying consistent, high-quality TBCs on hot-path engine parts. The thermal spray technology could also be applied to improve oxidation-resistant, corrosion-resistant, and wear-resistant coatings, which would have additional broad industrial applications through their ability to:

- Tolerate higher temperatures (increasing efficiency)

- Use less costly alloys for some construction materials (reducing the cost of production)

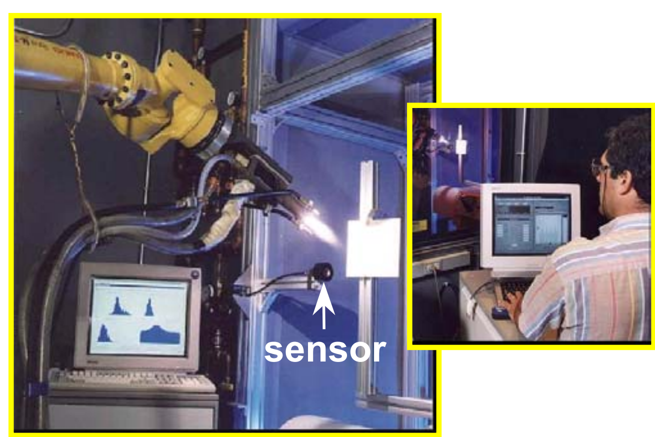
- Reduce consumption of fuel (reducing specific emissions of CO2)

- Reduce corrosion and wear (enhancing the part's life)

The ATP-funded project developed processes to apply TBCs on flat sample substrates. After project conclusion in 1998, GE still needed to transition the technologies to real, complex geometry parts. After the technical issues were resolved, GE would also need to conduct cost-benefit assessments as they implemented the program technologies in a phased approach.

Application of TBCs to Gas Turbine Engines Improves Efficiency

Following the completion of the ATP-funded project, GE conducted business and technology assessments and incrementally implemented the IPM technology. In addition, they used knowledge from parallel programs to apply TBCs to complex-shaped parts. GE was then able to apply IPM technology to develop improved thermal spray processes implemented for power plant production. To achieve higher operating temperatures, GE required better thermal performance throughout the hot sections of the turbine. To survive these high temperatures, super-alloy components would be coated with enhanced, high-performance TBCs. GE assembled a multidisciplinary team to improve thermal spray technology for depositing high-performance TBCs on hot-path engine components.



The GE intelligent plasma spray process: A robot moves the plasma gun while sensors mounted in the sensor head monitor the speed, angle, and other parameters. The operator monitors the results on a Windows-based screen and makes real-time adjustments.

In 1999, GE introduced an upgraded version of its existing F-System combined-cycle gas turbine, which operated at 56-percent fuel efficiency. The increases in firing temperature and efficiency were accomplished in part through the expanded use of enhanced TBCs on key components.

By December 2000, GE had delivered its first H-System combined-cycle gas turbine, the latest development in power-generation technology. This engine demonstrated a technology that could achieve 60-percent efficiency. The engines firing temperature increased to 1430 °C (up from 1300 °C) and used a steam-cooling cycle, among other advances. Closed-loop, steam cooling results in higher thermal stresses on the airfoil materials, so GE used single-crystal super-alloys, in conjunction with high-performance TBCs, on the flow-path surfaces of the steam-cooled turbine airfoils.

GE researchers could not be sure that high-performance TBCs could be deposited reliably on high-temperature components to meet the required lifetimes.

As of 2004, GE continues to develop the TBC technology that originated during this project. The improved thermal, wear, and corrosion-protection qualities of the thermal spray coatings can raise the level of U.S. competitiveness in the aircraft, automotive, steel, pulp and paper, electronics, and biomedical industries.

Improved TBCs Strengthen GE's Market Position

GE had a 34-percent market position in sales of gas turbines for power generation in 1995, a market that was growing at a rate of 2 percent annually. This project took place prior to the beginning of deregulation in the domestic U.S. energy market in 1998. Power plant sales were weak as U.S. companies anticipated regulatory changes. "Energy efficiency was critical to remaining competitive in a soft market and to preparing for anticipated significant growth, once the new requirements would become clear," said Dr. James Ruud of GE Corporate Research and Development. To protect GE's market position and to retain or increase the number of manufacturing jobs, U.S. manufacturers had to maintain technical superiority of turbine engines through three market differentiators: low initial cost, high efficiency, and low maintenance cost.

A 1-percent improvement in engine efficiency can save $20 million in fuel over the life of a typical gas-fired 400- to 500-megawatt combined-cycle plant.

The slow period immediately preceding the 1998 deregulation of the U.S. domestic power market allowed GE to test the use of TBCs in their turbine manufacturing facilities. GE geared up production in anticipation of deregulation and benefited from the process improvements in this project. Deregulating the U.S. energy market led to a sales "bubble" from 1999 to 2002, and GE was able to increase production of TBCs to meet this demand.

GE continues to be the dominant world leader in gas turbine manufacturing; its global market position grew to 48 percent in 1997, 53 percent in 1999, and 64 percent in 2001. Global gas turbine power system sales totaled $101 billion in 2000, but dropped 20 percent in 2001 due to the global economic downturn. GE's power division sales grew from $8.0 billion in 1997 to nearly $23 billion in 2002, in spite of an overall economic slowdown. And, most importantly, GE's installed power plants are operating at higher efficiency, thereby reducing fuel cost, generating less pollution, and saving money for industry and consumers.

The present supply of power in the United States is inadequate to meet the nation's projected demand for electric power through 2020. Therefore, the anticipated market for power plant modernization and new construction is relatively strong, especially compared with U.S. manufacturing as a whole. In the face of foreign competition, GE has developed the right combination of advanced materials, design, and manufacturing technology to continue to grow.

Efficiency Benefits the U.S. Economy

Gas turbine engines used in power plants consume vast amounts of fuel. Therefore, improving fuel efficiency by even a minute amount contributes to reducing the cost of electricity in the United States and protecting U.S. jobs. For example, a 1-percent improvement in engine efficiency can save $20 million in fuel over the life of a typical gas-fired 400- to 500-megawatt combined-cycle plant. Moreover, environmental benefits accrue in the form of reduced emissions of nitrous oxide (NOx) and carbon dioxide (CO2).

This project also positively impacted the U.S. thermal spray industry. The thermal spray market segment for industrial gas turbines was growing at approximately 10 percent per year in the mid- to late 1990s, but it was negatively affected by the changes in the U.S. economy. Potential for growth still remains; for example, the worldwide market in 2002 for applying TBCs to turbine engine components exceeded 1 million units per year. With an average cost of $200 per unit, the market for applying TBCs in turbines was approximately $200 million annually.

An additional market for thermal spray coatings is the 14 million diesel engines operating in the United States. The potential market for diesel-engine coating retrofits or rebuilds could be as large as $150 million. Unfortunately, the major market for the U.S. thermal spray manufacturers is the U.S. manufacturing industry, which has experienced a 15-percent decline in employment since 2000. The manufacturing industry continues to suffer, due to the worldwide economic downturn since 2001, especially in the aircraft industry. In addition, foreign outsourcing to Mexico and especially China has hurt U.S. manufacturing as a whole. Thermal spray industry representatives hope that their business will grow again as companies seek to retrofit, rebuild, and improve the efficiency of their engines.

GE Disseminates TBC Knowledge

The GE team provided expertise in controls, manufacturing sensors, materials, and modeling. This knowledge was disseminated throughout the TBC industry through publications, workshops, and symposia for the thermal spray community.

Conclusion

In 1995, the highest fuel efficiency available in a combined-cycle, gas turbine power plant was 53.5 percent. This successful ATP-funded project resulted in an integrated, expandable intelligent process to apply high-performance thermal barrier coatings (TBCs) in gas turbine engines for power plants. The high-performance TBCs developed in part using that technology contributed to General Electric's (GE) ability to achieve 56-percent power plant efficiency in 1999 and to demonstrate a technology that achieved 60 percent efficiency in 2000. The project researchers used chemistry, engineering, statistical analysis, and manufacturing processes to systematically seek solutions to the process of applying TBCs to hot-path mechanical alloy parts. The team shared these methods with the thermal spray industry for use in other industries, such as aircraft and heavy manufacturing.

PROJECT HIGHLIGHTS
General Electric (GE) Global Research (formerly GE Corporate Research and Development)

Project Title: Increased Fuel Efficiency and Decreased Emissions Through TBCs (Intelligent Processing of Materials (IPM) for Thermal Barrier Coatings [TBCs])

Project: To develop an "intelligent process" for applying ceramic thermal barrier coatings (TBCs) on hot components of turbine engines used for generating power to improve the engines' efficiency, power production, emissions, and lifetime.

Duration: 9/1/1995-8/31/1998
ATP Number: 95-07-0018

Funding (in thousands):**

ATP Final Cost	$1,595	48.8%
Participant Final Cost	1,676	51.2%
Total	$3,271	

Accomplishments: By the end of this ATP-funded project, the team of General Electric (GE) and its three subcontractors had successfully completed all its tasks and had met all its milestones. The team developed an integrated, expandable Intelligent Processing of Materials (IPM) controller, which improved the TBC properties.

GE's work on this project contributed to significant knowledge sharing in the thermal spray community. GE communicated the program accomplishments internally and externally at strategic times. During 1997 and 1998, they held two day-long workshops, which were open to the thermal spray community. They described their progress, which was based on this project and on parallel programs, on sensors and control for the thermal spray process. Attendees represented 21 different companies and universities, including heavy industry, coating vendors, and thermal spray equipment and sensor manufacturers. GE also visited three manufacturing and repair sites that use thermal spray. They gave conference presentations and provided process technology to other programs covering sensor and data acquisition software, the monitoring system, and the use of historical data to capture and interpret TBC results.

During and after the ATP-funded project, GE has continued to share its extensive expertise and knowledge through conferences, including the following:

- Park, J.H., Z. Duan, J. Heberlein, E. Pfender, Y.C. Lau, and H.P. Wang. "Modeling of Fluctuations Experienced in N2 and N2H2 Plasma Jets Issuing into Atmospheric Air." Proceedings of the 13th International Symposium on Plasma Chemistry, August 18-22, 1997, vol. I, pp. 326-331. Ed., C. K. Wu. Beijing: Peking University Press.

- Park, J.H., J. Heberlein, E. Pfender, Y.C. Lau, J. Ruud, and H.P. Wang. "Particle Behavior in a Fluctuating Plasma Jet." Proceedings of the 2nd International Symposium on Heat and Mass Transfer Under Plasma Conditions, April 19-23, 1999, Antalya, Turkey. vol. 891, pp. 417-424. Ed., P. Fauchais, J. van der Mullen, and J. Heberlein. New York Academy of Sciences.

- Symposium on "Thermal Spraying-Materials Synthesis by Thermal Spraying." Materials Research Society, Fall Meeting, November 1999.

- Park, J.H., E. Pfender, and C.H. Chang. "Reduction of Chemical Reactions in Nitrogen and Nitrogen-Hydrogen Plasma Jets Flowing into Atmospheric Air." Plasma Chem. Plasma Process, 20(2) pp. 165-181, 2000.

- Symposium on "High-Temperature Thermal Spray Coatings: Thermal Barrier Coatings." Materials Research Society, Fall Meeting (sponsored by General Electric Global Research Center and Sulzer Metco, Inc.), December 2002.

- Symposia on "Controls and Sensors for Thermal Spray Processes" and "Gas Turbine Coating Symposium." International Thermal Spray Conference, May 2003, Orlando, FL; GE's Dr. Y.C. Lau was the symposia co-organizer.

Commercialization Status: GE successfully produced an improved gas turbine engine for its new H-System combined-cycle power plant, which can achieve 60-percent energy efficiency. The high-performance TBCs developed in part using technology from this project were essential to the design of this model. GE also applied the knowledge to upgrade existing F-System plants, which achieved 56-percent efficiency. Other companies have used the process on marine aircraft and heavy diesel engines, as well as other applications.

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

PROJECT HIGHLIGHTS
General Electric (GE) Global Research (formerly GE Corporate Research and Development)

Outlook: The outlook for IPM of TBCs and other thermal spray coatings is excellent. Global demand for power is increasing. Significant growth is anticipated over time, depending on world economic health. Continued strong global economic health will assure the continued need to improve existing plant efficiency and to construct new power plants. In addition, the thermal spray technology advances are continuing to spread through the automotive, marine, aircraft, and diesel engine markets.

Composite Performance Score: * * *

Focused Program: Materials Processing for Heavy Manufacturing, 1995

Company:

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Contact: Dr. Y. C. Lau, Principal Investigator
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Contact: Vince Kwasniewski
Phone: (630) 961-7403

Subcontractor:

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National Research Council of Canada
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Ottawa, Ontario
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Research and data for Status Report 95-07-0018 were collected during April - June 2003.

IBM Corporation

Automated Tool Suite to Aid Interoperability of Manufacturing Execution Systems

In the mid-1990s, the U.S. electronics industry, which had an estimated compound annual growth rate of 10.5 percent, was one of the largest and fastest growing manufacturing industries in the nation. Its ability to respond quickly to market changes required a well-functioning manufacturing execution system (MES) that could provide up-to-the-minute information from the factory floor to front-office systems. These systems included customer-oriented manufacturing management (COMM) systems for accounting, planning, analysis, and decision-making. At the time, though, approximately 85 percent of the installed MES software was developed in-house, which made it difficult to upgrade or change.

In 1994, International Business Machines (IBM) Corporation received an award from the Advanced Technology Program's (ATP) focused program competition, "Computer-Integrated Manufacturing for Electronics" (renamed "Technologies for Integrated Manufacturing" the following year). IBM received funding for a two-year project to create an automated tool suite that would enable commercial software vendors to rapidly develop, maintain, and join families of interoperating products. To complete the project, IBM collaborated with the University of North Carolina in Charlotte, which conducted research and assisted with the development of the new technology.

In March 1995, a month after the ATP-funded project began, IBM changed the project focus from COMM planning and control systems to the more advanced enterprise resource planning (ERP) systems, which could integrate systems across an enterprise. By the end of the project in 1997, IBM had successfully developed an ERP/MES automated tool suite; however, the company chose not to commercialize products from the new technology. Instead, it commercialized services for linking applications of manufacturing software (enterprise application integration services), which are based on the technology developed during this project.

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

Research and data for Status Report 94-03-0012 were collected during April 2003 – January 2004.

Forming "Families" of Applications Is Time Consuming and Costly

Manufacturing execution systems (MESs) are used by businesses to capture real-time data from factory floor information systems. These data include the availability of tools, labor, and materials; maintenance schedules; records of past process performance; and the status of work in progress. The data are then communicated either to front-office systems such as customer-oriented manufacturing management (COMM) systems, which are dedicated to accounting, forecasting, and other resource planning activities, or to the factory's design and engineering systems. In the early 1990s, many MES solutions were custom-developed by manufacturers for their own use. The systems were typically complex; they often comprised applications that were isolated from other factory processes or were linked by unique computer codes. Incompatibilities in the software and processes made it difficult for companies to upgrade or change applications.

To address these problems, many MES vendors started to form "families" of applications, such as MES/COMM system applications, and to offer integrated software solutions to customers. However, the vendors were forming these families manually, determining the business rules and resolving business-rule differences between different systems, which was time consuming and costly. The cost of manually maintaining interoperability through frequent product upgrades was also high; product upgrades could take place as frequently as every six months.

Automation Tool Suite Could Reduce Cycle Time

International Business Machines (IBM) Corporation wanted to significantly reduce the cycle time (and, thus, the cost) to distribute, change, and integrate MES applications for the electronics manufacturing industry. Further, the company wanted to increase the use of MESs among electronics manufacturers. IBM planned to accomplish this by using a framework or structured approach to develop an automated set of tools for developing, maintaining, and joining families of interoperating products. The framework would include a reference model to guide vendors in the development of the interoperating products and to assist them in creating standardized products for specific processes or types of manufacturers. The framework would consist of three levels:

- *Top level:* the reference object model, which would include the definition of the interoperation boundary in a product family. This boundary is generally defined in terms of data objects, methods involving the data objects, and event triggers.
- *Second level:* vendor specifications.
- *Third level:* integration specifications between products within the same family.

The automated tools would include a workbench, or repository and software tools, which would be used to create and store the vendor specifications for each product, as well as an individual user's interoperation specifications. The tools would also include the business rules, such as activity management or accounting rules, for different MES/COMM products. Another automated tool would be a reengineering "assistant" to help a vendor update and link preexisting legacy software with newer software. The assistants would perform tasks such as the following:

- Recover business rules from program scripts
- Add event triggers to MES solutions, when necessary
- Use interoperation specifications to manage gaps that might occur when linking different products

IBM Anticipates Broad-Based Benefits

IBM believed that an automated tool suite, which would reduce much of the manual programming effort currently required, had the potential to significantly increase the speed with which MES vendors could develop, maintain, and join families of interoperating products. Electronics manufacturers would be able to obtain integrated products quickly and at a lower cost. This would lead to a significant increase in the use of MES solutions by electronics manufacturers throughout the United States, resulting in greater speed and efficiency within their manufacturing operations, as well as higher profits. IBM believed that eliminating incompatibilities in manufacturing and business software could trim production lead times by as much as 40 to 60 percent.

IBM wanted to significantly reduce the cycle time to distribute, change, and integrate MES applications.

Use of an automated tool suite would also lower a vendor's cost to develop family-based software. This would encourage more vendors to become involved in product family formation, which would increase competition and further lower the cost of the software.

IBM anticipated that after the first family of interoperating MES/COMM products was released, the company would realize revenue of several million dollars within 48 months from the sale of the products. The release of MES/COMM products could also potentially lead to an increase billions in revenue for the electronics manufacturing industry.

Development of Automation Tool Suite Poses High Risk

IBM understood that creating an automated tool suite was a high-risk endeavor. At the time, a significant amount of manual programming was required to form product families. Many of the required activities, such as reengineering business rules and event triggers and maintaining the consistency of the legacy codes during product upgrades, would be performed differently with an automated system.

In particular, IBM anticipated difficulty in working with legacy software. It would be difficult to determine the existing data definitions, data manipulation rules, business rules, and application logic that trigger each legacy application's function. IBM would need to expose these features in order to manipulate elements in the system to resolve interoperation problems. Also, at the time, there was no industry-wide MES software interoperation standard, because of the diverse technological and business concerns of the different manufacturing enterprises. Without an MES industry standard, it would be difficult to quickly develop, change, and integrate MES software, even with an automated tool suite.

Because the project risks were more than IBM could assume at the time, the company sought financial support from ATP. They were awarded cost-shared funding in 1994 for a two-year project under ATP's focused program, "Computer-Integrated Manufacturing for Electronics" later subsumed into "Technologies for Integrated Manufacturing." This support would allow the company to develop an automated tool suite 18 months sooner than if IBM funded the project itself.

FAIME Technology Meets Project Goals

In March 1995, a month after the ATP-funded project began, IBM decided to expand its objectives and renamed the project, "Framework for Adaptive Interoperability of Manufacturing Enterprises (FAIME)." With FAIME, IBM planned to develop an object-oriented (OO) framework and to focus on interoperability between enterprise resource planning (ERP) and MESs. (An ERP system, which was capable of integrating systems across an enterprise, was a more advanced planning and control system than a COMM system.)

An OO framework would take all information related to a process and would create an object that could independently perform an operation within a system, as well as interact with other objects within the system. The automated tools developed with the OO framework would allow for "plug-and-play" interoperability between different applications. Therefore, ERP and MES applications could be interchanged without significantly disrupting the integration. The automated tools would provide the following benefits:

- Considerably reduce the time it took to perform software integration
- Facilitate the introduction of MESs into the customer's business processes
- Reduce the time it took to perform system maintenance and modification
- Improve the overall quality of integrated ERP/MES software performance

With the assistance of the University of North Carolina at Charlotte, IBM successfully developed a flexible, automated tool kit by the end of the ATP-funded project. The tool kit could be used to develop, maintain, and join families of ERP and MES applications, as well as other manufacturing interoperating applications. IBM demonstrated that it had successfully met its objectives by using the tool kit to integrate the following ERP and MES applications:

- JD Edwards' ERPX Version 6.2 (ERP application)
- SSA's BPCS Version 4.0 (ERP application)
- IBM's Factory Operation eXecutive Version 1.3 (MES application)
- SynQuest's EnSync Version 4.45 (MES application)

FAIME Technology Becomes Platform for Services and Other Software

By 1996, a year before the project ended, IBM had developed and had started to implement a strategy to promote and commercialize the FAIME technology. That year, it started to promote FAIME through presentations and demonstrations and by publishing several papers about the new technology. The company also started to make plans to commercialize the technology. For example, it planned to package and announce the new technology as an IBM service offering in June 1997, three months after the ATP-funded project ended.

By the end of the ATP-funded project, IBM had taken the following steps:

- Demonstrated the new technology to CMD Systems, a subsidiary of Deloitte and Touche
- Presented the new technology at the IBM ERP Symposium in April 1997
- Made potential plans to use the FAIME tool set to integrate JD Edwards' ERPX 7.1 into IBM's factory operations
- Met with SynQuest regarding the company's interest in marketing FAIME's integration capability
- Met with CMD Systems regarding a potential collaboration for using the FAIME tools
- Met with the IBM TelTech group regarding a potential customer for the FAIME tools

IBM anticipated that it would receive revenue from FAIME by 2000. However, after the ATP-funded project ended, the company decided not to use the new technology to manufacture products. Instead, it commercialized enterprise application integration (EAI) services based on the FAIME technology. IBM also used the FAIME technology as a platform for more advanced technology that it was developing in two other ATP-funded projects: CIIMPLEX (An Agent-Based Framework for Integrated Intelligent Planning - Execution) and EECOMS (Extended Enterprise Coalition for Integrated Collaborative Manufacturing Systems).

IBM used the FAIME technology as a platform for more advanced technology that it was developing.

The following paragraphs provide a brief description of IBM's EAI services and the two technologies, intelligent manufacturing planning and execution and intelligent supply chain logistics, that it developed in the ATP-funded CIIMPLEX and EECOMS projects.

EAI Services

After the FAIME ATP-funded project ended, IBM applied the technology it had developed to a service that linked manufacturing software applications. This service helps businesses automate the way in which different e-business applications and databases share and update data. The service creates an architecture that aligns disparate networks within the business and allows the networks to work together efficiently.

From 1997 to 2001, IBM earned revenues of $8.2 million from its EAI services. Its customer base also increased from 12 in 1999 to 25 in 2001; the largest customers were SynQuest and British Aerospace. In 2003, its EAI services included application connection services, message-oriented middleware services, business process services, object-oriented middleware services, and e-business security/directory services.

Intelligent Manufacturing Planning and Execution

Under the CIIMPLEX project, which began in March 1996, IBM took the concept of using a flexible framework to rapidly integrate manufacturing information and control systems, which was being developed in the FAIME project. The CIIMPLEX project included the linking of real-time manufacturing information with planning and execution systems through the use of basic algorithms (electronic step-by-step procedures). The new CIIMPLEX technology was to be a self-configuring plug-and-play MES framework, based on the use of intelligent software agents (automated processes that could perform a task ordinarily performed by humans). This framework could be used for integrated intelligent planning - execution applications.

In 2001, IBM began to sell MQServices Adaptor Offering (MQAO) and business-to-business (B2B) integrators, two software products that incorporated the CIIMPLEX technology. B2B was the software used to connect applications. MQAO was the tool set designed in the CIIMPLEX project used to develop the connectors between the applications and the B2B integrator. IBM earned revenues of $13 million in 2001 from sales of these two products.

Intelligent Supply Chain Logistics

In the EECOMS project, IBM took the concepts developed in FAIME and CIIMPLEX to design a new framework that allows people, applications, and intelligent software agents to collaborate on supply chain logistics in real time. (Supply chain logistics refers to the details of planning, scheduling, and controlling the supply chain, which is a series of organizations and functions that produce or assemble materials and products from manufacturer to wholesaler to retailer to consumer.) The goal of the EECOMS project was to extend the capability of an MES by integrating supply-chain logistics across many organizations or enterprise boundaries.

The EECOMS solution would use intelligent, dynamic technologies for procurement and brokering, to which it would apply rules-based technology. The solution also offered information security (the protection of data against unauthorized access) and enabled users to construct virtual situation rooms, which are simulated rooms that could be used by groups to collaborate and manage supply chain problems from remote locations. As with the FAIME and CIIMPLEX technologies, EECOMS would involve a distributed computing environment that could readily accommodate the differences in the processes, practices, and software of supply-chain members.

After the FAIME ATP-funded project ended, IBM applied the technology it had developed to a service that linked manufacturing software applications.

Successful implementation of the EECOMS technology was expected to result in the more rapid delivery of products to customers, a reduction in costly inventories, and a further increase in the competitiveness of U.S. manufacturers in the global marketplace. The EECOMS project was completed in 2001. Since then, IBM has incorporated virtual situation rooms in several of its products, including its Lotus software.

Conclusion

With ATP's assistance, International Business Machines (IBM) successfully developed a new automated tool kit that could be used to develop, maintain, and join families of enterprise resource planning and manufacturing execution system applications, as well as other manufacturing interoperating applications. However, by the end of the ATP-funded project in March 1997, IBM decided not to commercialize this product. Instead, it commercialized enterprise application integration (EAI) services, which are based on the Framework for Adaptive Interoperability for Manufacturing Enterprise (FAIME) technology developed during this project. The company then focused on developing two more advanced technologies, business-to-business (B2B) integration and intelligent supply chain logistics. Both of these technologies used FAIME as the platform and were developed in two other ATP-funded projects: An Agent-Based Framework for Integrated Intelligent Planning - Execution (CIIMPLEX) and Extended Enterprise Coalition for Integrated Collaborative Manufacturing Systems (EECOMS).

As a result of the EECOMS project, IBM has developed and commercialized virtual situation rooms and has incorporated them into several of its products, including Lotus software.

From 1997 to 2001, IBM earned revenues of $8.2 million from its EAI services and, in 2001, $13 million from the sale of MQServices Adaptor Offering (MQAO) and business-to-business (B2B) integrators, two software products that incorporated the CIIMPLEX technology. Its EAI customer base also increased from 12 in 1999 to 25 in 2001; the largest customers were SynQuest and British Aerospace. In 2003, IBM's EAI services included application connection services, message-oriented middleware services, business process services, object-oriented middleware services, and e-business security/directory services.

PROJECT HIGHLIGHTS
IBM Corporation

Project Title: Automated Tool Suite to Aid Interoperability of Manufacturing Execution Systems (A Product-Family-Based Framework for Computer Integrated Manufacturing)

Project: To create an automation tool suite that would enable commercial software vendors to rapidly develop, maintain, and join families of interoperating products, which are sets of manufacturing and business applications that work together and can be updated in parallel.

Duration: 2/1/1995-3/31/1997
ATP Number: 94-03-0012

Funding (in thousands):**

ATP Final Cost	$1,864	59%
Participant Final Cost	1,296	41%
Total	$3,160	

Accomplishments: ATP funding enabled International Business Machines (IBM) to develop an automated tool kit that could be used by vendors to develop, maintain, and join interoperating families of enterprise resource planning (ERP) and manufacturing execution system (MES) applications.

Commercialization Status: IBM did not commercialize its new automated tool kit. Instead, it commercialized a service based on its new Framework for Adaptive Interoperability of Manufacturing Enterprises (FAIME) technology, enterprise application integration (EAI) services. The company also focused on the more advanced business-to-business (B2B) integration technology that it was developing in another ATP-funded project, An Agent-Based Framework for Integrated Intelligent Planning - Execution (CIIMPLEX) and the intelligent supply chain logistics technology that it later developed in the ATP-funded project, Extended Enterprise Coalition for Integrated Collaborative Manufacturing Systems (EECOMS).

By 2001, IBM had earned revenues of $8.2 million from its EAI services. The company had also earned revenues of $13 million from sales of MQServices Adaptor Offering (MQAO) and B2B integrators, two software products developed during the CIIMPLEX project. In 2003, IBM continued to offer EAI services and has incorporated virtual situation rooms, which were developed in the EECOMS project, into several company products, including Lotus software.

Outlook: The market for EAI services continues to grow for IBM, as well as for other firms. In 2003, EAI services that are in demand include application connection services, message-oriented middleware services, and business process services. IBM also continues to sell its B2B integrators and products that include virtual situation rooms. The company has no plans to commercialize its automated tool kit for developing, maintaining, and joining interoperating families of ERP and MES applications, which was the original target product of this project.

Composite Performance Score: *

Focused Program: Computer-Integrated Manufacturing for Electronics (renamed Technologies for Integrated Manufacturing the following year), 1994

Company:
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Subcontractor:
University of North Carolina at Charlotte
Charlotte, NC

Publications:
The group also shared its project research in the following publications:

- Chu, B., J.S. Long, M. Matthews, J.G. Barnes, J. Sims, M. Hamilton, R. Lambert. "FAIME: An Object-Oriented Methodology for Application Plug-and-Play," *Journal of Object-Oriented Programming*, 11(5):20, September 1998.

- Sims, J.E., B.B. Chu, J. Long, M. Matthews, J.G. Barnes, C.H. Jones, R.A. Anderson, R. Lambert, D.C. Drake, M.A. Hamilton, M. Connard. "Framework Adaptive Interoperability of Manufacturing Enterprises (FAIME)-A Case Study; Plug and Play Software for Agile Manufacturing Track," *Proc. of the International Society for Optical Engineering*, vol. 2913: 289-303, 1997.

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

- Drake, D., B. Chu, J. Sims, R. Anderson, M. Hamilton, R. Lambert, M. Connard, J. Long, A. Sartin, E. Wayne, J. Chen. "Framework for Application," *Proc. of the International Society for Optical Engineering*, vol. 2913: 267-88, 1997.

Presentations:

IBM disseminated knowledge gained during this project through the following presentations:

- IBM ERP Symposium, 1997.
- Chang, Robert. Enterprise Resource Planning Symposium, 1996.
- Long, Junsheng. Continuous Acquisition and Life-Cycle Support/Concurrent Engineering Conference, 1996.
- Sims, John. National Center for Manufacturing Sciences Conference, 1996.

Research and data for Status Report 94-03-0012 were collected during April 2003 – January 2004.

Montronix, Inc. (a division of Growth Finance)

Process Monitoring to Improve Machine Tool Performance

Machine tools are used to cut and shape a variety of high-quality metal components and are used extensively by major manufacturers, such as those in the automotive, aerospace, and heavy industrial sectors. Machine tools used in the automotive industry include lathes, mills, drills, and other kinds of industrial capital equipment used to fabricate components such as engine blocks and axles. In the 1990s, manufacturers were facing high costs due to downtime, rework, or scrap. Montronix, Inc. applied for and was awarded funding through the Advanced Technology Program's (ATP) focused program, "Motor Vehicle Manufacturing Technology," to improve the performance of machine tools. Montronix's proposal emphasized process monitoring to seek improvements, rather than simple tool-condition monitoring to measure wear. Montronix was a small firm without the resources to fund intensive research on its own. The University of Illinois at Urbana-Champaign (UIUC), a subcontractor, played a key role in the research.

During this project, which began in September 1995, the team performed research to develop agile systems to monitor and diagnose machine tool processes. The systems would consist of customized sensors, software to interpret the data, and Windows-based screens to display the results. Montronix and UIUC intended to transform the ability of a highly experienced machinist who could "sense" a problem into a network of sensors and computer diagnostics to analyze the same problem visually with graphical feedback displayed on a computer monitor. The research was intended to last two years (later extended to 33 months) and needed the collaborative support provided by ATP.

During the ATP-funded project, Montronix produced a prototype Machining Diagnostic system and introduced it at trade shows in 1997, while the project was ongoing. Montronix and UIUC shared the technology widely through extensive professional publications and presentations. After the project concluded, Montronix expanded by acquiring a competitor and had nine locations worldwide. They further developed and commercialized the diagnostic process. In 2001, Montronix encountered financial difficulties and was sold to Growth Finance. The company still sells systems that monitor quality and consistency, which are based on the technology developed in this ATP-funded project.

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

Research and data for Status Report 95-02-0020 were collected during June - July 2003.

Growth of the Tool-Condition-Monitoring Industry

A tool-condition-monitoring system measures the operation of a machine tool so that any deviation from nominal operating conditions can be identified and appropriate correction procedures can be instituted. This capability enables the production of precision, quality, and consistent parts. The first tool-condition monitoring began in the aerospace industry in the late 1970s. The sensor on this early system measured spindle deflection and when it detected a safety problem, it shut the machine down to avoid tool breakage. It relied on human intervention to recognize small problems, such as vibration and noise. Most tool-condition-monitoring systems had been installed in permanent, dedicated, continuous production systems and consisted of permanent, embedded sensor systems. The manufacturer's goal was primarily to monitor tool wear and breakage to protect the valuable machine tools. Manufacturers who used such systems have documented savings of three to five percent of manufacturing costs. The problems inherent with this method were that it was inflexible and that it focused on the machine tool, not on the product or on improving the process. This approach was adequate for long-term, large-volume production runs, but did not fit the needs of the evolving automotive industry.

In the mid-1990s, the automotive industry was trying to meet consumer demands for higher performance vehicles and more variety in the models available. The industry sought to meet these demands by trying to produce fewer identical parts with shorter machining runs; by using more flexible, general-purpose equipment; and by making frequent changeovers to new variations of parts. A primary cost of manufacturing is in setting up a production run, so the per-unit set-up costs are significantly lower if large volumes of identical components can be made. In order to cost-effectively produce a greater variety of smaller runs, manufacturers had to cut production costs by making more efficient use of labor (setting up and running these small production runs) and by producing less waste material (making precision parts right the first time and every time). Auto manufacturers needed to establish break-even points for models at unit-production volumes that were lower than they had achieved in the past.

Precise Machining Adds Value

Automotive components must be manufactured with high precision, and tolerances must be measured in the thousandths of an inch. Surfaces must be precisely parallel or perpendicular, perfectly round or square, depending on the specifications. With thousands of parts on a single car, any mismeasurements can result in alignment problems; or worse, the components simply will not fit. Parts that do not meet specifications have to be scrapped.

Machining a metal workpiece requires that it be placed securely and precisely on the base and that consistently sharp tools be used to cut it in order to avoid rough edges, crooked cuts, or damage to the part or the tool. An example of a component that posed challenges for auto manufacturers is the stamping die for producing body panels. A single stamping die is a high-value machined component. Dies are used on the assembly line to stamp sheet metal into automotive body panels. Because the quality of the panel is directly dependent on the dimensional precision of the dies that form it, dies must be machined very precisely. To achieve a desired final shape, the sheet metal is successively stamped (i.e., sandwiched between an upper and lower die) by a series of dies, each of which adds increasing geometric detail.

Stamping dies may be valued at hundreds of thousands of dollars. The primary cost factors in making the die are in the time and effort to test and retest the die before it is used in the manufacturing process. First-quality auto body panels depend on precise machining of the dies. Detecting defects such as voids, holes, or gaps in the metal must be done early in the process. An error introduced late in the process destroys the die and all the machine time and labor invested in it. Moreover, meeting production deadlines is critical to a successful model release. Any delay in producing a die could delay the release of a new automobile model, thereby increasing the cost of release (costs for releasing one new model, for example, are between $1.5 and $4 billion).

The industry strives for flexibility, speed, precision, low cost, and quality. Oftentimes, these are conflicting goals. Machine tools need to be flexible and need to be able to perform a variety of tasks. Components must be produced reliably, precisely, and quickly, with little or no waste and downtime (which results in lost material and labor). Manufacturers want to identify and remove defective parts as early in the process as possible and want to avoid introducing new errors. Machine-tool-monitoring systems can perform a vital diagnostic role in these tasks.

Montronix Seeks to Monitor Tools Intelligently

Montronix was an innovative provider of tool and process-monitoring systems for metal-cutting machines. The company believed that it could develop products to meet the challenges of reducing downtime, rework, and scrap. The University of Illinois at Urbana-Champaign (UIUC) Machine-Tool Agile Manufacturing Research Institute specializes in developing innovative machine-tool concepts and systems to stimulate national manufacturing competitiveness. Montronix and UIUC observed the weaknesses in the existing dedicated monitoring systems, which could not measure status frequently enough and thus allowed too much waste material. The existing solution was to stop production frequently to measure completed parts (this reduced production volume) and thereby assure that measurements were within specifications. Montronix and UIUC identified a concept to link sensors, hardware, proprietary software, and Windows-based personal computers (PCs). The sensors would detect vibration, force, speed, and temperature. The customized computer screens would visually depict the machining process, that is, the nominal (perfect) operations and the various problems that might arise.

This next-generation tool/process-monitoring system would be extremely precise in detecting changes in the monitored data coming from the sensors. These data changes would indicate process changes that can occur from variables in the manufacturing process, such as raw stock material variations (e.g., blemishes and imperfections in the metal), speed and feed rate changes, tool wear or breakage, and improper programming (e.g., the engineer set a measurement for 0.1 inches instead of 0.001 inches). The intent was to monitor the process in order to track performance and seek improvements, as well as to monitor the condition of the tools and notify the operator when the machine tool has a problem. Montronix and UIUC's plan consisted of the following:

- Use process modeling to interpret a process signal that contains one or more process faults
- Develop a fault diagnosis framework to identify underlying causes, based on the comparison with process-model-generated data
- Relate performance measures with ideal sensor or model information in a flexible diagnostic system
- Collect process data at high speeds and develop meaningful diagnostic parameters
- Present these data in graphs on a Windows-based screen
- Transform these data into solutions and improvements

The new system would also need to be more versatile, diagnostic, portable, and sensitive; moreover, it would need to be easily and unintrusively introduced into new or existing machine tools operating on the production floor. A system with these qualities would allow real-time adjustments and would keep measurements within specifications.

Project Emphasizes Process Monitoring to Achieve Continual Improvement

In 1994, Montronix applied to ATP for support and was awarded $1.2 million for a two-year project, as part of a focused program for "Motor Vehicle Manufacturing Technology." Funding was approved beginning in 1995. (The project was later extended to 33 months.) Montronix and UIUC believed they could produce a monitoring and diagnostic system that could handle more processes by a single machine tool, with real-time process and adaptive control. The machine tools would be harder to set up initially, because they would perform multiple tasks, which had never been done before. Furthermore, researchers would need a more advanced in-process monitoring system to respond to a range of machining applications, such as the following:

- Turning an axle to cut it smoothly
- Milling the surface of a cylinder head to make it flat
- Drilling a hole
- Reaming or enlarging the opening of a hole, with the cutting blades turning like a fan

The Montronix system would combine the following elements:

- Sensor data collection to measure the status and performance of the machine tool, the cutting tool, and the machining process
- Process modeling to predict the characteristics of typical process errors
- Fault diagnosis strategies to make recommendations to immediately correct errors before damage was done to a manufactured part or to the machine

The PC had improved dramatically in the mid-1990s, allowing greater speed, memory, data handling, and graphic display detail at a lower cost. The sensor technology had evolved along with the PC to provide higher performance and faster, more sensitive readings. Montronix and UIUC, with ATP support, wanted to incorporate PC technology advances to move the tool-condition-monitoring system from a stable, single-sensor response system to the next generation: flexible, multisensor monitoring that could measure forces, acoustic emission, vibration, and power.

Montronix, UIUC, and ATP believed that all monitoring processes must produce two results: the manufactured component itself and data that would enable the engineers to improve the process that was used to make the component. They wanted to emphasize process monitoring (constantly tracking performance and making comparisons in order to seek improvements), rather than tool-condition monitoring (measuring wear, such as when a cutting tool is dulled or measuring a chip, such as when a tool has a point broken off). Their focus was on achieving continual improvement, which could be applied to the next manufacturing run. Some of the activities that could benefit from Montronix's comprehensive process data collection included the following:

- Setting up, launching, and validating a process
- Assessing the performance of machines and/or processes and understanding changes in the performance of a given system over time (dedicated tool monitoring)
- Comparing the performance of two or more similar processes
- Analyzing process potential and capability
- Changing over quickly from manufacturing one component to another

The benefits of process monitoring would include improved system up-time and reliability, reduced set-up times, reduced cycle times, improved part quality and process capability, and increased machine longevity.

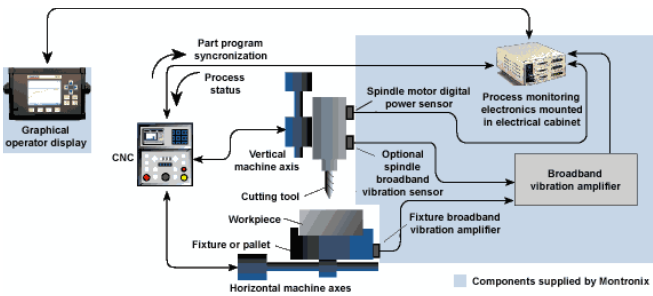
Field Tests Are Performed at an Automotive Plant

In order to test their project results, in March 1997, the Montronix/UIUC team conducted field tests. They used their prototype Machining Diagnostic (MD) system, which they had developed during this project, to detect process variations at a particular machining station in an automotive plant. The station conducted face-milling operations on a cylinder block line. The test involved three milling cutters with varying diameters. The plant had experienced downtime at this station due to several process variations, and the manufacturer had requested that Montronix investigate the problem.

The MD system was a computer-based diagnostic tool for rotating tool-machining processes that played a critical role in manufacturing many engine, transmission, and brake parts (see illustration below). The system used force and vibration sensors to collect data. It also used a digital signal processor (DSP) design that could sample and analyze sensor signals 5 to 10 times faster than a typical tool-monitoring system. The MD system used proprietary software to model the process and to diagnose faults, so the operator could rapidly collect, visualize, and analyze sensor data from machining processes. The MD system could analyze gears and other rotating assemblies. Utilizing easily attached retrofit sensors that were synchronized with spindle rotation and sophisticated DSP techniques applied in real-time, the MD system could be used to accomplish the following tasks:

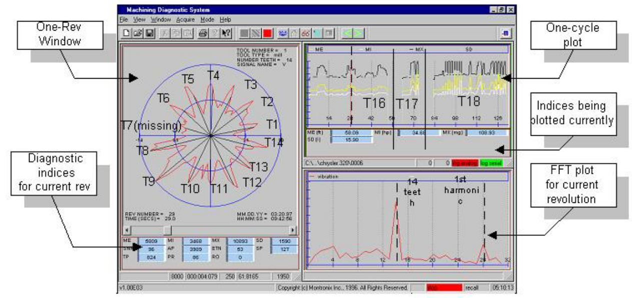
- Detect and isolate process faults such as run-out (measurements outside of specifications), throw, tilt, and misalignment
- Detect tool problems such as regrind errors, insert chipping, and breakage
- Assess the state of the machining process, rate of tool wear, and risk of tool breakage
- Perform comparative tooling studies
- Quantify vibration and noise in rotating assemblies

The Montronix MD system is a portable analysis tool for benchmarking and fault diagnosis in machining operations involving rotating tools. It includes a laptop computer with visual display and proprietary software to interpret data from the sensors.



In the diagram, note that sensors adhere to and monitor the machine tool's base, cutting tool, and motor. The data feeds Montronix's software, which continuously updates the Windows-based PC screen. The operator uses this feedback to update parameters on the machine tool itself through the computer-numerically controlled system.

The system extracts cutting signals on per-revolution and per-tooth bases, providing detailed diagnostic information (see illustration below). In the field tests, the system successfully detected insert breakage on one cutter and detected run-out and high vibration levels on another cutter much faster than was possible with a non-Montronix signal level. The team later conducted successful trials at three additional manufacturing locations for gear knock testing, turning of Teflon pump seals, and machining center testing.



This sample MD system software window layout displays the detailed information that would appear on the operator's screen. The example shows a missing tooth, number T7 of 14.

Project Team Meets All Milestones

At the end of the project in 1998, the team had met all its major milestones and technical goals:

- The team completed and tested the MD system. The system could sample data from retrofit sensors synchronously with tool rotation, process the data and extract diagnostic indices, and plot/store the data and indices in a Windows 95 software program. This system was introduced at trade shows in Detroit and in Hanover, Germany in September 1997.

- The UIUC achieved significant results in the mechanistic modeling and fault diagnosis areas. They enhanced models for end milling, face milling, and drilling to include geometry faults and tool breakage and chipping effects. The models proved useful in identifying and estimating multiple fault conditions and retrofit sensor data.

- The team achieved successful results for many of the high-risk tasks. These included developing a prototype MD system using synchronized sampling, retrofit sensors to characterize fault conditions, mechanistic models to predict fault behavior, and model-based fault diagnosis techniques.

By the end of the second year of the project, Montronix was promoting, testing, marketing, and selling the first release of the system, both as a portable diagnostic tool and as a dedicated monitoring module. The team published several articles and presented numerous lectures at conferences to share their knowledge within the manufacturing sector.

Tool Monitoring Enables Automation and Quick Response to Errors

The ATP-funded project continues to have an impact on machine-tool-process monitoring. The Montronix MD system uses menu-driven set-up routines and graphical feedback displays, which simplifies setting up, modifying, and monitoring the machine-tool process. The operator can learn to use the system in a matter of hours. Online tool monitoring enables greater automation, quicker response times to errors, and faster, more streamlined machining.

According to Professor Richard DeVor of UIUC, "This project allowed the team to develop a better understanding of machining processes to identify faults in data. We developed mathematical modeling, which carried on considerably past this project, benefiting the entire machine tool industry. New knowledge was developed, showcased in meetings, and momentum gained."

A key accomplishment of this project was providing free Internet-based simulated machine-tool modeling (http://mtamri.me.uiuc.edu/testbeds/testbed.intro.html). The web-based simulation is still in use by government, academic, and industry researchers. The web-based end-milling project, which includes fault modeling and diagnosis, has been executed online more than 50,000 times by government agencies, universities, and industries.

The team developed code, software, and algorithms (for the first time on a Windows platform). In addition, the team made advances in speed, user friendliness, and the ability to apply improvements from one component manufacturing process to another. The monitoring system developed in this project evolved into a standard Montronix product line called Spectra.

Finally, research into this area is ongoing. After the conclusion of this project, Montronix received internal funding and government grants for additional research. UIUC has continued tool-process-monitoring research and development work. They publish and provide ongoing cutting-edge research for individual manufacturers, which pay $50,000 annually for membership in UIUC's manufacturing consortium.

Montronix Monitoring Continues to Impact Manufacturing Efficiency

One of the significant aspects of this project was developing user-friendly Windows-based proprietary diagnostic software to monitor and view the process and diagnostics. Montronix later conducted additional research and further developed the MD system technology, which led to the production of several process controllers in the Spectra series, released in the fall of 2002. This next-generation diagnostic system includes a miniature monitoring system that uses micro-electronic-mechanical-systems technology. The company has installed more than 5,000 diagnostic systems worldwide. These systems are benefiting consumers by increasing efficiency and reducing manufacturing costs.

In a factory setting, a complex, multistage machine tool may require several Montronix systems. For example, one manufacturer uses approximately 400 Montronix diagnostic systems to monitor the process and the machine tools for horsepower, force, and vibration. The engineers report that the systems are most effective in detecting deviations in highly repeatable machining processes.

Another manufacturer uses eight Montronix systems. One machine tool has a large right-angle head whose gears need to be replaced approximately every three months, at a cost of $12,500 per head. An installed Montronix system consistently recognizes the increased vibration very early, which means that the head can be rebuilt for only $2,500. In addition, all waste parts have been eliminated, saving the material and labor from rework. This factory plans to install six more Montronix systems as soon as it can stop production long enough to do the initial set-up.

An installed Montronix system consistently recognizes the increased vibration (in a right-angle head) very early… waste parts have been eliminated. This factory plans to install six more Montronix systems.

Market Conditions Affect MD System Sales

Although market potential seemed significant and the project achieved technical success, sales were disappointing due to factors beyond Montronix's control. Montronix believed that after the project, the enabling technologies would be developed to the point where the company, in partnership with one or more automotive "Big Three" companies, could expand. However, they were unable to finalize the desired partnership, so they acquired other small companies and expanded into nine global locations.

Moreover, use of monitoring tools among manufacturers has been limited. For example, while there are approximately 3 million machine tools on the market, the current penetration for monitoring tools is only about 5 percent. Of these 150,000 monitoring tools, Montronix's share is approximately 5,000 monitoring systems worldwide. Montronix competitors provide only low-end standard monitoring systems, which lack the fault diagnostics elements. A few major manufacturers are using the Montronix systems for individual manufacturing processes. Usage is not widespread, even though the potential to achieve competitive advantage through process monitoring is tremendous.

Unfortunately, the anticipated growth in monitoring systems sales has not occurred. Major changes have taken place in the automotive industry, and sales have failed to meet expectations. For example, since 1998, auto manufacturers have been forming a variety of mergers, acquisitions, and alliances, blurring national boundaries and reducing the number of manufacturers. Off-shore production plants have lower labor costs, which reduces the impact of process monitoring labor savings. The performance of U.S.-based companies now reflects the global economy. Reducing overall costs has become a higher priority than improving U.S. manufacturing efficiency. Manufacturers are cutting costs by reducing the number of component parts, the number of dies for stamping sheet metal, and labor; they are also outsourcing parts production and receiving parts on an as-needed basis. U.S. unions complain that manufacturers are moving operations to low-wage countries such as Mexico and China. This trend is expected to continue; therefore, the manufacturing plants that could benefit from Montronix systems are being transferred outside the United States.

Following the recession in 2000 to 2001, the U.S. manufacturing recovery has been slow; for example, 2.6 million manufacturing jobs have been lost, representing a 15-percent employment drop in this sector. Montronix was not able to survive the economic downturn. In 2001, the company was purchased by Growth Finance, a Swiss-based company. In 2003, it had 40 employees, up from 24 at the project's start in 1995, but down from a peak of 80 in 1999. As a part of Growth Finance, Montronix now continues to sell the Spectra-series process controllers, built on MD system technology.

Conclusion

In this ATP-funded project, Montronix and the University of Illinois at Urbana-Champaign pioneered diagnostics for machine-tool monitoring and met all their major technical milestones. The project team focused on using real-time data to improve the manufacturing process as well as the components produced. Montronix Machining Diagnostic systems monitor the state of the workpiece and the rate of wear on the machine tool itself. The system compares the performance of two or more similar processes in order to consistently seek manufacturing process improvements. The technology developed during this ATP-funded project incorporated advances in PC computing power and speed, user-friendly Windows-based software, and precision in sensor measurements in machine-tool monitoring.

An installed Montronix system consistently recognizes the increased vibration (in a right-angle head) very early, which means that the head can be rebuilt for $2,500. In addition, all waste parts have been eliminated. This factory plans to install six more Montronix systems.

The team published many articles and gave numerous presentations about the process-monitoring techniques. They also developed a free, Internet-based simulation that is still available to government agencies, industries, and universities. In 2001, Montronix experienced financial difficulties and was sold to Growth Finance. Although the technology was a success and led to the development of Montronix's Spectra series, it is undersold at this time due to major changes in the automotive industry. The future of the business is uncertain.

PROJECT HIGHLIGHTS
Montronix, Inc. (a division of Growth Finance)

Project Title: Process Monitoring to Improve Machine Tool Performance (Machine Tool Process Monitoring Diagnostic System)

Project: To develop a diagnostic system that can monitor the vital signs of machining operations in real time to provide a trouble-shooting aid for process engineers who are increasingly challenged to efficiently machine smaller volumes of a wider variety of parts.

Duration: 9/1/1995 - 6/14/1998
ATP Number: 95-02-0020

Funding (in thousands):

ATP Final Cost	$ 1,225	81%
Participant Final Cost	295	19%
Total	$ 1,520	

Accomplishments: The pioneering research and development in this project led primarily to advancements in sensors to record the state of the workpiece, the cutting tool, and the machine tool motor, as well as the development of proprietary software on a Windows-based platform. Montronix monitoring system users can adjust machine tools on the fly to maintain precision in their components. This shortens set-up and testing time, reducing wasted labor and material. As part of this work, the team developed simulations of end-milling projects that are still provided for free on the Internet for use by engineers and scientists.

The initial Montronix Machining Diagnostic (MD) system laid the technological foundation for five Montronix products (as of 2003):

- Spectra PC for open architecture controls
- Spectra Gold for flexible, multistation tool and process control
- Spectra Silver for flexible tool and process control for single machine or process applications
- Spectra Blue for single machine or process crash detection
- Spectra Pulse for complete monitoring systems in a miniature package

Commercialization Status: Based on the MD system developed in this project, Montronix developed another generation of the technology, the Spectra series, which it still markets. More than 5,000 Montronix systems are being used by manufacturers to improve the efficiency of their machine tools. One product developed during the ATP-funded project, the free, web-based machine tool modeling simulation for end milling, is still in use. It has been executed more than 50,000 times for government, research, and industrial use. Montronix expects to continue marketing Montronix diagnostic systems, but the future depends on the manufacturing industry's health, especially that of the automotive industry.

Outlook: The outlook for Montronix process-monitoring tools is uncertain. The company made dramatic advances in speed, user friendliness, and process enhancement; however, the technology enabling these efficiency and precision improvements is undersold. It is difficult to measure the impact of Montronix diagnostic systems, because manufacturers are unwilling to divulge statistics on their efficiency improvements.

Composite Performance Score: * *

Focused Program: Motor Vehicle Manufacturing Technology, 1995

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PROJECT HIGHLIGHTS
Montronix, Inc. (a division of Growth Finance)

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Research and data for Status Report 95-02-0020 were collected during June - July 2003.

United Technologies Research Center

Novel Refrigerant Leak Detection Technology Development

In the mid-1990s, 75 percent of the refrigerants produced were used to replace refrigerants that had leaked out of refrigeration systems. Furthermore, the refrigerant leakage posed a significant environmental concern because refrigerants are destructive to the atmosphere's ozone layer. Therefore, most of the world community had agreed to use leak-detection techniques during the production of components containing refrigerant in order to reduce leakage. Refrigerants containing both chlorine and fluorine atoms are the most harmful to the ozone layer. At the time of the project research, manufacturers were able to detect only large leakage rates by using a mechanical "sniffer" device that detected chlorine- and fluorine-based refrigerants. However, sniffers could not detect minute leakage rates; this level of detection would require more advanced technology.

As part of the 1995 focused program, "Advanced Vapor Compression Refrigeration Systems," United Technologies Research Center, DeMaria Electro-optics Systems, and Adaptive Optics Associates applied for and received an Advanced Technology Program (ATP) award to research and develop more sensitive leak-detection technology. By the end of the ATP project, additional funding was needed to develop the technology. Although United invested its own resources for further development, refrigerant component manufacturing customers did not buy the device, due in part to the high cost of replacing their existing expensive equipment. As of 2004, the original partner companies are still in business, but are not pursuing further development of their leak-detection technology.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
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Research and data for Status Report 95-06-0011 were collected during July 2004.

Refrigerant Leakage Costs the Manufacturing Industry Millions

A refrigerant is a fluid used in cooling components of various machines to maintain a required temperature by removing unwanted heat. Seventy-five percent of the refrigerants that were produced in the mid-1990s were used to replace leaked refrigerant from systems such as refrigerators and automobile air conditioners. The leakage problem was due, in part, to the difficulty in detecting small refrigerant leaks in components during manufacturing and because existing leak-detection techniques relied on imprecise methods. However, it was estimated that if leaks in the defective components could be detected with greater sensitivity during the manufacturing process, component owners would save $650 million per year in refrigerant costs. Also, the industry could significantly reduce the accidental emission of ozone-depleting chemicals and their accompanying adverse environmental effects.

Refrigerant Leak-Detection Technologies Were Inadequate

In 1995, the techniques in use for leak detection in a factory's assembly line were either not sensitive enough or were not economical. The simplest, least expensive, and least sensitive technique was to apply a soap film to a welded component and watch to see if bubbles developed, which indicated that there was a leak.

This method could only detect the grossest of leaks. Pressurizing a welded unit and immersing it into a tank of water to look for bubbles would also indicate a leak, but with a level of accuracy that was similar to the soap-film technique.

A more sensitive technique was vacuum decay detection. This involved removing all the air to create a vacuum inside the welded component that needed testing. The component was then connected to an instrument that would measure the internal pressure to see if the pressure increased due to air leaking into the component. Although this method was more sensitive than the soap-film method, it could not pinpoint the source of the leak in the component.

Detectors based on ionization processes, or "sniffers," were more sensitive still. A sniffer device has a nozzle that sucks any leaking gas into an ionizing chamber where the gas reacts with a substance that causes electrons to be released from the substance. The released electrons are measured in the ionizing chamber as electrical current. Although this method is more sensitive than the ones described previously, large components with 60 welded parts took as long as 18 minutes to be tested, an unacceptable and uneconomical amount of time in an assembly-line setting. (These four leak-detection techniques are representative of the methods used in 1995.)

Partnership Forms to Advance Leak-Detection Technology

Prior to the start of the project, three companies formed a joint venture to develop a more sensitive and economical leak detector that could be used during refrigeration component manufacturing. The partners were the industrial research laboratory at United Technologies Research Center (UTRC), the research arm of United Technologies Corporation; DeMaria Electro-optics Systems, a world leader in laser technology; and Adaptive Optics Associates (AOA), an electro-optics laboratory. The unique detector design proposed by the partnership would be technically risky because it would incorporate a CO_2 laser into a handheld unit (see Figure 1).

Figure 1. Shown above is the prototype handheld laser leak detector. The armored fiber optic cable exits from the rear of the laser barrel to the left of the operator's hand. The small metal tube mounted on top of the barrel houses the visible laser guide beam to assist the operator in aiming the detector.

The joint venture's goal was to develop a detector that would enable the industry to economically detect leak rates of less than 3 grams per year.

The companies' research also targeted the need to preserve the atmosphere's ozone layer.

The risk involved several critical aspects of the detector that needed considerable development and testing, such as the CO_2 laser pulse, the fiber optic cable that would carry the detected data to the processor outside the handheld unit, and an algorithm for the data processor. Because the proposed technology was more advanced and more expensive to develop than any leak-detection technology in use at the time, the partners submitted a proposal to ATP to support their endeavor. They received ATP funding for a two-year project starting in late 1995 under the focused program, "Advanced Vapor Compression Refrigeration Systems." UTRC, the project lead, had already invested about $1 million between 1991 and 1995 to explore technologies in advanced leak detection.

Besides reducing the cost of manufacturing refrigerant that is lost due to leakage, the companies' research also targeted the need to preserve the atmosphere's ozone layer. Chlorine and fluorine, both contained in chloroflurocarbon (CFC) refrigerants, are extremely hazardous to the ozone layer.

Laser Technology Used for Refrigerant Leak Detection

The joint venture partners wanted to improve the sensitivity of leak detection in the factory setting from 100 grams per year to 3 grams per year. Reducing the leakage rate from 100 to 3 grams represented a 33-fold improvement, a goal that required a significant advancement in technology. The handheld device that the partnership proposed to develop was a combination of technologies: a gaseous laser beam to detect leaks, fiber optics to transmit the data collected by the device, and a digital signal processor (DSP) to analyze the sound produced if a leak was detected. The user would hold the device 1 to 3 feet away from the welded sites and would point it at the refrigeration component. The user would then activate the laser. If a gas leak were present, the leaking gas would interact with the laser CO_2 photons and would create a gas pressure (acoustic) wave. The acoustic wave would be detected as a sound by a microphone in the handheld unit. The fiber optic cable would then transmit these data to the DSP, where the sound data were analyzed to determine the location and size of the leak. The DSP could analyze leaks as small as 3 grams per year or higher.

Leak Detector Presents Design Challenges

The team identified three critical parts of the leak detector that would need development: the CO_2 laser pulse, the fiber optic cable for the transmission medium of the detector, and the DSP algorithm that would be used to analyze the signal collected. The partners intended to focus on developing the following components of the handheld detector:

- **CO_2 Laser Pulse.** The team would refine the design of the CO_2 laser pulse emitted by the handheld device. A CO_2 laser is made of light photons emitted from excited CO_2 gas molecules. CO_2 lasers, though inexpensive, are inherently inefficient at this task, so major design modifications would be necessary. For example, the correct wavelength of the CO_2 photons in the pulse needed to be determined.
- **Fiber Optic Cable**. The team would enhance an infrared fiber optic cable that minimized loss of the transmitted signal. The fiber optic cable transmitted the data gathered from the microphone that picked up the sound from a leak. All fiber optic cables experience some loss of signal during operation. The more signal lost, the less accurate the measurement of the collected data would be. The factory setting, in particular, was a more rugged environment than the medical environment for which the fiber was originally designed. The team would need to find a way to prevent background factory noise from “drowning out” the acoustic wave collected from the tested weld.
- **DSP Algorithm**. The team would develop a DSP algorithm to accurately analyze the acoustic waves. The algorithm would be installed as part of the software on the DSP chip. Such an algorithm would need to distinguish between the sounds made by a leak interacting with the laser and the factory background noise. In analyzing a sound wave made by the interaction of a leaking gas with the laser, the DSP algorithm must be sensitive enough to correlate the loudness or softness of the sound with a leak rate.

Partners Cooperated to Build a Prototype Handheld Leak Detector

In the early 1990s, a competitor built a detector using a CO_2 laser, but it was not a handheld unit. The device could not overcome noise levels in the factory environment, so the data gathered by the device were compromised. The UTRC partnership hoped to overcome the interfering noise problem.

UTRC and DeMaria Electro-optics Systems planned to evaluate several technologies for the infrared gas pulse generator aspect of the handheld design. DeMaria would help develop the optimum infrared pulse shape and duration to achieve the highest sensitivity in leak detection. Moreover, the technology would be developed with an eye toward transferability in detecting new, as-yet-undeveloped refrigerants. There are several types of refrigerants in the CFC family of refrigerants. If the team could find a CO_2 laser frequency that would react with most of them, even ones that had not yet been developed, this would provide an additional economic benefit to the ATP-funded project research.

AOA would evaluate several types of optic fibers available for use in the prototype, with the assistance of Rutgers University. AOA brought extensive expertise to the project, including 15 years of experience in pressure wave (acoustic) sensors; micro-optics; high-speed, high-resolution cameras; and high input/output bandwidth commercial processors. In an assembly-line setting, the proposed leak detector would need all of these capabilities.

Joint Venture Completes Prototype Device

After the ATP-funded project concluded, UTRC received additional money from other government agencies, internal funding, and other private sources to develop the technology. However, by 2003 they had ceased development. By the project's end, the team had developed a working prototype that could detect leaks of several refrigerant gases at a leak level of approximately 2.8 grams per year at a distance of 1 to 3 feet from a known, calibrated leak. However, despite a five-month project extension, the laser pulse emitter still needed more development to reduce its cost. Consequently, the lack of an economical prototype forestalled efforts to develop a marketable product. Even though the potential customers for the device were currently relying on technology that was often unreliable, they had already invested millions of dollars in their existing technologies and were unwilling to spend more. Carrier, a subsidiary of United Technologies Corporation, purchased a prototype handheld unit from UTRC, but suspended further testing and development due to a reduction in research funds. Then Carrier decided to shut down its research division in 2001, further reducing the possibility of reviving the technology.

DeMaria also exhausted funding from non-ATP governmental and private sources in the years immediately following project conclusion. DeMaria was subsequently acquired in 2001 by Coherent, a laser manufacturer for the research community. AOA decided not to pursue further development of the technology following the conclusion of the project. In post-project surveys conducted by ATP in 2001 and 2003, all three partners cited cost of development, lack of funding, competition, and uncertain market demand as contributing factors to discontinuing research into this technology. The markets for the laser emitter for the handheld unit were also limited.

As of 2004, refrigeration component manufacturing companies primarily use the sniffer technology. According to Bill Veronesi of UTRC, a principal investigator on the project, not much progress has been made in improving sniffer technology sensitivity in the years after this project ended. Although no product resulted from this project, the company was granted five patents. UTRC also completed one presentation to the Connecticut Microelectronics and Opto-electronics Consortium related to aspects of photo-acoustic leak-detection technology using lasers.

Conclusion

Since the 1970s, engineers have sought ways to detect refrigerant leaks with greater accuracy to meet the world community's standards on atmospheric ozone preservation and to save money during the refrigeration component manufacturing process by producing fewer defective components. Three companies, United Technologies Research Center (UTRC), DeMaria Electro-optics Systems, and Adaptive Optics Associates, formed a joint venture to develop the first handheld leak detector that incorporated a laser, a sound detector, and a digital signal processor.

Each partner worked on a specific part of the detector development. Rutgers University was also involved in evaluating the optimum fiber optic cable to use to transmit the collected signal from the units tested. However, at the project's end, the laser in the prototype detector was still too expensive to use in a marketable product. Although UTRC and DeMaria spent additional non-ATP funds in the post-project years, they were not able to produce an economical product. UTRC did receive five patents related to the ATP-funded project, and researchers made one presentation on the subject of laser photo-acoustic detection techniques.

PROJECT HIGHLIGHTS
United Technologies Research Center

Project Title: Novel Refrigerant Leak Detection Technology Development

Project: To develop a novel leak-detection technology that is 33 times more sensitive than existing methods for detecting leaks in air-conditioning systems during manufacturing.

Duration: 10/1/1995–11/15/1997 (project was extended 6 months)
ATP Number: 95-06-0011

Funding (in thousands):**

ATP Final Cost	$ 708	49%
Participant Final Cost	743	51%
Total	$1,451	

Accomplishments: With ATP funding, United Technologies Research Center and its two partner companies, DeMaria Elector-optics Systems and Adaptive Optics Associates, successfully demonstrated a prototype device that met the target leak detection level of 3 grams per year for chloroflurocarbons.

The following patents for technologies related to the ATP-funded project: were granted:

- "Photo-acoustic leak detector with improved signal-to-noise response"
  (No. 5,780,724: filed March 27, 1997; granted July 14, 1998)
- "Photo-acoustic leak detector with baseline measuring"
  (No. 5,824,884: filed April 16, 1998; granted October 20, 1998)
- "System to control the power of a beam"
  (No. 6,089,076: filed September 18, 1998; granted July 18, 2000)
- "Method and apparatus to diffract multiple beams"
  (No. 6,154,307: filed September 18, 1998; granted November 28, 2000)
- "Photo-acoustic leak detection system"
  (No. 6,327,896: filed March 20, 2000; granted December 11, 2001)

Commercialization Status: No leak detection product was commercialized.

Outlook: The outlook for this technology is weak due to the expense of further development and the lack of customer interest.

Composite Performance Score: *

Focused Program: Advanced Vapor Compression Refrigeration Systems, 1995

Company:
United Technologies Research Center
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East Hartford, CT 06108

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Phone: (860) 610-7592

Subcontractors:

- Coherent, Inc. (formerly DeMaria Electro-optics Systems, Inc.)
  Santa Clara, CA
- Adaptive Optics Associates, Inc.
  Cambridge, MA

Presentations: UTRC gave the following presentation on the ATP-related project:

- "Photo-acoustic System for the Detection of Leaking Refrigerants." Connecticut Microelectronics and Opto-electronics Consortium (CMOC '98), Trinity College, Hartford,CT, March 24, 1998.

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

Research and data for Status Report 95-06-0011 were collected during July 2004.

York International Corporation

Improving Air Conditioning Efficiency

In 1995, experts in the $22 billion air-conditioning and refrigeration industry predicted that U.S. manufacturers would lose market share because of growing foreign competition. At that time, the United States had a 40-percent market share; however, air-conditioning and refrigeration sales by Japanese manufacturers were also at 40 percent and growing faster than U.S. sales. Worldwide sales were expected to reach $150 billion by 2005 as demand from developing countries increased. The Advanced Technology Program (ATP) established a focused program, "Advanced Vapor Compression Refrigeration Systems," in order to help U.S. manufacturers remain competitive and increase their market share. York International Corporation applied for and was awarded cost-shared funding from 1995 to 1998 to develop a novel cooling coil design and manufacturing technologies that would reduce air conditioner size, improve the unit's efficiency and reliability, and improve indoor air quality. York intended to apply innovative concepts from the automotive air-conditioning industry to large stationary systems in order to capture a wider market share. This was risky, because it meant redesigning the coatings and the shape of the fins and tubes that were used in automotive systems, as well as integrating the systems.

By the conclusion of the project, York had designed a heat exchanger that was 25 percent smaller. The company continued development for another year after the project ended. Although York decided to postpone commercializing the coil technology, the company developed a fin calorimeter that it used for measuring heat transfer and a method to rapidly prototype fins. The company later used the tool and the method in additional research and development efforts that led to commercialized products.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

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Research and data for Status Report 95-06-0004 were collected during October 2003.

Improved Air-Conditioning Efficiency Could Maintain U.S. Market Share

In 1995, approximately 40 percent of the estimated $22 billion annual global air-conditioning and refrigeration equipment industry was supplied by U.S. manufacturers. The global market was expected to grow to $150 billion by 2005 as demand increased in developing countries. Innovation and efficiency gains would be key to maintaining and increasing U.S. market share.

Air handling units (AHUs) are a style of air conditioning suited for large buildings. Air conditioners cool and dehumidify air through the use of internal heat exchangers, or "cooling coils," in which liquid refrigerants extract heat from air removed from a populated area, called an occupied space (see illustration of an AHU). Fans blow a mixture of outside air and return air (coming back from the occupied space) onto the coil, located in the AHU. This warm-air mixture is cooled as it is blown over the tubes that contain liquid refrigerant. Metal fins attached to the tubes help to conduct the heat. Cool liquid refrigerant enters the coil tubes, snakes through the coil as it absorbs heat, and exits. Moisture from the warm air condenses on the cool tubes and fins and must be drained. The fan blows cool air from the coil, through the ducts, back to the occupied space.

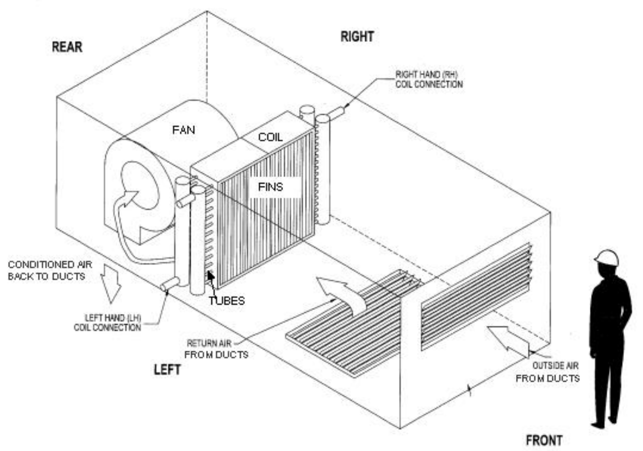

Diagram of an air handler unit. Warm outside air and return air enter from the ducts and blow across the coil, which absorbs heat through the fins and tubes. Cool liquid refrigerant enters the coil tubes from the right-hand coil connection, snakes through the coil, and exits to the left. Moisture from the coil collects and drains down to a pan beneath it. The fan blows cool air from the coil back to the occupied space.

The performance of heat exchangers is restricted by various factors, including the choice of liquid refrigerant, the type of metal used in the tubes, the dimensions of the tubes, and the need to keep air velocity low. In the case of the latter, this is necessary so that condensed moisture and dirt are not blown beyond the coil back to the occupied space, which would lower the indoor air quality (IAQ).

By reducing the coil size and improving its efficiency, a manufacturer could capture more of the large-scale heating, ventilation, and air-conditioning (HVAC) market. Moreover, these improvements could reduce material costs (as a result of producing smaller units), capital costs (by requiring a smaller footprint), electricity costs (by operating more efficiently), and health care costs (by reducing bacteria and moisture reentering the occupied space). The improvements could potentially reach hundreds of millions of dollars annually.

ATP Funding Enables Collaboration

York International Corporation, the largest independent supplier of HVAC and refrigeration products in the United States, wanted to apply recent energy-efficient automotive air-cooling concepts to the HVAC industry. The HVAC industry had not achieved lasting innovations in new technology in the years prior to 1995. For example, they had not experimented with improving the design of heat exchangers or changing the shape of the tube technology used in the units. As a result, they lagged behind the auto industry in cooling efficiency innovation. Furthermore, while high-performance, compact heat exchanger designs that used brazed (hardened) aluminum oval-tube technology were gaining acceptance in the auto industry, there had been no similar innovation in the $2.7 billion commercial and industrial HVAC markets. There were two reasons for this: 1) brazed aluminum offered no cost savings over existing copper technology (because weight savings is not a significant factor in commercial systems), and 2) existing copper systems can be repaired on site, and they work well with heat transfer fluids. These fluids, which include water and brines, are preferred over Freon or other "evaporating refrigerants" in building air supply systems, because a potential leak of water is less hazardous to IAQ. Moreover, interior corrosion of the aluminum results in reliability problems (e.g., clogs and leaks). In order to improve efficiency, York would need to develop new coatings and a new design for the fins and tubes. York would then need to integrate the parts into a single system. The company also planned to reduce the size of the heat exchanger by 25 percent and increase energy efficiency.

Reducing the coil size and improving its efficiency could reduce material costs, capital costs, electricity costs, and health care costs. The improvements could potentially reach hundreds of millions of dollars annually.

If successful, new HVAC systems would require smaller space while maintaining performance, which would reduce capital costs for new systems over time. Furthermore, IAQ would improve as a result of reduced coolant leaks because leaks contribute to odors and bacterial growth. In order to research and test these potential innovations, York submitted a proposal in 1995 to ATP's focused program, "Advanced Vapor Compression Refrigeration Systems." The program sought to support the development of cooling products that were more efficient, less costly, and better performing than the products manufactured by foreign competitors.

York received $1 million in ATP cost-shared funding. The company teamed with the Mechanical Engineering Department at Pennsylvania State University, which provided the concepts for heat exchanger technology and preliminary testing of sample miniature coils. York hired several subcontractors to support specific components of the research plan: Tridan Tool and Die Company (now Tridan International, Inc.) produced fin dies and fin stacks; Timesavers, Inc. provided roughened finishes on fins for initial testing; Materials Science Corporation conducted refrigerant pressure testing; and Automated Test Labs provided final results on thermal transfer and air-pressure drop.

York Develops Challenging Milestones

The York team's objective was to design and manufacture efficient, compact, high-quality, air-cooled, coil-style heat exchanger technology for cooling indoor air. Higher efficiency would result in lower operating costs for users and less adverse impacts on the environment. The smaller units would require less space and would cost less to manufacture. As described below, while York's goals were innovative, the project achieved mixed results due to technical difficulties.

- ***Task***: Reduce the size of the oval copper tubes by 25 percent (internal volume and material content), while maintaining performance, by using a slightly smaller oval-tube design. The goal was to make an aerodynamic shape and increase the exposed surface area relative to volume in order to enhance the heat transfer.
  Results: The team successfully formed oval copper tubes with a 4:1 diameter ratio (i.e., the length of the oval was 4 times longer than its width) and reduced volume for use in 12 prototype coils. The team manufactured oval tubes that were 10 percent more efficient in heat transfer than round tubes of comparable size. However, it was difficult to insert oval tubes into a fin stack. In the assembled condition, the tubes did not align and fit tightly in fin collars.

- ***Task***: Evaluate and select a cost-effective hydrophilic or "wettable" coating to apply to the heat exchanger fins produced by Tridan Tool and Die Company. Minimizing surface moisture retention would reduce the impact on the IAQ, as well as on the health of the building's occupants. The coatings increase the surface contact area of the water droplets to make them flatter; the water then sheets away, similar to a dull finish on an un-waxed car in the rain. As a result, moisture is less likely to blow off the fins into the supply air vent.
  Results: The team tested seven wettable treatment variations and experimented with roughening methods applied by Timesavers, Inc. Early results were favorable, but the coatings degraded over time due to dirt collecting on the surfaces.

- ***Task***: Test the air-pressure drop in the AHU as air moves over standard round coil tubes compared with the new oval-tube design. Reduced air-pressure drop would mean airflow moves freely from the AHU into supply air ducts (with greater energy efficiency).
  Results: Researchers turned the narrow end of the oval tube toward the moving air to reduce wind resistance. Airflow was 15 to 35 percent more efficient with the oval tubes (35 percent at the beginning of a cycle, when coils were dry; 15 percent with wet coils).

- ***Task***: Eliminate refrigerant or brine leaks through machine-driven joint bonding. Eliminating all leaks was important for two reasons: 1) to reduce maintenance costs due to leakage, which had been a chronic problem; and 2) to maintain the chemical uniformity of the fluid refrigerants in order to achieve the system's optimal efficiency.
  Results: Limitations of time and staffing prevented work on the sealed joint beyond the concept stage.

By project end, the York team had successfully designed a new heat exchanger that was 25 percent smaller than standard models. Smaller dimensioned oval tubes maintained the same cooling capacity compared to the standard larger round tubes, but the results with wettable coatings were disappointing. York applied for two patents related to project innovations, but both were denied. However, at the conclusion of the project, there were many tasks left to complete, such as selecting a wettable fin treatment, developing a better way to measure fin wettability, and optimizing tube spacing.

York Derives Lasting Benefit from ATP-Funded Project

During the ATP-funded project, York researchers developed a tool and a method that were of lasting value to the company as they continued their research and development:

- Fin calorimeter, which measures air-pressure drop and heat transfer
- Method for rapidly prototyping fins, which reduces the research and development cycle time for new fins from 24 to 12 months

After the project concluded in 1998, York continued to fund its development of the 12 test oval-tube coils for another year. And as of 2003, the company was still using its fin calorimeter and fin-prototyping method. The company also developed a new commercialized plate fin, called HiQ, using the prototyping method from this project. York uses the fin in its ECO2 rooftop heating/cooling units. The fin has proprietary enhancements that yield approximately twice the heat transfer when compared to a standard wavy or corrugated plate fin. York continues research into wettability today, and this research relies on the knowledge the company gained during this ATP-funded project.

York Decides to Postpone the Coil Project

In 1999, the company made a decision to postpone commercializing oval-tube coil technology. Although commercialization was technically feasible, an economic assessment revealed that it would have cost several million dollars to produce new fin dies and presses to manufacture fins that had the more precisely shaped holes needed to fit the oval tubes snugly. Because the industry was conservative, marketing the new oval-tube design would be challenging. In addition, economists were detecting a slow-down in the U.S. economy in 1999-2000. The company estimates that it would take five years of additional development time to implement the technology.

Conclusion

York International Corporation researched ways to apply successful automotive air-conditioning technology to commercial and industrial air conditioners. Using copper instead of brazed aluminum, York and its subcontractors redesigned the heat exchanger, or "coil," and fin geometry. They also changed the geometry of the tubes from round to smaller ovals in order to reduce coil size and still maintain heat transfer efficiency. They applied wettable coatings to the fins to improve moisture removal and planned to eliminate refrigerant leaks with machine-driven joint bonding. The team successfully produced 12 prototype heat exchangers, which were 25 percent smaller than those in use. Moreover, they demonstrated a 10-percent increase in cooling efficiency with oval tubes compared to standard round tubes.

If successful, new HVAC systems would require smaller space while maintaining performance, which would reduce capital costs for new systems over time.

York has postponed commercializing its novel coil technology due to technical problems that included the fin coatings degrading over time and oval tubes that could not be easily inserted into the fin stacks. York did develop a tool to measure heat transfer and a method to rapidly prototype fins, which the company still uses in the research and development of new products. The project researchers published their results extensively and filed for two patents. York is continuing the wettability research.

PROJECT HIGHLIGHTS
York International Corporation

Project Title: Improving Air Conditioning Efficiency (York Coil Technology)

Project: To develop novel cooling coil design and manufacturing technologies that will reduce the size of air conditioners, improve the units' quality and reliability, eliminate leakage, and improve air quality.

Duration: 9/1/1995-8/31/1998
ATP Number: 95-06-0004

Funding (in thousands):**

ATP Final Cost	$1,068	81%
Participant Final Cost	249	19%
Total	$1,317	

Accomplishments: York demonstrated that oval-tube geometry is 10 percent more efficient for heat transfer than round tubes. Researchers developed a prototype heat exchanger that was 25 percent smaller and had the same heat transfer capability as the standard size. Furthermore, York developed a method and a tool that they still use in their ongoing research and development:

- Method for designing fins, which reduced development time from 24 to 12 months
- Fin calorimeter to measure air-pressure drop and heat transfer

York used the fin calorimeter and new designing method to develop a new fin, called HiQ, which is used in the company's ECO2 rooftop heating/cooling units. This is a plate fin with proprietary enhancements that yield approximately twice the convective heat transfer when compared to standard wavy or corrugated plate fins.

York filed two patents for ideas generated by the ATP-funded project, but both were denied. Furthermore, the company shared its project knowledge through numerous presentations and publications, as listed at the end of this report.

Commercialization Status: Using the methods developed during this project, York developed a new commercialized plate fin, called HiQ. York uses the fin in its ECO2 rooftop heating/cooling units. Its proprietary enhancements yield approximately twice the heat transfer when compared to a standard fin. Due to the prohibitive manufacturing capital cost, York has postponed commercializing oval-tube coil technology.

Outlook: The outlook for this oval-tube coil technology is poor, and York has postponed plans to commercialize it. The company does continue to use its new method for designing fins and its fin calorimeter, which were both developed during the project. Moreover, the company is still pursuing alternate solutions for wettability, building on knowledge gained in this ATP-funded project.

Composite Performance Score: *

Focused Program : Advanced Vapor Compression Refrigeration Systems, 1995

Company:
York International Corporation
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York, PA 17403

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Phone: (717) 771-7890

Subcontractor:
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Mechanical Engineering Department
University Park, PA

Tridan Tool and Die Company
Danville, IL

Timesavers, Inc.
Minneapolis, MN

Materials Science Corporation
Fort Washington, PA

Automated Test Labs
Philadelphia, PA

Publications and Presentations:

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

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APPENDIX A

Development of New Knowledge and Early Commercial Products and Processes, 3rd 50 of Status Reports

Table A-1: Advanced Materials and Chemicals; Table A-2: Biotechnology; Table A-3: Electronics, Computer Hardware, or Communications; Table A-4: Information Technology; Table A-5: Manufacturing

Table A-1. Advanced Materials and Chemicals

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
ABB Lummus Global, Inc. (formerly ABB Lummus Crest)	95-05-0034	Developed a new, environmentally superior process to manufacture alkylate, an ideal unleaded gasoline additive, using solid-acid catalysts	As of 2005, the joint venture partners were seeking commercial opportunities to build new solid-acid alkylation plants
Advanced Refractory Tech	95-01-0131	Developed a diamond-like nanocomposite (DLN) coating technology. The company established improved manufacturing techniques for DLN films and developed several applications, such as electrosurgical blades and flat panel displays	A number of products with DLN coatings are currently being sold. These include components that are used in manufacturing CDs, DVDs, polyethylene terephthalate juice bottles, and metal cans and components used in semiconductor cluster tools
Air Products and Chemicals, Inc.	93-01-0041	Developed ceramic-steel seals and processes to remove contaminants from oxygen	The company is continuing its research and development (R&D) into their prototype air-separation unit for producing high-purity oxygen so that future commercialization may be possible. However, the company does not intend to pursue commercialization initiatives until a 30-percent decrease in production cost is achieved
Automotive Composites Consortium (a Partnership of DaimlerChrysler [formerly Chrysler], Ford and General Motors)	94-02-0027	Developed a composites-manufacturing process called Structural Reaction Injection Molding (SRIM) for f producing large automobile structural parts, such as the box of pickup trucks	Commercialized the access door and tail cone for the Air Force C-17 cargo plane by Boeing, firefighter helmet shells by Lion Apparel, the inner tailgate sections for the GM Cadillac Escalade EXT hybrid SUV beginning in 2001, the load floor sections for the "Stow 'n Go" system to fold down second-and third-row seats in the Chrysler

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
			Town & Country LX and Dodge Grand Caravan SCT beginning in 2005, the midgate (a door that folds down to extend cargo space) for the GM Chevrolet Avalanche beginning in 2001, the motor covers for marine applications by SeaRay (Marine division of Brunswick Corp), and the pickup truck box and tailgate assembly for the 2001 to 2004 GM Chevrolet Silverado. Boeing's 787 "Dreamliner" uses SRIM composites for structural parts, increasing fuel efficiency by 3 percent. Overall fuel savings is 20 percent compared with the 747. First commercial flight is scheduled for 2008
Bosch (formerly Allied Signal)	95-07-0020	Developed a synergy between design and casting processes that resulted in the following accomplishments: elimination of porosity problem (zero rejects for porosity); reduction from one large and three small defects per part to two small defects per part; acceleration of research by two years ahead of where it otherwise would have been through parallel research efforts; and reduction of defects in a specific type of valve body design by up to 85 percent	The technical challenges of this project were too numerous and difficult to overcome. As a result, AlliedSignal created no new products for brakes using the technology developed under the ATP-funded project. The Top Die Casting Company produced some components using the new processes, such as air brake valves and brackets. Stahl Specialty Company used one step of the aluminum manufacturing process to assist in aluminum filtration. That process had a small impact on several of the company's product lines
BP Amoco	93-01-0234	Developed a process using silver nitrate as a facilitating agent in high-efficiency contactors and had developed a promising new complexing agent that would potentially cost less than silver nitrate when used for facilitated transport	Although the process was technically sound, the company was experiencing costly operating problems. Amoco was unable to demonstrate the economic feasibility of using this new technology for olefin-paraffin separations and therefore did not commercialize the technology
Catalytica Energy Systems (formerly Catalytica, Inc.)	94-01-0190	Developed catalysts with enhanced activity and selectivity for use in the chemical and petroleum-refining industries	Developed a Multiple Stream Mixer/Reactor (MMR) which may prove to be a very valuable tool for the emerging nanotechnology sector, producing nanoparticles for many industries. The company expected to sell its first major

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
			production MMR system in 2005 or 2006
Crucible Materials Corporation, Crucible Companction Metals Division	94-01-0287	Developed alloys with high levels of nitrogen that demonstrated the potential to produce high-strength, corrosion-resistant stainless steel	Commercialized high-nitrogen alloys that could improve the performance of stainless steel (SS100)
GM Thermoplastic Engineering Design (Engineering Design with Thermoplastics)	92-01-0040	Developed models and generated data for "virtual design" in order to improve the design and development of thermoplastic automotive parts. The project team linked two commercial software tools, Moldflow (formerly C-MOLD) and ABAQUS, with new failure theories for plastics in order to integrate mold design with parts performance	Commercialized virtual design tools that have shortened development time and have improved the performance of thermoplastic parts, which has benefited many manufacturers (for example, Delphi's thermoplastic radiator tank and many other parts; GM's injection-molded plastic intake manifold and other engine components; GE Plastics' improved raw material, which is used in business equipment, optical media, and telecommunications devices). The project resulted in the International Organization for Standardization (ISO) issuing a new standard (ISO 94-5)
Honeywell (formerly Allied Signal)	93-01-0104	Developed powder injection molding used in the ceramic industry for chinaware, spark plugs, oxygen sensor components, and oxygen sensor insulators	Commercialized ceramic powder injection molding technology that is being used in chinaware, spark plugs, oxygen sensors, ball bearings, manufacturing components (for example, stamping punches and guide rollers), engine and machine components (for example, nozzles, seals, shafts, valves, and heating units), and bio ceramics (for example, artificial bones for human replacement surgery)
Honeywell (formerly Allied Signal)	95-07-0003	Developed "aqueous injection molding" (AIM) process improvements for ceramic splitter vanes	Commercialized ceramic splitter vanes in 1998. They had plans to commercialize other small, complex, high-volume parts like blades and nozzles

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
IBM T.J. Watson Research Center	93-01-0149	Developed a conducting polymer of acid-doped polyaniline (PANI) with thermal stability greater than 250 degrees C from 150 degrees C, increasing processability and solubility, and increasing conductivity by 2.5 orders of magnitude	Commercialized a water-soluble version of PANI that was licensed to Monsanto Chemical Corporation in 1997, and IBM is pursuing further licensing opportunities
PCC Structurals	95-07-0011	Developed a casting technology that combines the superalloy processing capabilities of investment casting with the economic advantages of sand casting and achieves part sizes sufficient to produce exhaust frames for industrial gas turbine engines	PCC did not commercialize the new casting technology. They did develop prototypes of a new casting technology that will allow manufacturers to produces large structural superalloy components for industrial equipment industries, such as the Industrial Gas Turbine industry
Praxair, Inc.	94-01-0111	Developed new materials highly selective for oxygen, including IC-2, IA-1, IA-2, and IA-3, which have the potential of meeting all characteristics of a successful material with further development	The O2-selective materials developed during this ATP-funded project have not been commercialized. However, as of 2003, Praxair has continued work on their development through a project with the Department of Energy with hopes to commercialize in the future
The Dow Chemical Company	95-05-0002	Developed a direct, economical, single-product oxidation process incorporating a silver-based catalyst for conversion of propylene to propylene oxide	Dow researchers expect that they might complete a process to develop a direct oxidation propylene sometime between 2006 and 2014. A successful process will reduce energy consumption, cost, and waste in the manufacturing of many types of plastics, lubricants, coatings, surfactants (detergents), and composite materials
Wyman-Gordon	95-07-0026	Developed an incremental forging process to produce near-net shape forgings for industrial gas turbines using a lower-tonnage press than was previously possible	Wyman-Gordon has incorporated the incremental forging process into its business operations

Table A-2. Biotechnology

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
Aphios Corporation	95-01-0263	Developed a knowledge base and technology platform to tap into the pharmaceutically, industrially, and environmentally valuable chemical diversity that remains unexplored in enormous numbers of marine microorganisms	An anti-plaque solution for toothpaste or mouthwash, which is being optimized through chemistry, is the nearest product to commercialization. Novel therapeutics for multiple-disease-resistant (MDR) bacteria, influenza, HIV/AIDS, cancer, and smallpox are also undergoing trials in preclinical drug discovery and development
Cengent Therapeutics Inc. (formerly Moldyn Inc.)	94-01-0137	Developed a software that adapts a technology developed in the aerospace industry to simulations of biological molecule and drug interactions, for the purpose of qualifying drug research candidates in a more timely and efficient manner than by using trial-and-error techniques	The MD simulation software was briefly commercialized through a license to Molecular Simulations Incorporated, but failed to gain sufficient sales and was discontinued. However, Moldyn's software was incorporated with Harvard's Chemistry at Harvard Macromolecular Mechanics (CHARMM) molecular modeling tool through a licensing agreement between Moldyn and Harvard University
Dow AgroSciences LLC (formerly Mycogen Corporation)	95-01-0148	The company made strides in genetic research and demonstrated for the first time that yeast is transformable. They demonstrated that squalene could be hyper-produced in oleaginous yeast; and they gained a broader understanding of the metabolic pathways for isoprene formation in yeast	No commercialization occurred because the oleaginous yeast fermentation project was ended due to technical barriers with enzyme manipulation
DuPont Qualicon (formerly DuPont FQMS Group)	94-05-0033	Developed a functioning automated, rapid DNA diagnostic prototype system that reduced analysis time from 3 hours to 30 minutes. The system can determine the presence or absence of specific microbial contamination as a means of quality control in the food industry. However, DNA pattern results from sample testing were somewhat inconsistent and needed further development	Additional steps were required in sample preparation that negated the time saved in analysis. DuPont Qualicon ended the research into this automated system in 1998, but the company did apply some of the automation knowledge gained in this project to its ongoing alternate food-borne pathogen-testing technologies

Genosensor Consortium (c/o Houston Advanced Research Center)	92-01-0044	Developed a technology for automated DNA sequence analysis	Provided sample analysis and database services for genotyping and gene expression research to organizations such as the Schering Plough Research Institute. In 1999, consortium member Sigma Genosys began to sell Panorama Gene Arrays, which profile gene expression in human cytokines, B. subtilis, and E. coli. In 2003, Sigma Genosys sold human cancer oligoarrays. In 2003, consortium member Beckman Coulter started to commercialize arrays
Incyte Corporation (formerly Combion, Inc.)	94-05-0019	Developed a method akin to ink-jet printing for synthesizing large arrays of specific DNA fragments suitable for medical diagnosis, microbial detection and DNA sequencing, and for creating supplies of detachable oligonucleotides for subsequent use	Microarray expertise and knowledge gained in this project formed the foundation for Incyte's highly successful bioinformatics business, which operated from 1999 to 2001 (selling subscriptions to databases of DNA information). Although Incyte put the specific chem-jet microarray manufacturing techniques developed in this project on hold from approximately 1998 to 2004, the company licensed the technology to Agilent in 2001. As of 2004, Agilent was about to commercialize the ATP-funded technology in conjunction with their numerous other patented chem-jet technologies
JDS Uniphase (formerly The Uniphase Corporation)	94-05-0004	Although the attempt to develop a compact, efficient, and cheaper source of blue light for fluorescence-based diagnostic instruments and techniques for physicians and biomedical researchers was unsuccessful, the project led to the development of two unanticipated products	Commercialized the Blue Laser Module, a stripped-down, inexpensive blue laser for tabletop applications within the biotechnology industry, that reached the market in 1999 and has achieved sales as high as $500,000 per year. They also sold the MicroBlue SLM, a specialized, low-noise blue laser for digital photo-finishing, that was first marketed in 2000 and generated $1 million in annual sales
Large Scale Biology Corporation (formerly Large Scale Proteomics Corporation)	94-01-0284	Developed the ProGEx product line for protein identification and research. The company also completed the first version of the Human Protein Index by identifying more than 115,000 proteins from 157 medically relevant human tissues	The 2-D gel and ProGEx line of protein analysis tools has been upgraded and improved over the years. Large Scale Biology Corporation (LSBC), which acquired LSPC in 1999, still sells research products and databases created through use of technology flowing from the knowledge acquired during this ATP-funded

			project. The company performs up to one million mass spectrometry analyses of proteins per week
Medical Analysis Systems (formerly NAVIX)	95-08-0017	Developed a two-stage reaction for DNA identification and amplification. The process identifies areas of DNA that correlate with disease	Navix did not commercialize any products from its ATP-funded research. Business issues delayed research long enough for another competitor to beat Navix to the market
Monsanto (formerly Agrecetus)	94-01-0074	Developed a prototype plant with elevated levels of poly-3-hydroxybuteric acid (PHB). Although the PHB concentration was not high enough for commercialization, simply raising the PHB level at all represented a technical achievement	Due to the difficulty in attaining high enough PHB levels in the cotton fibers without "crowding out" the fibers' favorable traits, no commercialization efforts resulted from this ATP-funded research.
Orchid BioSciences (formerly Molecular Tool, Inc. Alpha Center)	94-05-0034	Developed techniques for micromachining and for handling fluids on a microscopic scale to make a simple, compact DNA typing instrument	Developed the SNPstream Ultra High Through-Put (UHT), automated array-based genotyping tool. Entered the market through Orchid BioSciences in 2001. Product, intellectual property, and research and development were sold to Beckman Coulter in December 2002. As of 2004, Beckman continues to develop and enhance the system, marketing to research and clinical laboratories. Orchid BioSciences provides genetic analyses using SNPstream UHT on a fee-for-service basis (for biotech companies, pharmaceutical companies, and criminal justice agencies). Orchid's facility was providing up to 1 million SNP scores per day by the end of 2000 on a fee-for-service basis
Valentis, Inc. (formerly Progenitor, Inc.; a subsidiary of Internueron Pharmaceuticals)	94-01-0301	Developed an understanding of how the Del-1 gene regulates angiogenesis and can be used to treat ischemia	In 2003, the company completed a Phase I clinical trial and initiated a Phase II clinical trial for Del-1 angiogenesis product for the treatment of peripheral arterial disease

Table A-3. Electronics, Computer Hardware, or Communications

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
eMagin Corporation (formerly FED Corporation)	93-01-0154	Developed manufacturing techniques for large-scale, flat-panel displays based on arrays of field emitters, a sort of "flat CRT"	Commercialized two microdisplays, SVGA 3D and SVGA+ rev2. The microdisplays are integrated into hundreds of medical, commercial, and military applications. For example, firefighters see through thick smoke by looking through a thermal-imaging camera lens to find victims, even under a blanket. They can also use the lens to find the source of a fire quickly and put it out. Researchers and doctors are using the display to enhance vision for magnetic resonance imaging (MRI), endoscopic surgery, and eye surgery
INSIC (formerly NSIC) - Short Wavelength	90-01-0231	Developed optical recording standards to improve upon traditional magnetic recording	NSIC members did not commercialize optical recording devices because remaining technical obstacles would have required significant further development of the frequency-doubling technology; and by the end of the project, competition was looming from direct-lasing green and blue diode lasers
Kopin Corporation	94-01-0304	Developed liquid crystal projection display technology capable of producing high-quality, high-resolution images for high-definition TV	Commercialized the CyberDisplay 320 Monochrome, the CyberDisplay 320 Color, the CyberDisplay 640 Color, the CyberDisplay 1280 Monochrome 60" diagonal projection HDTV, the CyberDisplay 1280 Monochrome 55" diagonal projection HDTV, the CyberDisplay 1280 Monochrome 46" diagonal projection HDTV, and CyberDisplay 1280 Monochrome 43" diagonal projection HDTV
Planar Systems, Inc. (American Display Consortium)	93-01-0054	Developed a group of patterning technologies necessary to manufacture color flat-panel displays, including large-area photo exposure tools, large-area masks, wet and dry etching tools, printing tools, panel alignment methods and a final inspection tool	Subcontractor, Photronics (now Infinite Graphics, Inc. [IGI]), commercialized customized large-area photo masks for use in high-end printer circuits, calibration plates, x-ray systems, and flat-panel displays. Photonics also developed two processes: mask cleaning & laser pattern generator

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
			Subcontractor, Plasma-Therm successfully commercialized dry etching processes in its Clusterlock 7000 for 6-inch wafers. The company was sold to a Swiss company, Oerlikon-Buehrle in 1999. Planar used the Plasma-Therm etcher to produce AMEL microdisplays until 2002. Subcontractor, YieldUp (now FSI) developed drying tools for wet-etched substrates. This is now used for flat-panel displays and primarily computer chip manufacturing. Also used in hard disk drive cleaning and photomask cleaning. Currently, the ATP-funded component is key in seven larger processing systems:ZETA Spray Cleaning System, ANTARES CX Advanced Cleaning System, EXCALIBUR Vapor HF Etching System, MERCURY Spray Cleaning System, YieldUP 4000 Immersion Etch System, YieldUP 2000 Rinse Dry Module, and YieldUP 2100 STG Rinse Dry Integration Module
SDL, Inc. and Xerox Corporation	91-01-0176	Demonstrated the first integration of multiple-wavelength laser diodes on a single semiconductor device. In the course of this work, the team established several intermediary technologies and accomplished important research in the field of gallium nitride (GaN)-based blue laser diodes. Demonstrated technologies include two alternative methods for monolithic integrations of red, infrared, and blue emitters; red laser diodes with powers of up to 120 mW single mode; lasers in the 700- to 755-nm range; green and blue lasers with frequency doubling; and the lasing of blue GaN diodes at room temperature	After the ATP-funded project, SDL commercialized several laser products that were based on technologies developed in the course of the project: a single-mode laser using facet passivation technology; a single-mode laser for PDT applications; a dual-spot single-mode laser for data storage, printing, displays, and alignment; a multi-mode laser; fiber coupled laser bars for solid state laser pumps, medical systems and displays; and a DBR laser for frequency doubling, interferometry, atomic clocks, and spectroscopy
Superconductor Technologies Inc. (formerly Conductus)	91-01-0134	Developed a prototype superconducting DSP switch	Commercialization of the technology developed and tested during this ATP-funded project was not pursued due to a lack of interest in the technology on the

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
			part of the semiconductor and communications industries
Texas Instruments Inc.	94-01-0221	Developed a special insulating material, known as aerogel, to be integrated adjacent to on-chip interconnects in order to overcome problems with interconnect delay as a result of the continuing trend toward miniaturization. Texas Instruments and NanoPore developed the world's first fully automated manufacturing process to dry an aerogel quickly	The company overcame impediments to aerogel processing early in the project, but in 1997, an industry competitor announced that it would begin using copper interconnect wiring in future integrated circuit designs. Texas Instruments then shifted focus away from aerogels for aluminum and began to develop copper interconnects. Before shifting focus, however, Texas Instruments transferred its aluminum circuit aerogel knowledge to NanoPore, which later sold the rights to continue development of the product to Honeywell. Honeywell's development efforts resulted in a product that they marketed briefly in 2002 to companies for use in manufacturing semiconductors. However, Honeywell withdrew the product in 2004 after it did not fulfill its potential as a new and innovative insulator

Table A-4. Information Technology

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
Accenture (formerly Andersen Consulting Center for Strategic Research)	94-06-0012	Developed a prototype technology for reusable software components based on software architecture considerations, including formal languages to express semantics, a graphical user interface programming environment, automated techniques for assuring that the separate components are logically compatible and properly combined, and automated systems to generate executable systems	No product was commercialized as the technology focus of the industry changed shortly after the project concluded
Cerner Corporation	94-04-0008	Developed information tools to automate, validate and distribute clinical practice guidelines for mass use	Used general concepts from the ATP-funded project to execute guidelines in its Cerner Millennium product. With Cerner Millennium, clinicians are electronically alerted about potential patient safety and regulatory issues through evidence-based medical information
Cerner Corporation (formerly DataMedic - Clinical Information Advantages, Inc.)	94-04-0038	Developed a knowledge-base-driven automated coding system in the form of a software component, CHARTnote which uses MEDencode, a technology that automatically gathers, codifies, and records specific detailed information about a patient	The software is currently incorporated into and sold with approximately 7 CHARTstation products, manufactured by VitalWorks. It is also sold separately and with other products. Products include GIstation, EMstation, EYEstation, RADstation, and other areas including internal medicine and family practice, renal dialysis, and rehabilitative medicine
InStream	94-04-0018	Developed the first behavioral healthcare (BHC) Web portal for claims processing	The software product was briefly commercialized in 1998, but was quickly overtaken by competing products after a lack of funding prevented InStream from providing the necessary upgrades and market penetration to reach positive cash flow
Lucent Technologies (formerly AT&T Bell Laboratories)	94-06-0011	Developed and successfully demonstrated their software (Symphony) to develop an easy-to-use, graphics-user interface (GUI) software assembly system for nonprogrammers that handles the complexity of building reliable,	No commercialization resulted from this project because of AT&T's corporate restructuring in 1996. Lucent decided to discontinue its development of the reusable software component product

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
		custom-designed software by using libraries of reusable, software components	
SciComp, Inc.	94-06-0003	Developed a component software and a software synthesis technology for creating mathematical models in the field of scientific computing	As of 2004, SciComp offered three software tools in the SciFinance solution that incorporate the ATP-funded software synthesis technology; SciFinance also includes two additional products that enhance SciPDE and SciMC. SciComp experienced greater demand for these products as the market
Titan Systems (formerly Intermetrics)	94-04-0040	Developed a script language and a related suite of software tools to facilitate the process of developing customized home healthcare workstations for homebound or limited-mobility, chronically ill patients	A product was not commercialized. The intellectual property was acquired by HealthVision, which chose not to further develop it
Xerox Palo Alto Research Center	94-06-0036	Developed a new programming technique called aspect-oriented programming (AOP). They also developed two prototype applications of specialized computer languages	AspectJ, an open-source language that extends Java, is now used in a significant percentage of IBM's new products and is an open-source platform. PARC transferred AspectJ to the open-source eclipse.org project in December 2002

Table A-5. Manufacturing

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
Abrasive Technology Aerospace, Inc.	95-02-0053	Developed an integrated CAD/CAM approach to applying superabrasive coatings to complex surfaces of electroplated superabrasive grinding wheels	In 2000, Abrasive Technology began to market and sell electroplated superabrasive grinding wheels using the CAD/CAM technology it developed during the ATP-funded project, and still continues to do so. The company has used the new technology to produce grinding wheels for a variety of industries, including automotive and aerospace
Cincinnati Lamb, UNOVA (Lamb Technicon)	95-02-0019	Developed an experimental prototype of a flexible line boring station with intelligent tooling and controls	The BOA technology was not commercialized because auto manufacturers found less expensive machine tools to meet their specifications
General Electric Corporation R&D	95-07-0018	Developed an intelligent process for applying thermal barrier coatings to critical components in turbine engines for power plants in order to raise firing temperatures and increase fuel efficiency	GE successfully produced an improved gas turbine engine for its new H-System combined-cycle power plant, which can achieve 60-percent energy efficiency. The high-performance thermal barrier coatings developed in part using technology from this project were essential to the design of this model. GE also applied the knowledge to upgrade existing F-System plants, which achieved 56-percent efficiency. Other companies have used the process on marine aircraft and heavy diesel engines, as well as other applications
IBM Corporation	94-03-0012	Developed an automated tool kit that could be used by vendors to develop, maintain, and join interoperating families of enterprise resource planning (ERP) and manufacturing execution system (MES) applications	IBM did not commercialize its new automated tool kit. Instead, it commercialized a service based on its new Framework for Adaptive Interoperability of Manufacturing Enterprises (FAIME) technology, enterprise application integration (EAI) services
Montronix	95-02-0020	Developed a diagnostic system that can monitor the vital signs of machining operations in real time to provide a trouble-shooting aid for process engineers who are increasingly challenged to efficiently machine smaller	The developed monitoring system later evolved into a standard Montronix product line called Spectra. A key accomplishment of this project was providing free Internet-based simulated machine-tool modeling

A. Awardee Name	B. Project Number	C. Technology Developed	D. Products or Processes Commercialized or Expected to be Commercialized Soon
		volumes of a wider variety of parts	(http://mtamri.me.uiuc.edu/testbeds/testbed.intro.html). The web-based simulation is still in use by government, research and industry
United Technologies Research Center	95-06-0011	Developed a prototype handheld device to detect refrigerant leaks during manufacture of components containing refrigerant	No commercialization occurred. All three companies cited cost of development, lack of funding, competition, and uncertain market demand as contributing factors to discontinuing research into this technology. The markets for the laser emitter for the handheld unit were also limited
York International	95-06-0004	Developed a prototype heat exchanger that was 25 percent smaller and had the same heat transfer capability as the standard size. Furthermore, York developed a method and a tool that they still use in their ongoing research and development. They also demonstrated that oval-tube geometry is 10 percent more efficient for heat transfer than round tubes	Using the methods developed during this project, York developed a new commercialized plate fin, called HiQ. York uses the fin in its ECO2 rooftop heating/cooling units. Its proprietary enhancements yield approximately twice the heat transfer when compared to a standard fin. Due to the prohibitive manufacturing capital cost, York has postponed commercializing oval-tube coil technology

APPENDIX B

Reasons for Terminating ATP Projects

At the end of an ATP competition, projects are selected for award and the winners are announced. Most of these projects proceed through their multi-year research plans to completion. Some are not carried through to completion for a variety of reasons. These projects are collectively called "terminated projects."

Between 1990 and September 2004, there were 768 ATP awards issued, of which 84[22] projects ended before completion. Below is a percentage distribution by category of the reasons for termination.

Change in goals

- 54 percent ended because of changes in the strategic goals of the companies, changes in the business climate or markets, changes in company ownership, or other business-related facts.

Lack of technical progress

- 12 percent ended because of lack of technical progress, which sometimes occurs at go/no-go decision points recommended by the participant(s).

Project no longer meets ATP criteria

- 11 percent ended because changes in scope, membership, performance, or other factors meant that the project no longer met ATP's technical and/or economic criteria.

Lack of agreement among joint venture members

- 2 percent ended because the joint venture members could not reach an agreement on some issues.

Financial distress

- 11 percent ended due to the financial distress of a key participant.

Early success

- 5 percent ended due to early success of the project!

Although projects may end early, it is not necessarily an indication of total failure. Projects that ended early produced important knowledge gains; involved integrated planning for research, development, and business activities that may have some benefit to participating companies; and entailed substantive cross-disciplinary contact among scientists and other researchers, cross-talk among technical and business staff, and negotiations among executives at different companies.

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[22] Included in this figure are four projects that were cancelled before the project began, comprising approximately 5 percent of the total.

These characteristics still benefit the economy by stretching the thinking and horizons of participants in the process. Companies may learn about new opportunities and apply integrated planning of research and business activities to other projects. In summary, terminated projects may have some positive impact even though they incur costs.

APPENDIX C

Composite Performance Rating System (CPRS) Star Ratings—First 150 Completed Projects

Project Number	Project Identifier (Title/Lead Organization)	Data Set	Overall Project Success
91-01-0243	Aastrom Biosciences, Inc.	1st 50	****
91-01-0146	American Superconductor Corp.	1st 50	****
94-02-0027	Automotive Composites Consortium (a Partnership of DaimlerChrysler [formerly Chrysler], Ford and General Motors)	3rd 50	****
94-04-0038	Cerner Corporation (formerly DataMedic - Clinical Information Advantages, Inc.)	3rd 50	****
96-01-0263	ColorLink, Inc.	2nd 50	****
91-01-0256	Cree Research, Inc.	1st 50	****
91-01-0184	Engineering Animation, Inc.	1st 50	****
93-01-0085	Integra LifeSciences	1st 50	****
94-01-0304	Kopin Corporation	3rd 50	****
94-01-0284	Large Scale Biology Corporation (formerly Large Scale Proteomics Corporation)	3rd 50	****
91-01-0041	Nanophase Technologies Corporation	2nd 50	****
90-01-0154	National center for Manufacturing Sciences (NCMS)	1st 50	****
94-05-0034	Orchid BioSciences (formerly Molecular Tool, Inc. Alpha Center)	3rd 50	****
94-06-0003	SciComp, Inc.	3rd 50	****
91-01-0176	SDL, Inc. and Xerox Corporation	3rd 50	****
94-05-0012	Third Wave Technologies, Inc.	2nd 50	****
92-01-0133	Tissue Engineering, Inc.	1st 50	****
94-06-0024	Torrent Systems, Inc. (formerly Applied Parallel Technologies, Inc.)	1st 50	****

Project Number	Project Identifier (Title/Lead Organization)	Data Set	Overall Project Success
94-06-0036	Xerox Palo Alto Research Center	3rd 50	****
91-01-0112	X-Ray Optical Systems (XOS), Inc.	2nd 50	****
95-05-0034	ABB Lummus Global, Inc. (formerly ABB Lummus Crest)	3rd 50	***
95-01-0131	Advanced Refractory Tech	3rd 50	***
93-01-0113	Amersham Pharmacia Biotech (formerly U.S. Biochemical Corporation)	1st 50	***
91-01-0177	Auto Body Consortium	1st 50	***
94-01-0115	Calimetrics, Inc.	1st 50	***
93-01-0055	Caterpillar Corporation	2nd 50	***
95-01-0022	Corning Tropel (formerly Tropel Corporation)	2nd 50	***
92-01-0136	Cynosure, Inc.	1st 50	***
95-02-0055	Dana Corporation	2nd 50	***
92-01-0115	Diamond Semiconductor Group, LLC	1st 50	***
98-02-0034	Digital Optics Corporation	2nd 50	***
94-01-0402	Displaytech, Inc.	2nd 50	***
90-01-0064	E.I. Du Pont de Nemours & Company	1st 50	***
94-02-0025	Ebert Composites Corporation	2nd 50	***
95-11-0012	EDO Specialty Plastics (formerly Specialty Plastics Inc.)	2nd 50	***
93-01-0154	eMagin Corporation (formerly FED Corporation)	3rd 50	***
91-01-0178	Ford Motor Company	2nd 50	***
95-07-0018	General Electric Corporation R&D	3rd 50	***
92-01-0044	Genosensor Consortium (c/o Houston Advanced Research Center)	3rd 50	***
92-01-0040	GM Thermoplastic Engineering Design (Engineering Design with Thermoplastics)	3rd 50	***

Project Number	Project Identifier (Title/Lead Organization)	Data Set	Overall Project Success
92-01-0116	Honeywell (formerly Allied Signal Inc.)	2nd 50	***
95-09-0052	Hynomics (formerly Hybrithms Corporations, formerly Sagent Corporation)	2nd 50	***
94-05-0018	Hyseq, Inc.	2nd 50	***
93-01-0149	IBM T.J. Watson Research Center	3rd 50	***
92-01-0017	Illinois Superconductor Corporation	1st 50	***
94-05-0019	Incyte Corporation (formerly Combion, Inc.)	3rd 50	***
91-01-0016	Information Storage Industry Consortium (INSIC, formerly NSIC)	2nd 50	***
91-01-0262	Kopin Corporation	1st 50	***
93-01-0101	Kurzweil Applied Intelligence, Inc	2nd 50	***
93-01-0183	MicroFab Technologies, Inc.	2nd 50	***
91-01-0224	Molecular Simulations, Inc. (formerly Biosym Technologies, Inc.)	1st 50	***
96-01-0172	Nanogen, Inc.	2nd 50	***
90-01-0166	Nonvolatile Electronics, Inc.	1st 50	***
93-01-0071	Perceptron, Inc.	1st 50	***
93-01-0205	Physical Optics Corporation (POC)	2nd 50	***
94-04-0024	PPD Informatics (formerly Belmont Research, Inc.)	2nd 50	***
92-01-0123	Sage and 3M Corporation	1st 50	***
94-02-0010	Strongwell Corporation	2nd 50	***
94-04-0046	Surgency (formerly Benchmarking Partners)	2nd 50	***
95-05-0002	The Dow Chemical Company	3rd 50	***
97-01-0087	TopicalNet (formerly Continuum Software, Inc.)	2nd 50	***
93-01-0124	Vitesse Semiconductor Corporation	1st 50	***

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94-04-0027	3M Company, Health Information Systems	2nd 50	**
95-02-0053	Abrasive Technology Aerospace, Inc.	3rd 50	**
91-01-0187	AlliedSignal, Inc.	1st 50	**
90-01-0060	American Display Consortium	1st 50	**
95-01-0263	Aphios Corporation	3rd 50	**
91-01-0142	AstroPower, Inc.	1st 50	**
93-01-0250	BioTraces, Inc.	1st 50	**
95-07-0020	Bosch (formerly Allied Signal)	3rd 50	**
93-01-0234	BP Amoco	3rd 50	**
94-01-0190	Catalytica Energy Systems (formerly Catalytica, Inc.)	3rd 50	**
94-01-0137	Cengent Therapeutics Inc. (formerly Moldyn Inc.)	3rd 50	**
95-02-0019	Cincinnati Lamb, UNOVA (Lamb Technicon)	3rd 50	**
90-01-0210	Communication Intelligence Corporation	1st 50	**
93-01-0211	Communication Intelligence Corporation	1st 50	**
94-01-0287	Crucible Materials Corporation, Crucible Companction Metals Division	3rd 50	**
93-01-0091	Elsicon (formerly Alliant Techsystems, Inc.)	2nd 50	**
92-01-0022	FSI International, Inc.	1st 50	**
92-01-0074	Geltech Incorporated	1st 50	**
94-01-0147	Genzyme Corporation (formerly GelTex Pharmaceuticals, Inc.)	2nd 50	**
91-01-0034	HelpMate Robotics, Inc. (formerly Transitions Research Corporation)	1st 50	**
93-01-0104	Honeywell (formerly Allied Signal)	3rd 50	**
95-07-0003	Honeywell (formerly Allied Signal)	3rd 50	**

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94-05-0004	JDS Uniphase (formerly The Uniphase Corporation)	3rd 50	**
94-01-0133	Laser Power Corporation	2nd 50	**
90-01-0212	Light Age, Inc.	1st 50	**
90-01-0121	Lucent Technologies Inc.	1st 50	**
93-01-0191	M&M Precision Systems Corporation	2nd 50	**
92-01-0053	Mathematical Technologies Inc.	1st 50	**
91-01-0088	Michigan Molecular Institute	1st 50	**
93-01-0027	Micron Optics, Inc.	2nd 50	**
95-02-0020	Montronix	3rd 50	**
95-08-0009	Nanogen, Inc.	2nd 50	**
94-01-0357	Norton Diamond Film	2nd 50	**
93-01-0054	Planar Systems, Inc. (American Display Consortium)	3rd 50	**
94-06-0026	Reasoning Systems, Inc.	2nd 50	**
90-01-0232	Saginaw Machine Systems, Inc.	1st 50	**
91-01-0263	Spire Corporation	1st 50	**
94-01-0221	Texas Instruments Inc.	3rd 50	**
94-06-0034	TopicalNet, Inc. (formerly Continuum Software, Inc.)	2nd 50	**
94-01-0063	Union Switch and Signal, Inc.	1st 50	**
94-01-0301	Valentis, Inc. (formerly Progenitor, Inc.; a subsidiary of Interneuron Pharmaceuticals)	3rd 50	**
91-01-0261	Westinghouse Plasma Corp.	1st 50	**
93-01-0041	Air Products and Chemicals, Inc.	3rd 50	*
94-04-0017	American Healthware Systems	2nd 50	*

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94-02-0040	Budd Company, Design Center	2nd 50	*
92-01-0132	GE Corporate Research and Development	2nd 50	*
91-01-0069	Honeywell, Inc., Technology Center	2nd 50	*
94-03-0012	IBM Corporation	3rd 50	*
92-01-0034	Ingersoll Milling Machine Company	2nd 50	*
90-01-0231	INSIC (formerly NSIC) - Short Wavelength	3rd 50	*
94-04-0037	KOOP Foundation, Inc.	2nd 50	*
95-10-0067	KOOP Foundation, Inc.	2nd 50	*
91-01-0258	Microelectronics Center of NC	1st 50	*
95-02-0005	Perceptron (formerly Autospect, Inc.)	2nd 50	*
93-01-0045	Philips Laboratories	2nd 50	*
94-01-0111	Praxair, Inc.	3rd 50	*
91-01-0267	PreAmp Consortium	1st 50	*
91-01-0134	Superconductor Technologies Inc (formerly Conductus)	3rd 50	*
93-01-0109	Thomas Electronics, Inc.	1st 50	*
95-06-0011	United Technologies Research Center	3rd 50	*
95-07-0026	Wyman-Gordon	3rd 50	*
95-06-0004	York International	3rd 50	*
94-06-0012	Accenture (formerly Andersen Consulting Center for Strategic Research)	3rd 50	-
94-04-0025	Accenture (formerly Andersen Consulting)	2nd 50	-
92-01-0055	Accuwave Corporation	1st 50	-
91-01-0135	Aphios Corporation	1st 50	-

Project Number	Project Identifier (Title/Lead Organization)	Data Set	Overall Project Success
91-01-0025	Armstrong World Industries, Inc.	1st 50	-
92-01-0007	Calmac Manufacturing Corporation	2nd 50	-
94-04-0008	Cerner Corporation	3rd 50	-
95-01-0148	Dow AgroSciences (Mycogen Corporation)	3rd 50	-
94-05-0033	Dupont Qualicon (formerly Dupont FQMS Group)	3rd 50	-
92-01-0109	Eagle-Picher Research Laboratory	2nd 50	-
92-01-0122	ETOM Technologies, Inc. (formerly Optex Communications, Inc.)	1st 50	-
95-05-0031	General Electric Company	2nd 50	-
90-01-0126	Hampshire Instruments, Inc.	1st 50	-
91-01-0017	IBM Corporation	1st 50	-
92-01-0103	IBM Corporation	1st 50	-
94-04-0018	InStream	3rd 50	-
94-06-0011	Lucent Technologies (formerly AT&T Bell Laboratories)	3rd 50	-
91-01-0057	MediaBin (formerly Iterated Systems Incorporated)	2nd 50	-
95-08-0017	Medical Analysis Systems (formerly NAVIX)	3rd 50	-
94-01-0074	Monsanto(formerly Agrecetus)	3rd 50	-
92-01-0124	NetOptix Corporation (formerly Galileo Corporation)	1st 50	-
95-07-0011	PCC Structurals	3rd 50	-
95-07-0006	Praxair Surface Technologies, Inc.	2nd 50	-
92-01-0035	Sheffield Automation (formerly Giddings & Lewis)	2nd 50	-
91-01-0071	Thermo Trilogy Corporation	1st 50	-
94-04-0040	Titan Systems (formerly Intermetrics)	3rd 50	-