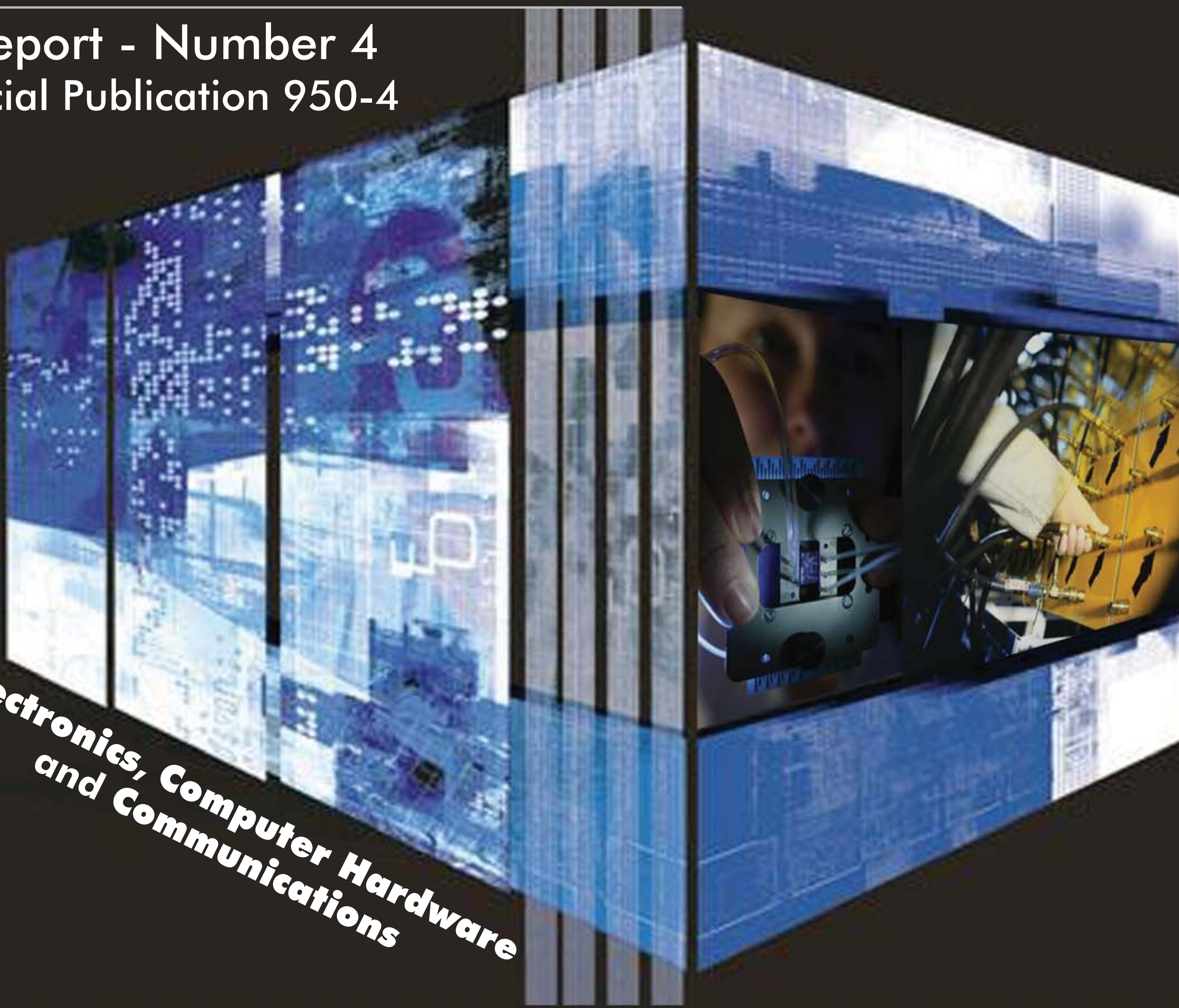
ADVANCED TECHNOLOGY PROGRAM

Performance of the Third 50 Completed ATP Projects

Status Report - Number 4

NIST Special Publication 950-4



Electronics, Computer Hardware and Communications

September 2006

NIST
National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce

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U.S. DEPARTMENT OF COMMERCE
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TECHNOLOGY ADMINISTRATION
Robert Cresanti, Under Secretary for Technology

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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Advanced Technology Program, Economic Assessment Office
NIST Special Publication

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON, D.C.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Internet: bookstore.gpo.gov — Phone: (202) 512-1800 — Fax: (202) 512-2250
Mail: Stop SSOP, Washington, DC 20402-0001

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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

P A R T 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.)

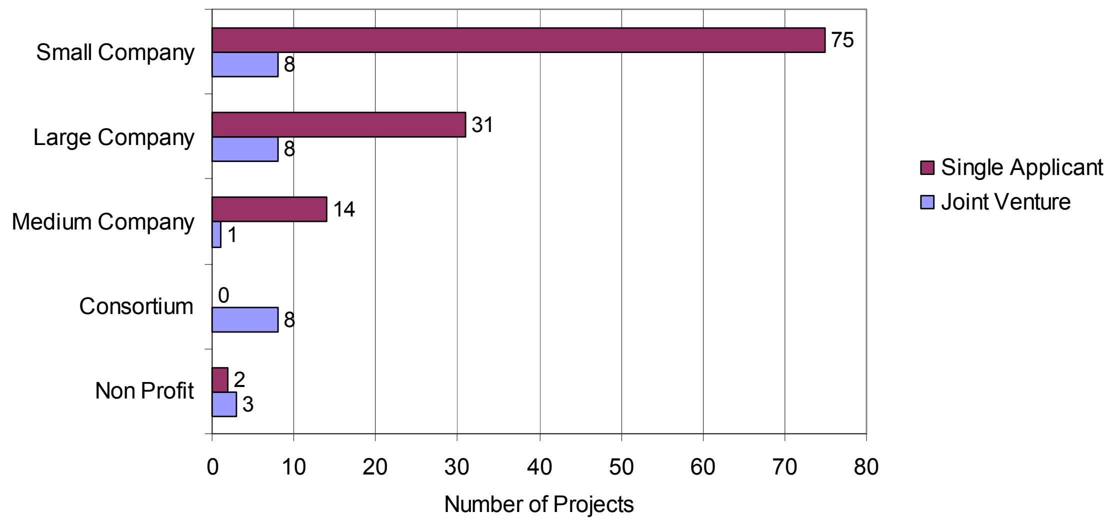
Single Applicants and Joint Ventures

"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

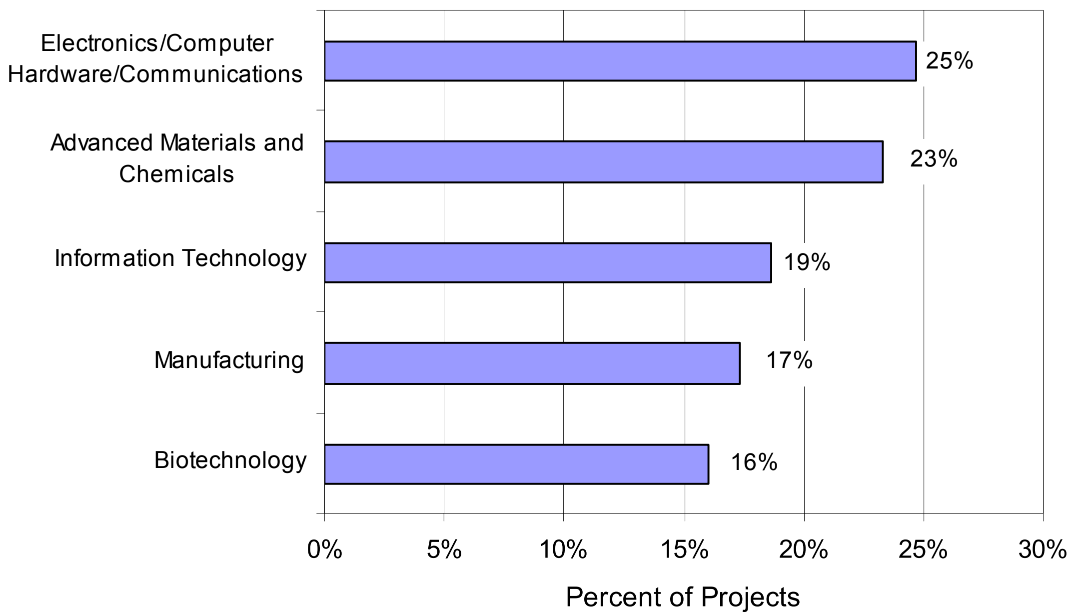
The 150 completed projects fall into the five technology areas used by ATP for classification purposes. Figure 1-2 shows the percentages of completed projects by technology area. The highest concentration, accounting for 25 percent of the total, is in "Electronics, Computer Hardware, or Communications." 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.

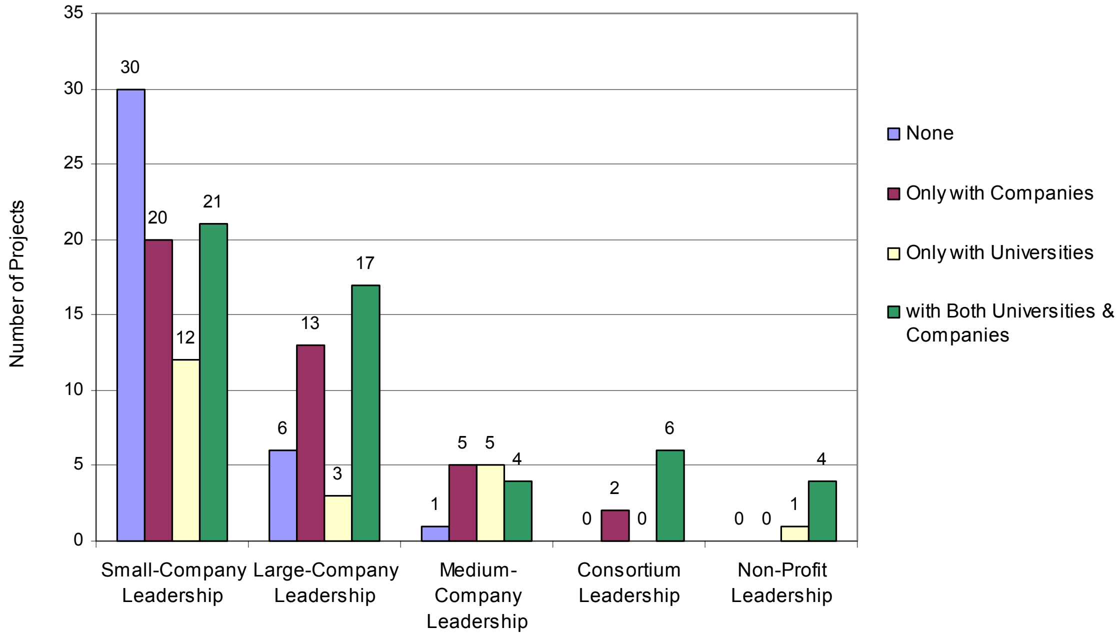
Table 1-1
Collaborative Activity

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.

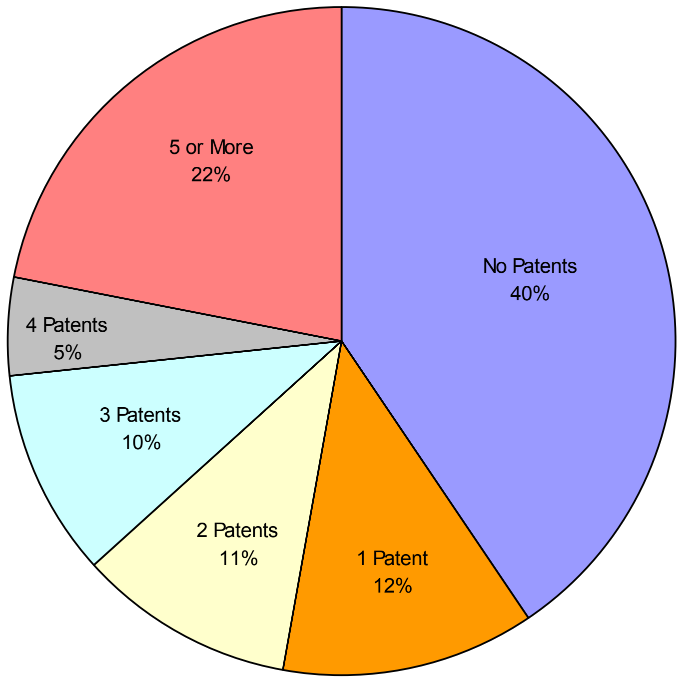
At the same time, patent data are not perfect signals of knowledge creation and dissemination. The decision to seek patent protection for intellectual property is influenced by many factors, including the ease with which others can copy the property's intellectual content and the difficulty of defending 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

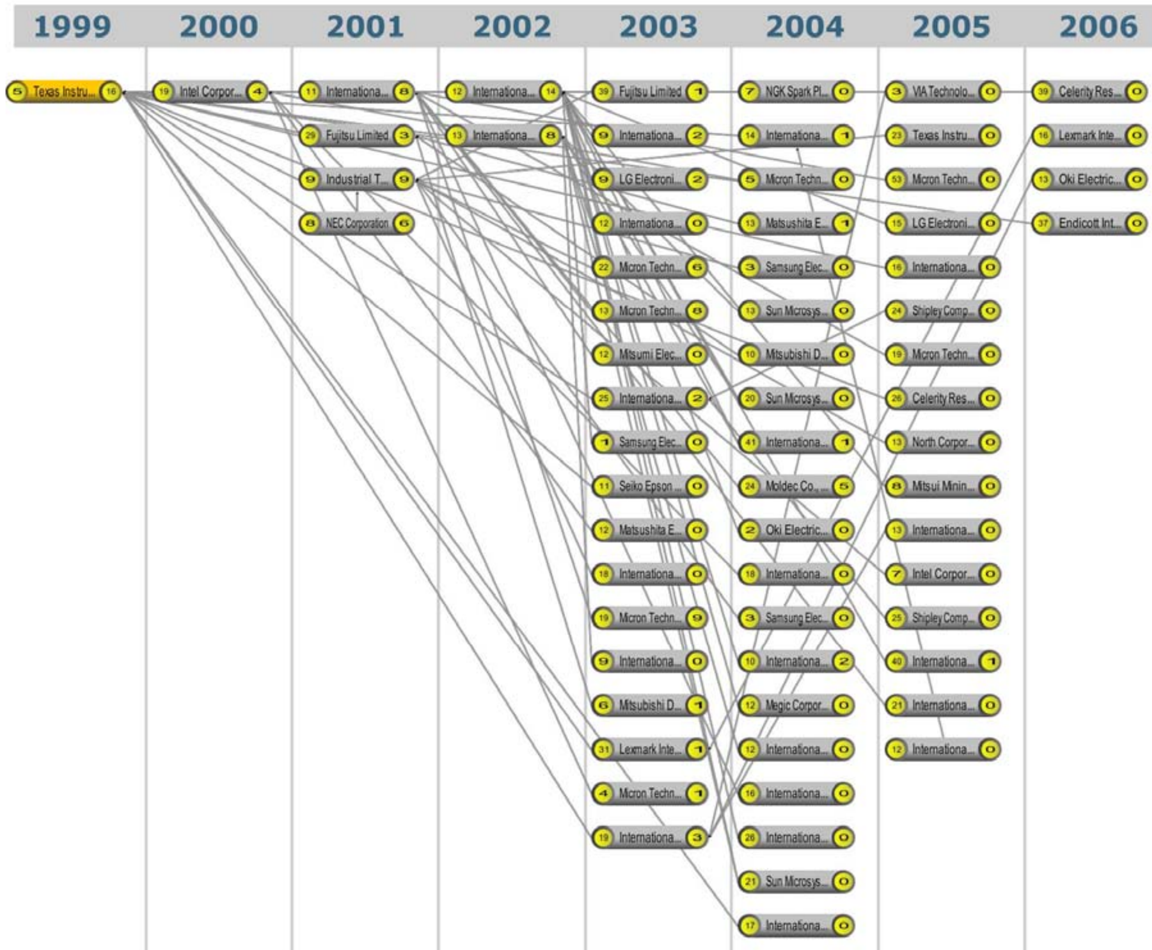


Figure 3-3
Patent Tree for Large Scale Biology Corporation - Patent 5,993,627
Project Impact Where Innovator Went Bankrupt

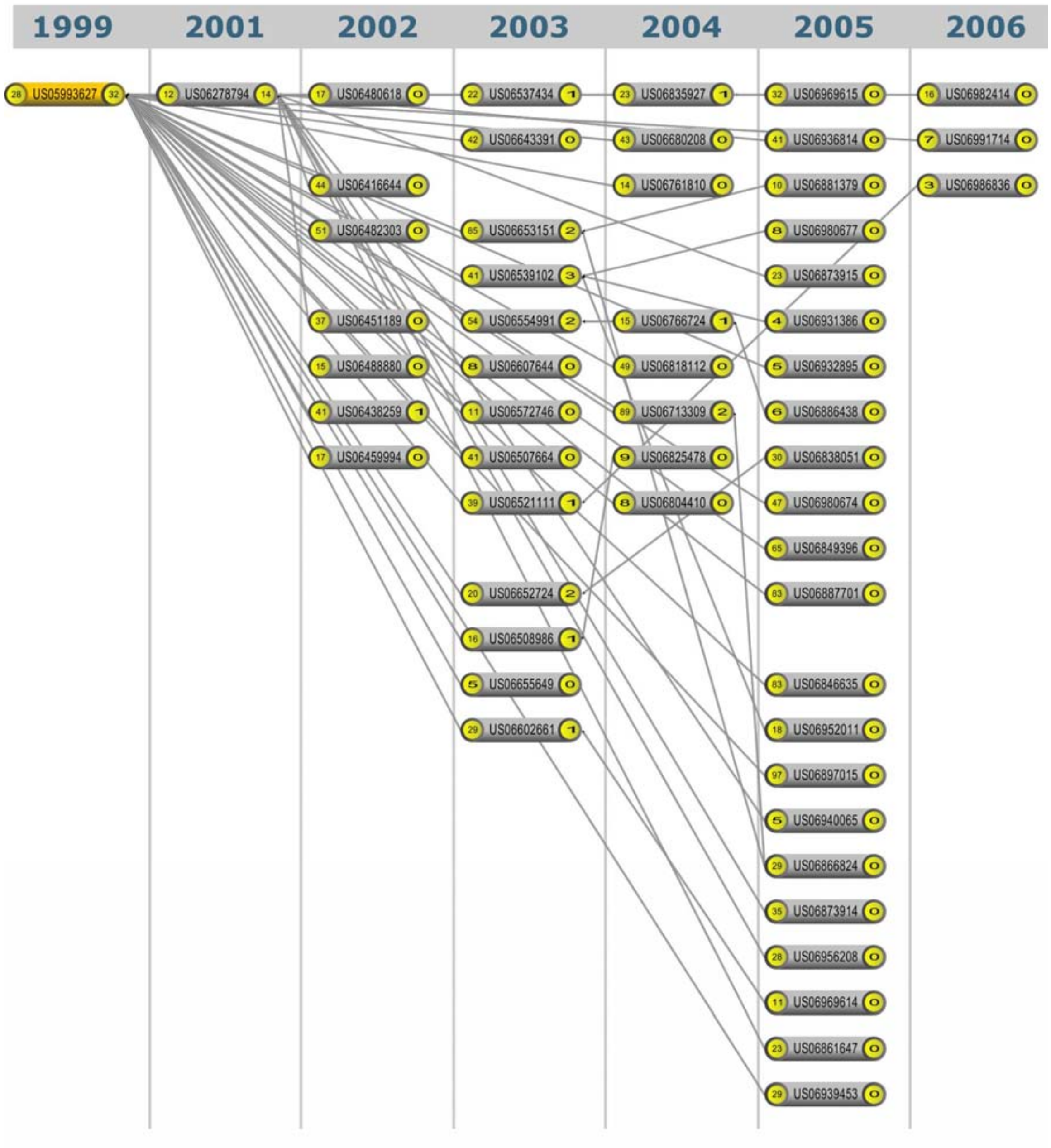


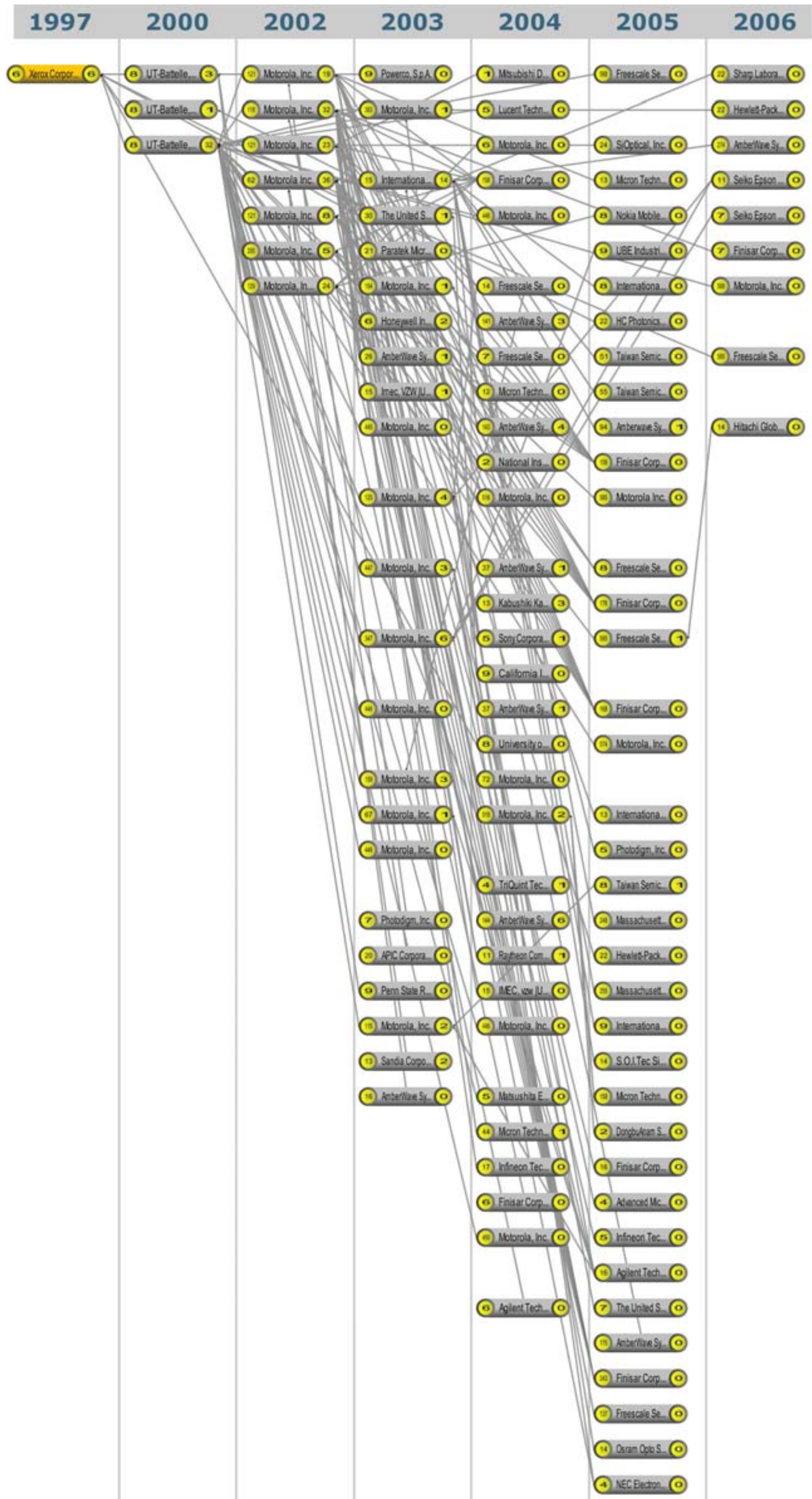
Figure 3-3 shows citations of a patent resulting from a project led by **Large Scale Biology Corporation**. Though the company went bankrupt, the patent tree illustrates how knowledge can outlive its creator and continue to be disseminated. An observer who equates business success of the innovator, one-to-one,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

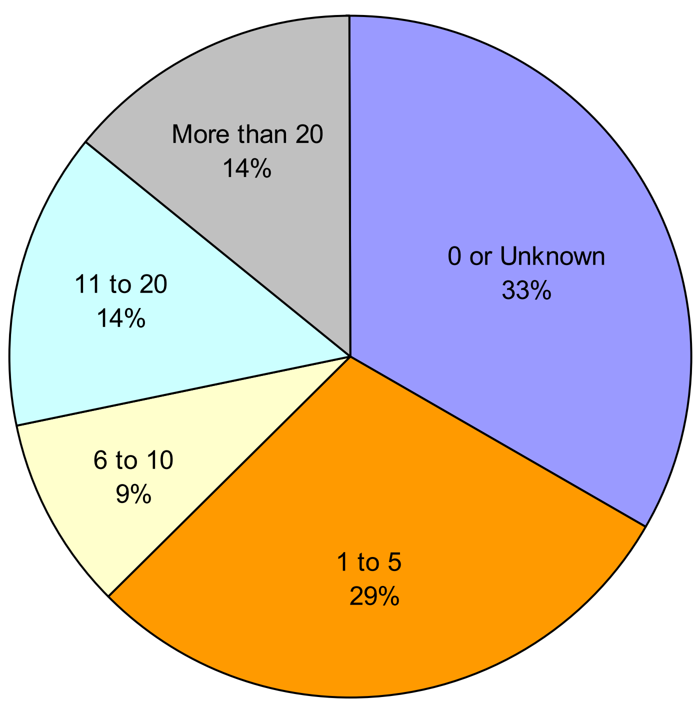


Knowledge Dissemination through Publications and Presentations

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

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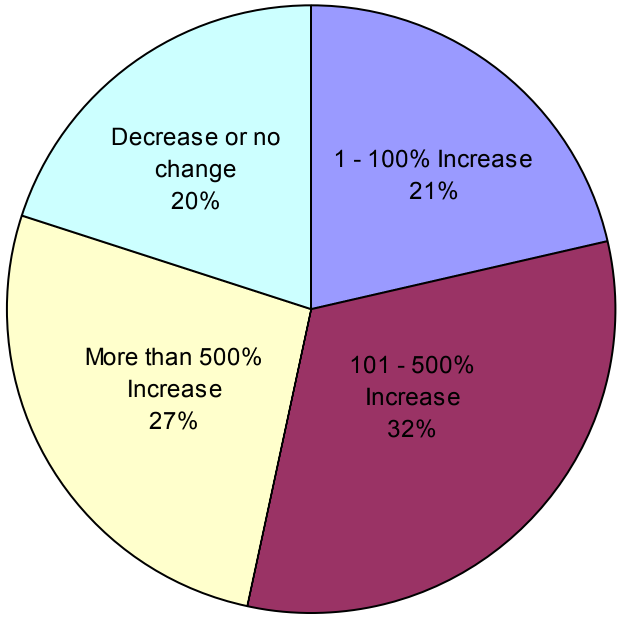
[7] Employment within the small companies is considered as an indicator of commercial progress. Assessing macroeconomic employment gains from the technological progress stimulated by the 150 projects is beyond the scope of this report.

[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.

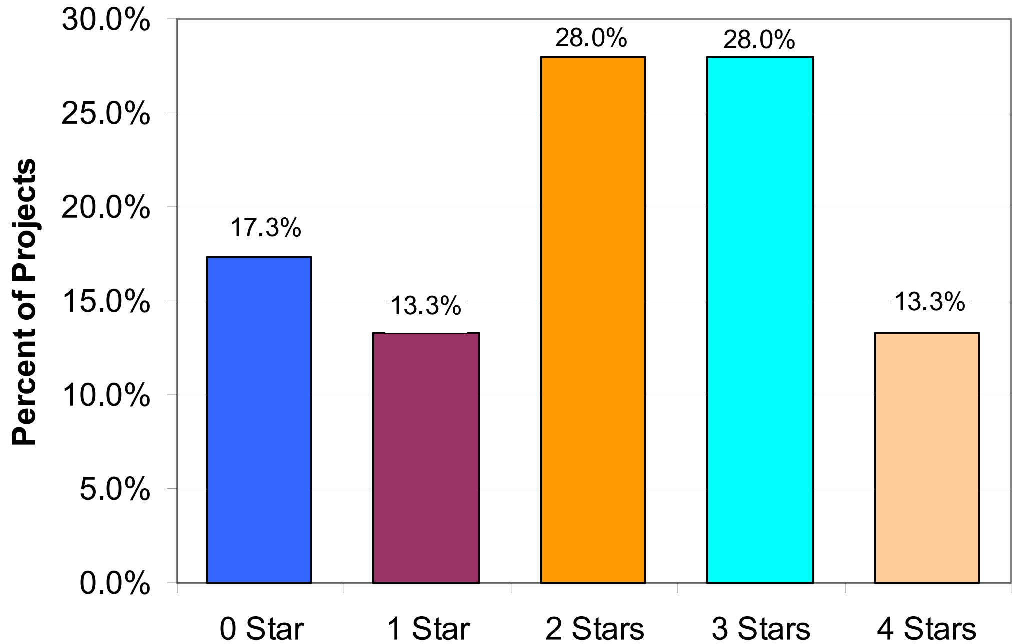
The performance metrics are consistent with the view of varying degrees of success—with knowledge creation and dissemination constituting partial success, and a continuation into commercialization constituting a fuller degree of success in terms of project progress. Some companies carried out their proposed 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.

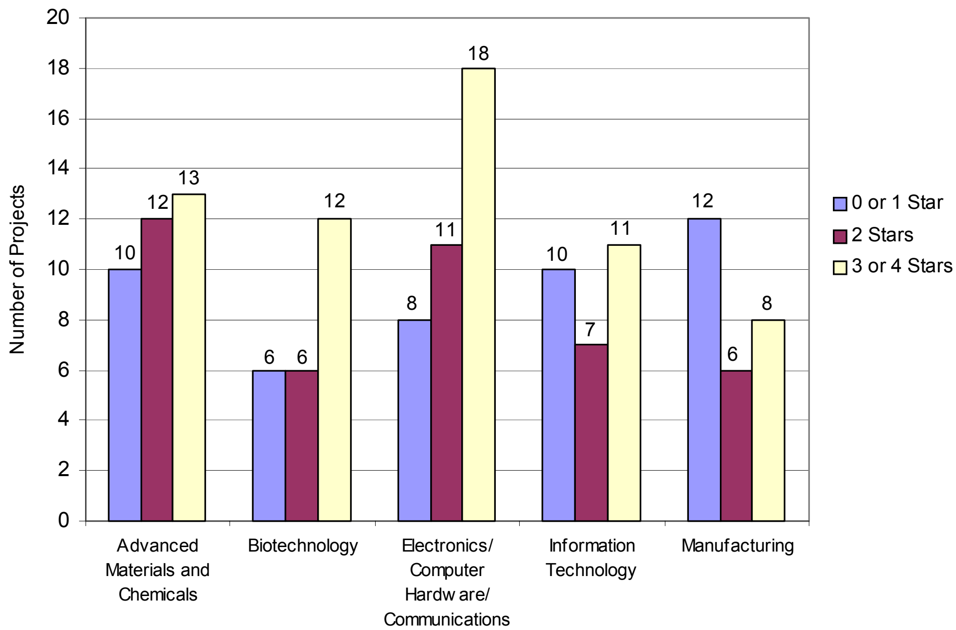
The three-star projects included 35 single-applicant projects and 7 joint-venture projects. Of the single-applicant projects, 25 were led by small companies, two by medium companies, and eight by large companies. Of the joint ventures, two were led by small companies, two by an industry consortium, two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

<u>*Scalable Parallel Programming*</u>

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

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[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.

eMagin Corporation (formerly FED Corporation)

Field Emission Displays Combine Benefits of Cathode-Ray Tubes and Flat-Panel Displays

In 1993, flat-panel displays (FPDs) were considered the most important competitive product in the electronics industry. The advent of low-cost FPDs was expected to usher in a host of new electronics applications, particularly high-definition television. Existing FPDs were lightweight and compact, but they had poor contrast and slow image refresh speeds; moreover, they were harder to read than the established cathode-ray-tube (CRT) displays. FED Corporation was a start-up company that was pioneering a new method for producing FPDs called field emission display. Field emission display would blend the lightweight and compact features of existing FPDs with the speed, brightness, and image quality of CRTs. In order to create the image, rows of tiny emitters fired electrons across a minute vacuum gap onto a phosphor coating. However, the vacuum was difficult to maintain. FED applied to the Advanced Technology Program (ATP) for cost-shared funding to develop this unproven technology. If successful, field emission displays could be manufactured in large quantities at reasonable prices, creating U.S. jobs and improving the nation's global position in this market dominated by foreign competitors.

By the end of the project in 1997, FED had accomplished many of its technical goals, but was unable to prevent flashover (short-circuiting) in its prototype FPDs due to problems with the vacuum. Flashover destroyed individual rows of pixels and destroyed the FPDs. Even though FED researchers received significant additional funding after the ATP-funded project concluded, they could not solve this fundamental problem. In 1999, relying on foundational knowledge gained in this project, FED Corporation redirected its research and development efforts to focus on active-matrix organic light-emitting diode (OLED)-based high-resolution microdisplays. The company changed its name to eMagin Corporation in 2000 and currently markets two high-resolution OLED-based microdisplays for use in computer monitors, headsets, and portable DVD players.

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

Research and data for Status Report 93-01-0154 were collected during March 2004.

Flat-Panel Display Image Quality Was Poor

The basic process that enables a television or a computer monitor to display images involves lighting up thousands of tiny pixels, which are "turned on" by a high-energy beam of electrons based on a video signal. In most televisions and monitors, three pixel colors (red, green, and blue) are evenly distributed on the screen. By combining these colors in different proportions and intensities, the screen displays millions of colors and shades.

The liquid crystal display (LCD) flat-panel technology of 1993 had slow image refresh speeds, resulting in jerky movements and minimal detail. Moreover, because the contrast was poor, displays were hard to read. Most LCDs relied on a backlight, a small fluorescent tube or an array of conventional light-emitting diodes (LEDs), to supply enough light for a full white screen at all times. The average level of light emission for viewing applications is only about 25 percent of that required for a full white screen, wasting 75 percent of the energy. As a result, these LCDs consumed more power than was desirable for battery-operated products (for example, personal digital assistants and mobile phones).

Flat-panel display researchers were trying to match or improve upon the image quality of the cathode-ray tube (CRT), the dominant technology used to generate images for computer monitors and TVs. CRT technology relies on sophisticated long glass vacuum tubes with accompanying lenses and/or a filter wheel built in. The back of the CRT display contains three electron guns (one for each color: red, green, and blue), which direct electron beams to the front of the tube. The inside front of the tube is coated with phosphor, a fluorescent material that reacts and lights up once the electron beams hit. In order to increase the screen width and height, manufacturers had to increase the length of the tube and depth of the display or monitor to give the scanning electron gun room to reach all parts of the screen. Large CRT display images lose high definition over large areas, become curved (which distorts the image), and require a glass plate up to an inch thick. CRT displays produce crisp, vibrant images, but they are heavy, bulky, and inherently analog rather than digital (consider the image quality of a movie on videotape, which is analog, compared to a DVD, which is digital).

FED Proposes Flat CRTs

The 1990s were forecast to be the “era of displays,” and flat-panel displays (FPDs) were considered to be the largest emerging electronics technology growth market, which was dominated by foreign manufacturers. FED Corporation was a start-up company that proposed to develop a technology base for field emission displays, which would be an alternative to LCDs and CRTs. Field emission displays would be flat (with minimal depth, unlike CRTs) and inexpensive, and they would display vibrant colors, with even better quality than LCDs. Each pixel would be supported by many emitters (cathodes, which were like tiny color CRT vacuum tubes) that would fire electrons simultaneously across a minute vacuum gap onto a glass layer coated with phosphor. Like conventional CRT screens, field emission displays are emissive devices, meaning they emit electrons to create light. This feature has potential benefits: high resolution, simpler construction, wide viewing angle, and low manufacturing cost, which could promote large-scale U.S. manufacturing. Field emission display devices would use less power than LCDs and would produce images with high brightness and color.

Electronic products were a $30 billion global market in 1994 and were becoming increasingly critical in non-electronic products such as cars and aircraft. While foreign firms dominated the display manufacturing market in 1994, FED Corporation believed that flat CRTs, based on field emission display technology, could bring a portion of the flat-screen market back to the United States. In addition to FPDs for high-definition television (HDTV), FED Corporation researchers also expected to provide technology support of field emission displays for applications such as cellular telephones, virtual reality, avionics, printing, high-speed computer network systems, and more. They intended to manufacture products using this technology in collaboration with partners and subcontractors by sublicensing the technology once it was proven. Sufficient private funds were not available due to the high technical risk of the unproven technology. Strong foreign competition increased the need to quickly develop the technology domestically. FED applied to ATP in 1993 for cost-shared funding to support this development, and funding was approved for a three-year project that began in 1994.

Prototype FPDs Have Excellent Color and Efficiency

FED Corporation researchers believed they could develop a complete working FPD within three years. Their key activities included the following:

- Develop minute diamond-coated field emitter electronics for displays, with excellent uniformity. FED had already built working, proof-of-concept diamond-coated pixels using two different vendors’ equipment prior to the ATP-funded project.
- Develop vacuum spacer technology for large areas. Spacers minimize electron spread, so that electron beams go only to the pixels for which they are intended.
- Achieve adequate energy to activate high-efficiency phosphors. The phosphors light up when they are excited by electrons, creating the image.

- Develop vacuum-sealing technology to control stray electrons by removing gas (called self-gettering) as well as integrating the systems into large displays. If a vacuum could not be maintained, stray gases would interfere in electron movement.
- Integrate the components into a 7.5” diagonal prototype display system during the first 18 months of the project; then develop an experimental 21” super-video-graphics-array display that has more than one million pixels displayed in full color.

By the end of the ATP-funded project in 1997, FED researchers had successfully assembled prototype FPDs that had excellent color and energy efficiency. Image refresh speeds were suitable for a high level of detail (256 gray levels, with resolutions up to 500 lines/inch). The prototypes indicated that further work would result in even higher resolutions. The ATP-funded researchers were granted four patents for this work, received extensive press coverage, and gave a number of presentations at conferences. They achieved the following technical accomplishments: increased the image refresh speed, which allowed more detail and smoother movements; enhanced the optics around pixels for high resolution; implemented a low-cost method for manufacturing high-density electronics; reduced surface gases (water, hydrocarbons, carbon dioxide, and oxygen) in the sealed vacuum display; and improved their understanding of flashover (short-circuiting) issues. Flashover, more commonly known as arcing, is an energy-discharge phenomenon that can destroy a display’s electronics. This flashover typically destroys the display and its support electronics within minutes to hours after the display is first raised to full brightness. The team added power protection circuits and other tools to prevent flashover. More work, however, was needed to prevent re-adsorption of gases.

Problems Continue with Flashover

FED continued research after the ATP-funded project ended, but technical problems plagued the developers until 1999. Researchers had not yet achieved commercially suitable video brightness without serious high-voltage flashover. The problem started with the vacuum inside the field emission display. “You’d see the flashover phenomenon as a flash of light and then, perhaps, a line of pixels going out,” said FED president, Gary Jones ("Display Vendors See Hurdles in FED Race," *Electronic Engineering Times,* July 28, 1997). Furthermore, the process to create and maintain a clean vacuum field emission display “tube” was expensive.

In 1997, FED researchers had successfully assembled prototype flat-panel displays (FPDs) that had excellent color and energy efficiency.

As an alternative to high-voltage field emission displays, FED explored using lower voltage. Low-voltage field emission displays avoided the flashover problem, but they suffered from fast phosphor burn-in (ghost images left on the display). In addition, the efficiency dropped as the voltage went down, Jones said, "…because at higher voltages, more of the [phosphor] grain is being activated. At lower voltages, more of the power is dissipated in the outer portion of the grain, so the grains degrade faster.” This meant that the screensaver needed to activate quickly. Screensavers prevent burn-in of images on the display.

Company Moves to New Technology

After the ATP-funded project ended in 1997, FED began testing microdisplays based on organic light-emitting diodes (OLEDs) on silicon substrates, licensing the organic materials from Eastman Kodak. These microdisplays are viewed close to the eye, with the aid of lenses. Their benefits include high resolution, high contrast, low power consumption, and vibration tolerance. The ATP-funded project had allowed FED to build the basic technology, working with active matrix silicon substrates after FED abandoned the field emission display technology. According to Gary Jones, “ATP’s support of field emission display research provided a basic technology understanding. We did incorporate pieces of it, and we learned not to do certain things. The project was valuable and helped to guide us into [microdisplays]. It came together about a year after ATP. We could not have done it without the prior ATP support.” In 1999, the company began marketing high-resolution microdisplays. FED merged with Fashion Dynamics Corporation in 2000 and changed its name to eMagin. eMagin raised approximately $27 million in connection with the merger and continued its licensing collaboration with Eastman Kodak. In the same year they were awarded a $3 million grant from the U.S. Air Force to develop OLED devices for use in head-mounted displays. eMagin markets two basic microdisplays, SVGA 3D and SVGA+ rev2, which 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 when they are under a blanket. They can also use the lens to find the source of a fire quickly. Researchers and doctors are using the display to enhance vision for magnetic resonance imaging (MRI), endoscopic surgery, and eye surgery. The displays are also used in consumer goods, such as ultra-portable, high-quality DVD players, computers, and other electronic devices.

Conclusion

In 1993, FED Corporation's research into field emission display technology attempted to develop high-resolution flat-panel displays (FPDs) with exceptional image quality and low energy consumption. The industry was striving to develop lightweight FPDs with vibrant colors to match those of the analog cathode-ray tube (CRT). The company was awarded four patents but failed to produce marketable products, due to flashover (short-circuiting) problems that they were unable to solve. However, beginning in 1999 (two years after the ATP-funded project ended), the company was able to apply its basic display technology knowledge to its development of organic light-emitting diode (OLED) microdisplays. They have received four patents for project-related technology and have shared their project research through publications and presentations. FED Corporation changed its name to eMagin in 2000 after a merger with Fashion Dynamics Corporation. The company currently markets OLED-based microdisplays.

PROJECT HIGHLIGHTS
eMagin Corporation (formerly FED Corporation)

Project Title: Field Emission Displays Combine Benefits of Cathode-Ray Tubes (CRTs) and Flat-Panel Displays (FPDs) (Large-Area Digital HDTV Field Emitter Display (FED) Development)

Project: To develop techniques to manufacture large-scale, FPDs based on arrays of field emitters.

Duration: 3/1/1994 - 5/1/1997
ATP Number: 93-01-0154

Funding (in thousands):

ATP Final Cost	$2,000	68%
Participant Final Cost	943	32%
Total	$2,943	

Accomplishments: FED Corporation ultimately abandoned its proposed field emission display technology due to difficulties with flashover (short-circuiting) caused by stray voltage. However, the company (renamed eMagin in 2000) acquired knowledge of display technology during the project that it later applied to the development of organic light-emitting diode (OLED)-based microdisplays. With ATP funding, research and development led to the following four patents.

- "Selectively shaped field emission electron beam source, and phosphor array for use therewith" (No. 5,583,393: filed March 24, 1994; granted December 10, 1996)
- "Field emitter device, and veil process for the fabrication thereof" (No. 5,844,351: filed August 24, 1995; granted December 1, 1998)
- "Field emitter structure and method of making the same" (No. 5,587,623: filed April 3, 1996; granted December 24, 1996)
- "Field emission display devices, and field emission electron beam source and isolation structure components therefore" (No. 5,663,608: filed April 17, 1996; granted September 2, 1997)

Commercialization Status: Although field emission display technology failed, eMagin has successfully applied knowledge gained during this project to its development and marketing of OLED-based microdisplays. eMagin has commercialized two basic microdisplays, SVGA 3D and SVGA+ rev2. These 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 and locate the source of a fire quickly; displays enhance vision for magnetic resonance imaging (MRI), endoscopic surgery, and eye surgery. The displays are also used in consumer goods such as ultra-portable, high-quality DVD players, computers, and other electronic devices.

Outlook: The outlook for OLED-based microdisplays is good. eMagin has successfully transferred the essential knowledge gained from field emission display technology to new applications. Although the market has been challenging in recent years, the company continues to develop and enhance its two commercial products.

Composite Performance Score: * * *

Number of Employees: 4 employees at project start, 64 as of March 1997, 24 as of December 2003.

Company:
eMagin Corporation
2070 Route 52
Building 334
Hopewell Junction, NY 12533

Contact: Gary Jones
Phone: (845) 838-7900

Publications: FED Corporation and eMagin received significant industry and financial analyst attention for work with field emission displays and OLEDs. The technologies were covered in more than 20 trade publications, such as those that follow:

- "A Closer Look… Field Emission Display Update." *Electronic Display World,* May 1994.
- "A New Type of Flat Panel Could Dethrone Matrix Displays." *Washington Technology,* June 9, 1994.
- "Start-up Steals a March on Production of FEDs." *Electronics Times*, June 23, 1994.
- "Startup claims lead in FED production." *Electronic Engineering Times,* July 4, 1994.
- "First Dedicated Field Emission Display Facility Getting Ready for Takeoff." *Photonics Spectra,* August 1994.

PROJECT HIGHLIGHTS
eMagin Corporation (formerly FED Corporation)

- “FED Technology Takes Display Industry by Storm.” *Electronic Design,* October 25, 1994.
- “Beyond AMLCDs: Field emission displays?” *Solid State Technology,* November 1994.
- “Flat Panel Displays: An Interesting Test Case for the U.S.” *Semiconductor International,* November 1995.
- “FEDs Show Impressive Gains.” *Electronic Design News,* April 11, 1996.
- Lieberman, David. "Display Vendors See Hurdles in FED Race." *Electronic Engineering Times,* July 28, 1997.
- Grossman, Steve. "Head-Mounted Displays Almost Here." *Electronic Design* 48, no. 20 February 2000.
- "Fashion Dynamics Enters Agreement and Plan of Merger with FED Corporation." *Business Wire,* March 15, 2000.
- "Covion, eMagin Evaluate OLED Display Materials." *Electronic Chemicals News* 15, no. 8, May 15, 2000.
- “Alliances Brighten Future For OLED Displays." *Electronic Design* 48, no. 12, June 12, 2000: 30.
- “eMagin Receives $3 million to Develop OLED Displays: The U.S. Air Force Has Awarded a $3 Million Grant to eMagin." *Laser Focus World* 36, no. 9, September 2000: 73.
- "OLED Displays Gain on LCDs." *Solid State Technology* 44, no. 10, October 2001: 22.
- "eMagin's Colors Deepen: Firm Develops OLED Video." *Laser Focus World* 37, no. 10, October 2001: 55.
- “eMagin to Unveil SVGA-3D OLED in Japan." *Asia Pulse,* October 31, 2001.
- "eMagin Struggles toward OLED Production." *Laser Focus World* 38, no. 2, February 2002: 51(1).
- "eMagin and ROHM Announce Strategic Investment; ROHM Invests $1 million in eMagin; Companies to Explore Partnering." *Business Wire,* April 3, 2002.
- "eMagin And VRX Announce Strategic Marketing Agreement for Interactive Electronic Games and Virtual Reality Hardware." *Business Wire,* May 22, 2002.
- "eMagin Corp.: Company Received Funding for Contract." *Solid State Technology* 45, no. 7, July 2002: 22(1).
- "Organic LEDs Will Receive New Materials Technologies that Will Lend Higher-Resolution." *Electronic Design* 52, no. 1, January 12, 2004: 74.

Presentations: FED scientists gave presentations at the following 12 academic conferences:

- “Field Emitter Displays for Future Avionics Applications,” SPIE, Orlando, FL, April 1995.
- DisplayWorks Investors Conference, February 1996.
- “Field Emitter Displays for Future High Requirements Applications,” SPIE Aerosense, Orlando, FL, April 1996.
- “Future Consumer Applications for Field Emitter Devices,” ICEE International Conference on Consumer Electronics, June 1996.
- “High Resolution Field Emitter Displays,” IEEE Lithography Workshop, August 1996.
- EuroDisplay Workshop, Birmingham, England, September 1996.
- “Field Emitter Based Automotive Displays,” SID Conference, September 1996.
- Michigan Display Conference, September 1996.
- Access Avionics Conference, Los Angeles, CA, October 1996.
- Flat Information Display Conference, San Jose, CA, December 1996.
- SPIE Aerosense, Orlando, FL, April 1997.
- “Field Emitter Displays,” SID Conference, Boston, MA, May 1997.

Research and data for Status Report 93-01-0154 were collected during March 2004.

Information Storage Industry Consortium
(formerly National Storage Industry Consortium)

Improved Data Storage and Access with Optical Recording Technology

In the late 1980s, optical disk storage technology promised to provide more storage and faster access times than the most advanced magnetic recording systems available. As of 1989, optical disk storage already enjoyed higher density of data on the disk surface by a factor of 10 compared to magnetic systems. Though the data were densely packed onto the disk surface, overall storage was limited by deficiencies in the lasers used to read data. Therefore, although data could be written on small areas on the disk surface, the lasers used to read the data became the limiting factor. Specifically, the lasers could not focus on areas as small as data could be written. The spot size for diode lasers could be reduced if the laser wavelength could be decreased from wavelengths in the then-available infrared or red part of the spectrum to wavelengths in the green or blue part of the spectrum. However, no commercially available diode lasers with such short wavelengths existed. An alternative approach to achieve short-wavelength light sources involved generating light from available lasers at double their normal frequency (or half the wavelength).

Because optical storage promised outstanding potential, members of the U.S. storage industry were independently conducting pre-competitive research into optical recording and, specifically, into laser-frequency doubling. This redundant research was an inefficient use of industry resources in such a highly competitive, low-margin business. Therefore, the National Storage Industry Consortium (NSIC) was founded in 1990 to encourage the storage industry to work together on pre-competitive research, including research on optical disk storage.

Through their cooperative efforts, project participants funded by NSIC (including NSIC members Eastman Kodak, Carnegie Mellon University, IBM, JDS Uniphase, University of Arizona, and SDL) hoped to gain mutually beneficial knowledge and to accelerate the development of short-wavelength light sources for optical disk storage technology. However, because of the project's risks and the participants' inability to capture all of the economic benefits from the research, private funding was not available. Therefore, in 1990, NSIC applied for and was awarded cost-shared funding from the Advanced Technology Program (ATP). By 1996, the team had demonstrated working devices that provided blue light based on frequency doubling of infrared lasers, but the efficiency and reliability of the devices were not yet adequate for commercialization. However, one participant developed spin-off products based on the thin-film electro-optical deflection technology developed during the ATP-funded project.

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

Research and data for Status Report 90-01-0231 were collected during February 2002 - March 2003.

Magnetic Recording Technology Fails to Keep Pace with Advancements

Magnetic recording, the dominant form of storage in the computer industry in the late 1980s, could neither store as much data nor retrieve it fast enough to keep pace with advancements made in computing. Though scientists had expanded magnetic recording storage capacity by 30 percent annually for several years, they predicted that, in the near future, they would reach the limits of magnetic recording. Magnetic recording researchers estimated that by 1993, magnetic recording capacity would hinder progress in computer technology. Therefore, the industry needed to explore new storage sources to keep up with growing computer capabilities.

Optical Recording Devices Held Tremendous Promise and Substantial Risks

In the late 1980s, optical recording could already write data onto disks 10 times more densely than magnetic recording. The technology could also read data in a nonlinear fashion, allowing for data storage in clusters rather than in lines, which enabled faster data recording and reading. Before it could become the dominant form of computer storage, however, the optical recording industry first needed to develop the scientific basis and technology capabilities for improved data storage as a precursor to determining appropriate industry standards for materials. This would lead to a predictable rate of improvement so that computer manufacturers could plan their product enhancements to coincide with available storage.

This pre-competitive research plan was extremely risky, demanding a significant level of initial research before product planning could even be conceived. Working separately, industry members would have required 10 years to complete the necessary research. Therefore, to meet this need, the National Storage Industry Consortium (NSIC) was founded to encourage the storage industry to work together on pre-competitive research, including research on optical disk storage. NSIC's research plan called for a five-year program to speed innovation. NSIC proposed to conduct research in two critical areas in parallel, each of which carried substantial risk. The first area was to expand areal density by focusing an optical beam to increasingly smaller sizes. Since data bits are stored in widths that correspond to the diameter of the optical beam, halving the wavelength of the light decreases the optical beam diameter used to read data by 75 percent. The second research area involved using waveguides to double light frequencies, transforming available red or infrared lasers into the more powerful blue light lasers.

Pursuing these two different research paths in parallel required significant resources and presented substantial risk to private firms. NSIC's process, if successful, would provide a set of technical and engineering tools, along with norms for material standards and testing data, that would improve and standardize optical recording technology. Further, this improvement would significantly enhance the capabilities and competitiveness of the U.S. storage industry.

ATP Funds Collaboration Among Industry Rivals

Optical recording presented an opportunity to develop an alternative technology in order to capture some of the Japanese firms' market share. To create a viable optical recording system, however, substantial research was needed to develop standards for materials and design engineering, as well as to set protocols for how the optical recording device would interact and exchange information with devices in need of that information. That kind of industry-creating research was too expensive to conduct at the individual company level. Even after the industry coalesced around NSIC, the project did not receive private funding because of the inherent risks and the participants' inability to capture sufficient economic benefits from the required research investment. Therefore, in 1990 NSIC turned to ATP for funding assistance.

Through this NSIC project, optical recording advances could extend storage capabilities and could enable far more computing power than was previously available. To help NSIC reach these goals and to generate broad-based economic benefits, ATP awarded the NSIC-led joint venture $5.4 million in cost-shared funds over a five-year period.

Scientific Obstacles Hinder Optical Recording Device Advances

In the early 1990s, blue-light spectrum lasers with beams that were clean and precise enough for use in optical recording systems were not commercially available. After a number of vendors attempted and failed to use blue lasers, NSIC focused its efforts on generating appropriate blue wavelengths from lasers in the red and infrared spectra, a strategy intended to circumvent existing technical barriers.

NSIC targeted its research efforts on the use of waveguides, which are crystal lenses that, when fabricated from appropriate nonlinear optical materials, can increase a light beam's frequency, thereby decreasing its wavelength. NSIC sought to take an infrared laser with an 800-nanometer wavelength and decrease it to 400 nanometers with a waveguide. During the course of the waveguide research, NSIC encountered a number of problems. First, crystals pure enough to serve as waveguides were extremely difficult to find from an existing vendor. Second, when a vendor was found, the laser passing through the waveguide actually damaged the crystals, rendering them useless.

Optical recording presented an opportunity to develop an alternative technology in order to capture some of the Japanese firms' market share.

After further research, NSIC discovered that a lack of synchronization between the peaks and valleys of the infrared and blue waves prevented the efficient generation of blue light. To correct that problem, NSIC scientists began doping the crystals to make sure the peaks and valleys of the infrared and the blue light remained synchronized. Although they demonstrated considerable progress with this approach, at the end of the project, the team still needed to increase the efficiency and reliability of the devices before commercialization could be considered.

Magnetic Recording Industry Achieves Large-Scale Storage Density Improvement

Concurrent with the ATP-funded project, the magnetic recording industry achieved a major breakthrough that enabled storage density to increase 60 percent per year instead of the 30-percent increases the industry had experienced. The 60-percent annual improvement rate would keep magnetic recording ahead of the computer industry's needs, thereby eliminating the pressing need for optical recording systems.

As a result of scientific and business difficulties, however, several NSIC members halted their research into optical disk recording. Even though much of the research in this area ended with the ATP-funded project, the focused research effort generated a substantial amount of new information and knowledge for the industry. Twelve patent applications resulted, with three granted, and nearly 80 publications contained information generated by the NSIC project.

NSIC sought to take an infrared laser with an 800-nanometer wavelength and decrease it to 400 nanometers with a waveguide.

Of the participants that remained active in the ATP-funded project until its completion in 1996, one achieved success with spin-off products. A group of Carnegie Mellon University scientists realized during the project that it was possible to rapidly deflect a beam within an electro-optical waveguide. With that knowledge, the scientists incorporated the company Applied Electrooptics and developed a compact and efficient device that applies voltages to influence the properties of light passing through a waveguide.

Conclusion

In 1990 the National Storage Industry Consortium (NSIC) brought together a group of consortium members to address a problem affecting the optical recording industry. They hoped to develop a method of optical recording to store and retrieve data in a manner that would increase the overall storage of individual optical disks. Through the project, NSIC generated a solid body of research surrounding lasers used for optical recording. The pre-competitive research helped the storage industry decide that blue lasers were not ideal for optical recording and allowed the industry and the companies to research other, potentially more promising, recording technologies.

PROJECT HIGHLIGHTS
International Storage Industry Consortium (formerly National Storage Industry Consortium)

Project Title: Improved Data Storage and Access with Optical Recording Technology (Short-Wavelength Advanced Technology)

Project: To develop optical recording as a platform that is more efficient and effective for computer data storage than traditional magnetic recording and to develop the scientific basis and technological capabilities for improved data storage as a precursor to determining appropriate standards.

Duration: 6/1/1991-6/30/1996
ATP Number: 90-01-0231

Funding (in thousands):

ATP Final Cost	$ 4,270	43%
Participant Final Cost	5,757	57%
Total	$10,027	

Accomplishments: The National Storage Industry Consortium (NSIC) conducted a tremendous amount of research on frequency doubling during this ATP-funded project. Moreover, the recording industry gained an understanding of frequency-doubling infrared lasers to achieve light in the blue spectrum. Specifically, the industry learned that generating precise blue-light spectrum lasers efficiently and reliably was extremely difficult, and it began to define the challenges scientists must overcome to produce viable blue lasers.

One member of NSIC, Eastman Kodak, filed 12 patent applications, and its scientists wrote articles that appeared in nearly 80 publications and media outlets that reported on the project. The following three patent applications were granted:

- "Electrooptic device for scanning using domain reversed regions"
  (No. 5,317,446: filed September 29, 1992, granted May 31, 1994)
- "Waveguide nonlinear optical frequency converter with integral modulation and optimization means"
  (No. 5,317,666: filed September 29, 1992, granted May 31, 1994)
- "Quasi-phasematched frequency converters"
  (No. 5,436,758: filed June 17, 1994, granted July 25, 1995)

Commercialization Status: NSIC members did not commercialize optical recording devices based on the ATP-funded research because: (a) remaining technical obstacles would have required significant further development of the frequency-doubling technology; (b) by the end of the project, competition was looming from direct-lasing green and blue diode lasers; and (c) unexpectedly rapid advances in magnetic recording technology had reduced the urgency and the likelihood of the advanced optical storage technology's commercial success.

Outlook: Since the NSIC members did not continue their research plan beyond the duration of the ATP-funded project, the outlook for this technology is not good.

Composite Performance Score: *

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  San Jose, CA 95120-6099
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  San Jose, CA 95134
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Research and data for Status Report 90-01-0231 were collected during February 2002 - March 2003.

JDS Uniphase (formerly SDL, Inc.) and Xerox Corporation

Monolithic Array of Laser Diodes Expand Laser Applications

Since the invention of the first optical laser in 1960 and the subsequent development of low-cost lasers for widespread applications by the 1980s, the potential of laser technology has sparked an intense pursuit of higher powered laser diodes. Applications as diverse as supermarket bar code scanners and photodynamic cancer therapies have spurred the search for better technology. Funding was not available to advance laser research, because it was too high risk and long term for investors. In 1991, SDL, Inc., in cooperation with Xerox Corporation and Stanford University, submitted a proposal to the Advanced Technology Program (ATP) to expand the laser applications base by developing a monolithic array of laser diodes that could be individually activated and emit light at predetermined wavelengths ranging from infrared to blue.

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 have been commercialized into numerous products. SDL (currently a part of JDS Uniphase) sells laser products for several markets, including high-speed color reprographics, optical data storage, displays, medical therapy, and telecommunications. Xerox used these technologies to enable a new generation of high-performance, high-speed printers and multifunction office product systems that are on the market today. These products enable companies to fulfill their printing requirements, such as one-to-one marketing and on-demand book printing, in minutes instead of days.

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

Research and data for Status Report 91-01-0176 were collected during October - December 2001 and June 2003.

Laser Diodes Could Outshine Existing Technologies

By the 1990s, researchers understood the basics of optical lasers and were ready to exploit this technology. They imagined far-reaching applications for optical lasers, but many of the anticipated uses required that researchers move from infrared to blue lasers by developing shorter wavelength, higher powered laser diodes. SDL, Inc. and Xerox Corporation sought ATP funding to pursue single-mode laser diodes of previously unattained wavelengths and power levels. Although the research team outlined several worthwhile intermediary technologies, they ultimately hoped to build a single semiconductor device with an array of lasers tuned to different frequencies, resulting in a monolithic array of diodes that would operate at predetermined wavelengths in blue, green, red, and infrared.

The plan involved technically aggressive milestones, and success would have a significant impact on several industries, such as colors, compact color projection displays, high-density optical storage systems, high-resolution spectroscopes, medical devices, gas laser replacement markets, and medical therapy.

Proposal Highlights Impact to Multiple U.S. Markets

The companies' proposal to ATP highlighted the role of advanced laser technology in the growth of multiple industries over the next decade. For example, when this ATP-funded project commenced, the color printing and systems reprographics market promised lucrative opportunities for laser technology innovators. The U.S. xerographic marks-on-paper industry, valued at $48 billion in 1990, was expected to increase to $125 billion by 2000. Most of this increase would come from color printing systems and from replacing light-lens copiers with digital systems, if they were available. The reprographic industry needed the technology to develop compact printing engines capable of producing color graphics simply, quickly, and cost effectively.

At the time, existing high-speed printing systems were either limited in speed or needed to utilize complex multilaser optical systems. Limitations such as these also restricted the speed of color copier systems, which needed to print digitally in order to produce good print quality. SDL and Xerox proposed that monolithic multibeam lasers would enable print speeds to be increased, with a relatively small cost to the rest of the system. They further proposed that multiwavelength devices could enable new architectures in which single laser arrays would be able to address different photoreceptor layers.

The reprographic industry needed the technology to develop compact printing engines.

Thus, the SDL and Xerox team hoped to stimulate the expected growth of the color reprographic industry by providing the necessary technology for U.S. companies, including Xerox, Kodak, IBM, and 3M, to develop cutting-edge compact xerographic systems architecture.

Other possible applications of the ATP-funded research included:

- Compact color projection displays that are better than cathode ray tube (CRT) or liquid crystal display (LCD) technology, because the brightness of a multiwavelength laser diode array greatly exceeds the brightness available for a CRT or an LCD.

- Optical data storage systems that can scan, store, and rapidly retrieve copious amounts of data from the small space of a compact disc. Because increased data density requires shorter laser wavelength emissions, the team's goal of developing laser diodes with wavelengths as low as 430 nm held high promise to increase data storage density by as much as 230 percent. This early effort in blue-laser development was a precursor to later efforts using cyan lasers for DVDs.

- Retail bar code scanners would be more reliable and cost significantly less if they were based on a 630-nm laser diode instead of the existing gas laser technology.

- Photodynamic therapy (PDT) was a laser-powered alternative to chemotherapy that uses laser light in combination with photoactive drugs called photosensitizers that target and destroy diseased cells while limiting damage to surrounding healthy tissue.

- Noninvasive glucose monitoring would allow more than 20 million diabetics in the United States alone to manage their blood sugar levels with laser technology rather than using needles.

Applications of the JDS Uniphase single-mode laser diode, which was developed in this project, include image recording, printing, spectral analysis, optical data storage, and point-to-point communications.

Aggressive Technology Goals Target Development of High-Power Lasers

Through its ATP-supported research and development (R&D) efforts, the research team wanted to combine the features of high-power, single-mode output, wide-range wavelength accessibility, and close-aperture spacing in a compact and manufacturable laser diode. The researchers hoped to develop several contributing technologies, including the following:

- High-power visible laser diodes operating at greater than 100 mW with continuous wavelengths between 630 nm and 680 nm

- High-power, single-mode laser diodes operating between 700 nm and 780 nm

- Monolithic integration of multiwavelength laser diodes operating between 630 nm and 1.1 mm

- High-power, frequency-doubled laser diodes with wavelengths between 430 nm and 550 nm in hybrid format

- Epitaxial format (a single crystal layer growth of ferroelectric materials)

The research team expected to expand the U.S. knowledge base in key technologies, including visible laser growth capabilities; high-power, single-mode device design; epitaxial growth of ferroelectric materials; and frequency-doubling techniques.

ATP Funding Needed to Jump-Start Research

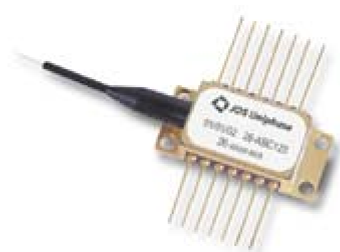
Before the ATP-funded project, laser technology presented a wide field of opportunity that was simultaneously enticing and intimidating to companies in various industries. The sheer magnitude of possibilities for laser technology made it difficult for any one company to take on the expense or risk of generic research. Venture capital firms shunned investment in laser technology for the same reason: initial research was high risk, broad based, and unlikely to yield a quick turnaround from technology to profitable products. Other sources of government funding, such as the Defense Advanced Research Projects Agency (DARPA), required that laser research produce technology for a specific application, such as missile defense or data storage.

ATP provided the jump-start by supporting the productive partnership between Xerox, a company interested in lasers specifically for xerographic applications; SDL, a company aiming to supply laser products to multiple industries; and Stanford University, which provided research support in modeling the frequency-doubling waveguides for the short wavelength devices. The project established broad laser capabilities and stimulated subsequent investment in application-specific research.

For example, SDL and Xerox joined Hewlett-Packard and others in an $8 million research program co-funded by DARPA to develop blue semiconductor lasers and light-emitting diodes (LEDs). Because of this ATP-funded project's success, Xerox's Palo Alto Research Center received approximately $8 million in internal R&D funds over four years for blue-laser-diode research to advance its xerographic products. SDL later channeled its knowledge into the telecommunications industry, where multiple lasers traveling on one fiber-optic cable allow faster Internet communication.

Technical Successes Lead to Commercial Impact

The R&D work of scientists from SDL, Xerox, and Stanford became a prolific source of new laser technologies. Donald Scifres, president of SDL at the time of the project, pointed out that without ATP, development of these technologies would have taken much longer, in an industry where time is critical. The ATP research team achieved several breakthroughs, including demonstrations of red lasers with powers up to 120 mW in single mode, lasing in the previously unattained 700- to 755-nm range, and green and blue lasers by frequency doubling. By the end of the project, SDL offered some of the lowest threshold laser devices available. Because low-threshold lasers produce less heat, which translates directly to higher data densities, SDL used these devices to produce competitive printing and data storage laser products. After it became clear that these devices were ideal for reprographic and printing applications, researchers also developed two alternative methods for monolithically integrated red, infrared, and blue emitters.



The JDS Uniphase 2600 Series of 98-nm pump modules for optical amplifiers are built on the monolithic multiwavelength laser technology developed in this project.

The transformation of the laser industry from gas tube lasers to semiconductor optoelectronic integrated circuits (OEICs) created a huge global market. "We were the first company in the world to successfully commercialize the integration of multiple lasers on a single OEIC device," said Scifres. This resulted from developing high-performance, multibeam red and infrared lasers by the end of the project in 1997. These multibeam lasers enabled a new generation of high-performance printers and multifunction office product systems later introduced by Xerox. Today, these machines continue to generate a large percentage of Xerox's total revenue and to create economic spillover for companies whose short-run office needs were met previously by lithographic printers that required several days to fill orders. These companies can now fulfill their printing requirements in just minutes, thereby increasing business efficiency.

The R&D work of scientists from SDL, Xerox, and Stanford became a prolific source of new laser technologies.

Digital printing capabilities that improved as a result of the ATP-funded project also enabled Xerox to tap the emerging "print-on-demand" market, which boasted a retail value of $21 billion in 2000. Xerox now sells print-on-demand machines that can print, cover, and glue a 300-page book in just over a minute, enabling rapid production for internal corporate and government publications departments and commercial print shops. These machines allow retailers to produce a customized sales brochure for each customer's model and color specifications, called one-to-one marketing.

The research team also completed significant work with gallium nitride (GaN)-based blue laser diodes, an area that began as a small focus of the project but became an increasingly attractive prospect during the research. After a breakthrough demonstration of long-lived blue LEDs in the GaN materials family by Nichia Chemical of Japan, SDL and Xerox decided to concentrate greater effort on blue laser diodes. They made this decision because of the diodes' appealing lower cost, higher efficiency, and smaller size compared with small gas lasers or frequency-doubled, diode-pumped solid-state lasers that require high power to double the frequency of red light. By shifting their focus to blue laser diodes, the researchers established epitaxial growth capability, fabricated high-quality LEDs, and demonstrated pulsed blue laser diodes.

The main application for blue laser diodes was in high-density optical storage. Since the end of the project, Xerox has continued to develop these devices, although to date they have not been introduced in Xerox products. SDL's smaller applications that take advantage of blue diodes include color printing (using blue diodes to expose commercial printing plates), biotechnology (DNA sequencing and cytometry), and measurement and inspection.

The transformation of the laser industry from gas tube lasers to semiconductor optoelectronic integrated circuits (OEICs) created a huge global market.

PDT technology has benefited significantly from the project's 635-nm single-mode laser diode. In the United States, PDT is currently used for treating cancer and a wide variety of other medical disorders. The combination of fiber delivery and the efficient laser diode source allow production of hand-held, portable machines that are highly reliable and moderately priced. Moreover, they consume less power and provide flexible energy delivery to the target. Previous PDT systems utilizing this wavelength relied on gas lasers and were unreliable, large, and expensive. The new laser flexibility allowed the development of new medications for treatment, with fewer side effects. SDL won the "Photonics Circle of Excellence Award" in 1999 for this work. In early 2000, the Food and Drug Administration approved the use of PDT for treating wet macular degeneration, a retina disorder (see illustration above).

The development of these technologies has enabled SDL to deliver laser products for applications ranging from optical storage to medical therapy, a laser diode for printing and data storage, and fiber-coupled laser bars for medical systems and displays. SDL revenue leveraged from the 84 technologies developed during the course of the ATP-funded project, particularly from red laser diode technologies, totaled $18.25 million from

1993 to 1997. The company grew from 200 employees in 1992 to 1,700 in 2000, prior to the merger with JDS Uniphase.

Broad Laser Capabilities and Bright Futures for SDL and Xerox

By 1998, SDL had attracted top researchers and had established broad capabilities in laser technology, in part because of the accomplishments of the ATP-funded project. With a solid track record in developing and commercializing innovative products, SDL felt confident in enlarging its strategic focus into the dynamic telecommunications industry, applying some of the laser technologies developed in this project directly to the new focus area. After making successful strides in this direction, SDL drew the attention of telecommunications leader JDS Uniphase. Evolving technology and fierce global competition were leading to consolidation in the high-tech industry, and, in 2001, JDS Uniphase acquired SDL for $41 million.

Today, JDS Uniphase focuses mainly on laser technology for fiber-optic telecommunications, using wavelengths of light from multiple lasers to travel simultaneously on one fiber-optic cable; this technology helps to reduce congestion on the Internet. A small division of the company remains committed to discovering applications for viable blue laser diodes. Some SDL components, such as the Laser Diode Driver, are being manufactured by third parties.

Xerox's customers continue to benefit from the ATP-funded technology, because the project's multibeam red lasers now enhance the majority of Xerox's xerographic systems. Moreover, the company is continuing its blue laser diode R&D to further enhance its products.

Conclusion

During this ATP-funded project, the SDL and Xerox research team, in conjunction with Stanford University, developed high-performance, multibeam red laser diodes; two alternative methods for monolithic integrations of red, infrared, and blue emitters; and several valuable intermediary technologies. These successes helped to build a strong U.S. technology base for multiple laser diode applications, allowed Xerox to manufacture best-in-class xerographic systems, and propelled SDL to the forefront of laser technology for the telecommunications industry. This ATP-funded project has also resulted in the filing of 29 patents of which 27 were granted.

PROJECT HIGHLIGHTS
JDS Uniphase (formerly SDL, Inc.) and Xerox Corporation

Project Title: Monolithic Array of Laser Diodes Expand Laser Applications (Monolithic Multiwavelength Laser Diode Array Spanning 430 to 1100 nm)

Project: To develop a monolithic process to produce multiwavelength arrays of individually selectable, high-powered laser diodes emitting infrared, red, green, and blue light.

Duration: 10/1/1992-9/30/1997
ATP Number: 91-01-0176

Funding (in thousands):

ATP Final Cost	$ 8,735	46%
Participant Final Cost	10,286	54%
Total	$19,021	

Accomplishments: The SDL, Xerox, and Stanford University research team successfully 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.

The project generated 84 inventions. The team filed 29 patent applications, with the following 27 patents granted to Xerox as a direct result of the ATP-funded project:

- "Stacked active region laser array for multicolor emissions"
  (No. 5,386,428: filed November 2, 1993; granted January 31, 1995)
- "Method of fabricating a stacked active region laser array"
  (No. 5,436,193: filed November 2, 1993; granted July 25, 1995)
- "Index guided semiconductor laser diode with shallow selective IILD"
  (No. 5,832,019: filed November 28, 1994; granted November 3, 1998)
- "Semiconductor laser or array formed by layer intermixing"
  (No. 5,708,674: filed January 3, 1995; granted January 13, 1998)
- "Index guided semiconductor laser diode with reduced shunt leakage currents"
  (No. 5,717,707: filed January 3, 1995; granted Febraury 10, 1998)
- "Thermally processed, phosphorus- or arsenic-containing semiconductor laser with selective IILD"
  (No. 5,766,981: filed January 4, 1995; granted June 16, 1998)
- "Method for replicating periodic nonlinear coefficient patterning during and after growth of epitaxial ferroelectric oxide films"
  (No. 5,654,229: filed April 26, 1995; granted August 5, 1997)
- "Alternative doping for AlGaInP laser diodes fabricated by impurity-induced layer disordering (IILD)"
  (No. 5,745,517: filed December 29, 1995; granted April 28, 1998)
- "Loss-guided semiconductor lasers"
  (No. 5,812,576: filed August 26, 1996; granted September 22, 1998)
- "Transversely injected multiple wavelength diode laser array formed by layer disordering"
  (No. 5,764,676: filed September 26, 1996; granted June 9, 1998)
- "Polarization mode selection by distributed Bragg reflector in a quantum well laser"
  (No. 5,784,399: filed December 19, 1996; granted July 21, 1998)
- "Semiconductor devices constructed from crystallites"
  (No. 5,977,612: filed December 20, 1996; granted November 2, 1999)
- "Edge-emitting semiconductor lasers"
  (No. 5,886,370: filed May 29, 1997; granted March 23, 1999)

PROJECT HIGHLIGHTS
JDS Uniphase (formerly SDL, Inc.) and Xerox Corporation

- "Deep native oxide confined ridge waveguide semiconductor lasers"
(No. 6,044,098: filed August 29, 1997; granted March 28, 2000)

- "Independently addressable laser array with native oxide for optical confinement and electrical isolation"
(No. 6,052,399: filed August 29, 1997; granted April 18, 2000)

- "In-situ acceptor activation in group III-v nitride compound semiconductors"
(No. 5,926,726: filed September 12, 1997; granted July 20, 1999)

- "Independently addressable semiconductor laser arrays with buried selectively oxidized native oxide apertures"
(No. 5,917,847: filed September 26, 1997; granted June 29, 1999)

- "Monolithic red/ir side by side laser fabricated from a stacked dual laser structure by ion implantation channel"
(No. 5,999,553: filed November 25,1997; granted December 7, 1999)

- "Monolithic independently addressable Red/IR side by side laser"
(No. 6,058,124: filed November 25, 1997; granted May 2, 2000)

- "Method of manufacturing vertical cavity surface emitting semiconductor lasers using intermixing and oxidation"
(No. 5,915,165: filed December 15, 1997; granted June 22, 1999)

- "Red and blue stacked laser diode array by wafer fusion"
(No. 5,920,766: filed January 7, 1998; granted July 6, 1999)

- "Infrared and blue stacked laser diode array by wafer fusion"
(No. 6,104,740: filed January 7, 1998; granted August 15, 2000)

- "Red, infrared, and blue stacked laser diode array by wafer fusion"
(No. 6,144,683: filed January 7, 1998; granted November 7, 2000)

- "Multiple wavelength laser arrays by flip-chip bonding"
(No. 6,136,623: filed May 6, 1998; granted October 24, 2000)

- "Fabrication of group III-V nitrides on mesas"
(No. 6,163,557: filed May 21, 1998; granted December 19, 2000)

- "AlGaInN LED and laser diode structures for pure blue or green emission"
(No. 6,233,265: filed July 31, 1998; granted May 15, 2001)

- "Structure and method for self-aligned, index-guided, buried heterostructure AlGalnN laser diodes"
(No. 6,567,443: filed September 29, 1999; granted May 20, 2003)

In 1999, SDL won the "Photonics Circle of Excellence Award" for its development of the 3-W, 630-nm Photodynamic Therapy (PDT) Laser, which resulted from the project.

Commercialization Status: After the ATP-funded project, SDL commercialized several laser products that were based on technologies developed in the course of the project, including the following:

- SDL-7511-30-mW, 650-nm single-mode laser using facet passivation technology (used in the early development of high-density optical storage systems; the technology has been discontinued).

- SDL-7311-30-mW, 680-nm single-mode laser (for PDT applications). Some of the second-generation PDT drugs were activated in the 680-nm range. PDT systems typically needed more power than 30 mW, so higher power multimode versions of this single-mode laser were typically supplied to PDT customers.

- SDL-7601-2-mW to 10-mW, 680-nm dual-spot single-mode laser (applications include data storage, printing, displays, and alignment). This monolithic multichannel device provided higher speed and lower cost.

PROJECT HIGHLIGHTS
JDS Uniphase (formerly SDL, Inc.) and Xerox Corporation

- SDL-7400-500-mW, 680-nm multimode laser (the high-power multimode cousin of the SDL-7311 for the PDT market).

- SDL-7470-3-W fiber-coupled laser bars at 665 nm to 690 nm (for solid state pump lasers, medical systems, and displays in niche applications).

- SDL-5700-up to 150-mW, 852-nm distributed Bragg reflector laser (applications include frequency doubling, interferometry, atomic clocks, and spectroscopy).

SDL, currently known as JDS Uniphase, continues to apply the broad knowledge gained in this project to the fiber-optic communications and commercial laser industries. The company is developing and supplying high-power semiconductor lasers for many applications. They are the leading supplier of high-power 980-nm pump lasers for optical amplifiers. They are also a leading supplier of single-mode and multimode lasers in ranges of 810 nm to 850 nm and 910 nm to 980 nm, which are used for pumping, printing, materials processing, inspecting, testing, and other applications. JDS Uniphase continues to market the SDL-7311 and the SDL-7400 for PDT applications, the SDL-7601 for data storage and other applications, the SDL-7470 for pump lasers and other applications, and the SDL-5700 for frequency doubling and other applications.

Third parties have purchased the rights and continue to produce SDL's Laser Diode Driver, Laser Diode Heatsink, and semiconductor lasers, as well as its pulsed laser diodes and its green, blue, red and infrared modules.

Xerox incorporated the multibeam red laser technology from the ATP-funded project that has enabled a new generation of high-performance, high-speed printers and multifunction office product systems.

Outlook: In 2001, SDL's success in developing and commercializing semiconductor laser technology prompted the company's merger with fiber-optics giant JDS Uniphase. Since this merger, SDL (now JDS Uniphase) has applied its knowledge mainly to the fiber-optic communications industry, with 86 percent of its revenues derived in this area. Some of the laser technologies from this ATP-funded project are used in this new focus area. JDS Uniphase continues to develop and supply high-power semiconductor lasers for many applications.

Xerox's customers continue to benefit from the ATP-funded technology, because the project's multibeam red lasers are used in Xerox's high-speed, high-performance xerographic systems. Moreover, the company is continuing its blue laser diode research and development to further enhance its products.

Composite Performance Score: * * * *

Number of Employees: 200 in October 1992 (SDL); 1,700 as of July 2000 (SDL, prior to the merger with JDS Uniphase).

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Subcontractors:

- Stanford University
  Stanford, CA

Research and data for Status Report 91-01-0176 were collected during October - December 2001 and June 2003.

Kopin Corporation

Miniature LCDs Enhance High-Definition Displays

In 1994, the computer industry was developing high-speed, advanced processors and high-capacity data storage. Display technology lagged behind; consumers wanted larger, faster, flicker-free video images and complex graphics (e.g., computer-aided design applications) on lighter weight, lower cost, energy-efficient displays. Kopin and Philips formed a joint venture and requested cost-shared funding from the Advanced Technology Program (ATP) to achieve numerous pre-commercial technical advances in liquid crystal display (LCD) color high-definition televisions (HDTVs). This project would have required additional years to accomplish without this joint venture collaboration and external funding. High-definition display technology was changing rapidly, and, at the time, the market was dominated 100 percent by foreign manufacturers.

ATP awarded funding from 1995 through 1998 to Kopin and Philips, who together with their subcontractor, Massachusetts Institute of Technology, planned to develop and integrate the optical and color system (e.g., lenses, mirrors, or light guides), digital signals, and LCDs into a single, integrated package. By 2003, Philips had successfully commercialized high-resolution projection HDTVs that used the ATP-funded technology.

Kopin applied the ATP-funded enabling technology in numerous applications to include miniaturized display applications for use in viewfinders for camcorders and digital cameras, wearable computers, virtual reality games, and military applications. LCD projection display technology is a key product differentiator in U.S. electronics manufacturing.

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

Research and data for Status Report 94-01-0304 were collected during June - September 2003.

Early Tests of Facilitated Transport Identify Problems

In 1994, the technology used to generate images for computer monitors, TVs, and projection televisions was the cathode-ray tube (CRT), a sophisticated glass vacuum tube with one to three tubes and accompanying lenses and/or a built-in filter wheel. CRT screens produce crisp, vibrant images, but they have serious drawbacks: they are heavy, bulky, and inherently analog rather than digital (consider the quality of a phonograph player, which is analog, compared to a compact disc player, which is digital). In order to increase the screen width and height, manufacturers had to increase the length of the tube (to give the scanning electron gun room to reach all parts of the screen). Scaling up this tube to create larger displays revealed its weaknesses: it loses high definition over large areas, becomes curved (which distorts the image), requires a glass plate up to an inch thick, and can produce distracting line and speckle patterns.

The basic process for a CRT television or computer monitor to display images involves lighting up thousands of tiny pixels with a high-energy beam of electrons based on the information in a video signal. In most systems, three pixel colors (red, green, and blue) are evenly distributed on the screen. By combining these colors in different proportions, the screen can produce millions of colors.

Kopin Corporation and Philips Electronics North America believed they could produce large, quality color images by projecting miniature high-definition liquid crystal displays (LCDs) onto a large screen (as in a slide projector). Small, direct-view monochrome LCDs were already being used in watches, calculators, and laptop computers, providing the lightweight and compact size (especially depth) that enabled these items to be portable. Liquid crystals are able to maintain their orientation, like a solid, yet they can move in response to heat and electric current, like a liquid. Predictable responses to electric current control light and create images. Existing LCDs were still slow, with a limited ability to present shades of gray. They were limited in size as well. Moreover, manufacturing the LCDs required a large up-front capital investment, because it is difficult to produce large flawless LCD panels. Producing large LCD direct-view displays was considered unsuitable for monitors or high-definition televisions (HDTVs) due to a high defect rate in manufacturing.

CRT screens have serious drawbacks: they are heavy, bulky, and inherently analog rather than digital.

At the time, all LCDs for laptop displays were manufactured outside the United States. If Kopin and Philips' proposed project could make the necessary advances in speed, grayscale resolution, and optics/color, LCD projection technology could provide an entrée for U.S. manufacturers to compete in the global high-definition market.

Kopin and Philips Propose to Collaborate

Kopin Corporation is a small, innovative U.S. company of scientists and engineers that focuses on developing personal, portable communication products. Philips Electronics North America is part of a leading global electronics firm that focuses on consumer electronics, with a strong research and development program in New York. The subcontractor, Massachusetts Institute of Technology (MIT), was brought into the project because they specialize in designing digital signal-processing methods (translating electronic signals into images). However, after the first year of the project, MIT dropped out and Philips took over MIT's task.

The joint venture applied and was awarded ATP funding support in 1994 in order to pursue an aggressive technology development path. ATP awarded three years of funding to advance LCD projection display technology and to build a U.S. infrastructure to manufacture the technology. This infrastructure would support high-definition projection displays for future HDTV and computer applications. The technology required integrating the optical and color system (such as lenses, mirrors, and light guides), digital signals, and LCDs. The team needed the ATP award in order to support collaboration between Philips and Kopin; to speed up the development; and to break into a newly expanding global market.

To accomplish the joint venture's goals, fundamental advances were needed in high-resolution LCD grayscale images, speed, optical/color filter systems, light manipulation, screens, electronics, and digital signal processing. The team needed to produce shades of gray first, in order to display image detail and richness. Kopin was producing Smart Slide, an LCD technology for small projection systems that projected like a photographic slide (at 640 x 480 pixels). Philips had developed color high-definition display systems with three panels, one for each color. Philips hoped to integrate systems and produce color projection HDTVs and computer monitors at a lower cost. The joint venture's goal was to combine Kopin's image quality with Philips' optics and color technologies.

Joint Venture Defines Specific Tasks to Meet Challenging Objectives

If Kopin and Philips' technologies could be combined successfully, the proposed projection displays would save production expenses:

- HDTV components could be manufactured on existing production lines.
- Reducing pixel size would reduce cost. If the size of each pixel could be reduced, the manufacturer could either provide more pixels in a given space, providing more detail, or else reduce the size of the image with the same image quality and lower cost.
- Production of small components would cost less than large, direct-view LCDs, which could not be produced in large sizes at the time, due to a high defect rate.

The team set challenging system requirements: over a million pixels (high resolution); full color; bright, sharp, and pleasing images; and a fast display that was capable of video speeds. The team's five specific tasks were the following:

1. Kopin would improve LCD speed (from 30 milliseconds (ms) to 2 ms). The basis of the technology was a cost-effective glass panel on which an overlying layer of liquid crystal is rapidly controlled with an underlying thin film of silicon-based circuitry.

2. Philips would integrate electronics into the display (projecting images using standard digital video formats).

3. Philips would design and develop the optical and color system, minimize light loss, and generate full color by filtering three colors on a single panel.

4. Philips would design external electronics for a test bed monitor and HDTV.

5. Philips would construct a prototype system and would evaluate image quality.

The entire system needed to be designed so that manufacturing costs would be low enough to open the technology to the large consumer markets expected in projection display for monitors, multimedia applications, and HDTV. The team anticipated that Philips or a third-party label would produce the displays that could interface with computer software, HDTV signals, or other image sources. Anticipated spillover products included home entertainment systems, business presentation graphics, printing, and graphic arts.

Projection Technology Makes Great Strides

By the end of the ATP-funded project in 1998, the joint venture had successfully developed and demonstrated the key components to support high-definition color projection display products. Kopin and Philips accomplished 95 percent of their five technical goals:

1. Kopin reached target LCD image refresh speeds of 2 ms (improved by a factor of 15). The company developed an active matrix liquid crystal display (AMLCD) and some electronics with a resolution of 1280 x 1024 pixels. Kopin developed proprietary methods to redesign circuits so that the foundry could manufacture AMLCD displays with fewer defects, thus increasing the yield and lowering production costs.

2. Philips integrated electronics into the display and achieved high-speed image transfer (1.8 gigabits per second). They developed and demonstrated high-speed image microprocessors using TM-1000 chips. Faster TM-2 chips were being developed, but were not expected to be available until 1999, after project conclusion. These new chips would accommodate parallel operation of all image enhancement and correction programs simultaneously. Philips intended to perform additional research using the faster TM-2 chips after the completion of the ATP-funded project.

3. Philips designed and developed the optical and color system (see illustration, below). Steps included controlling and processing light passing through the liquid crystal; developing the lenses; and demonstrating real-time correction of color, contrast, and resolution. The system scans sequential stripes of red, green, and blue light down the display panel. Simultaneous color data loading into the pixel array run ahead of the respective scanning color stripes. These parallel operations maximize the time that each color is displayed and increase brightness.

Magnified view of Philips' color optics. Mirrors separate and recombine the red, green, and blue colors.

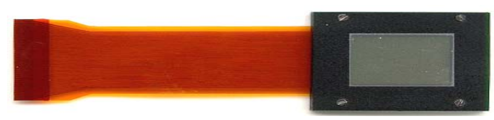
4. Philips designed the display drive electronics to take television-format video signals and display a picture, while controlling the picture's brightness and color saturation. The electronics module receives digital video signals and scales the image to match the display resolution (size).

5. The final color display demonstration was not performed at project conclusion, because the LCD technology was still too slow for commercial use. Philips demonstrated a prototype system to evaluate image quality. The company completed an operational TM-1000-based system in a personal computer (PC). Philips constructed 12 screen samples, which compared well with the design goals. The proof-of-concept implementation verified the algorithms and evaluated image quality (formatting, brightness, color, and contrast were demonstrated individually). While the demonstration system approached, but did not achieve, the resolution and speckle goals, the system did validate the viability of the technology.

Philips and Kopin's key accomplishments during the ATP-funded project included the following: achieving a 1280 x 1024 pixel display operating at 180 Hertz frame rate; correcting color in real-time; and demonstrating high color brightness. Philips received two patents for this technology. Philips and Kopin shared their advances with industry through publications and presentations. While these accomplishments encouraged the two companies to continue with additional investment and research into the technology, later changes in the industry led the companies to redirect their efforts. The computer monitor market changed as direct-view LCD manufacturing yield improved, as flat panels were being produced with fewer defects. This eliminated the need for projection technology in high-definition computer monitors. Therefore, Philips focused on HDTV only; Kopin applied its technology to other miniature near-to-eye displays (e.g., cell phones, viewfinders for camcorders, and eyewear viewers that allow wearers to view the display screen with one eye). Thus, the ATP-funded technology was successfully applied to other markets.

Kopin Moves toward Miniature Display Development

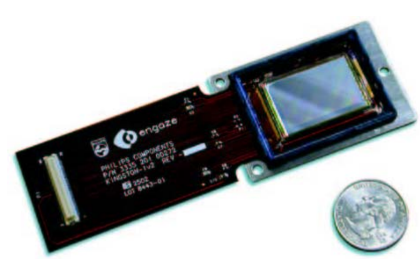
Kopin moved away from projection HDTV development, because the company could not reduce the manufacturing cost of LCD screens for large projections. Instead, it focused on miniature displays and commercialized its first CyberDisplay product in 1997 (see illustration below). This product includes a color sequential display, based on the technology developed during this ATP-funded project, that uses a 0.25-inch diagonal AMLCD. At the conclusion of the internally funded research, Philips developed its own project in October 1998, Kopin was marketing 10,000 AMLCD displays per month to U.S. original equipment manufacturers (OEMs) for miniature near-to-eye viewing (e.g., eyeglass attachments for medical and research applications) and military applications (e.g., helmet-mounted displays for pilots).



Example of a Kopin CyberDisplay LCD, with 0.25-inch diameter, used for a microdisplay.

Philips Continues HDTV Display Development after Project Concludes

After the conclusion of the ATP-funded project, Philips realized that Kopin's LCD technology was still too slow to meet commercial needs for HDTV. Continuing with faster miniature internal reflective display system (less than 0.2 ms image refresh speed) that relied on liquid crystal on silicon (LCoS), which would replace LCD for this product by 2000. LCoS devices have the crystals coated over the surface of a silicon chip. Electronic circuits are etched into the chip, which is coated with a reflective surface. LCoS devices are even smaller than LCDs, are easier to manufacture, and have a higher resolution (see illustration below). Philips had completed a full high-definition demonstration of the front-end electronics using the TM-2 chip by the end of 1999. Using the faster TM-2 chip showed full high-definition processing functionality in real time. Philips published several articles about its research and continued to pursue projection displays for HDTV.



Example of a Philips LCoS device used for a microdisplay.

High-Definition Technology Booms

Both Philips and Kopin were successful in marketing technology developed during this ATP-funded project.

In 1996, projection display was one of the fastest growing areas of the display industry, with sales increasing at 25 percent per year. Sales were driven by home-theater applications, which also included CRT projectors, light-amplifier systems for large audiences and theaters, electronic overhead projectors, and helmet-mounted systems for personal viewing. Demand for institutional applications for presentations and data projectors was growing by 15 percent per year.

The joint venture had successfully developed and demonstrated the key components to support high-definition color projection display products.

After conducting a business analysis in 2000, Philips decided to commercialize its projection HDTV, which it had initiated during this ATP project. Philips demonstrated its first commercial prototypes in January 2003 and began to market them in August 2003. Illustrated below, this 44-inch LCoS-based projection HDTV system later won the Consumer Electronics Show's "Best Innovation" award.

Philips' prototype 44-inch LCoS-based projection HDTV system, demonstrated in January 2003, won Consumer Electronics Show's "Best Innovation" award.

Philips' model has a short depth and a low weight, when compared with CRT technology. Because of its small components, Philips' projection HDTVs can be manufactured at 50 to 70 percent lower cost than direct-view displays (plasma and LCD), with higher quality images than CRTs. For example, in 2003, Philips' projection HDTVs ranged in price from $1,700 for a 43-inch screen to $2,700 for a top-end 60-inch screen. In comparison, a CRT analog TV up to 36 inches, with 1024 x 768 resolution, sold for $2,100, and super-thin 42-inch plasma HDTVs cost from $3,000 to $11,500.

Philips plans to offer more models of LCoS-based projection short-depth, low-weight HDTVs. The company believes it will continue to gain a price advantage over time, as sales grow and LCoS manufacturing costs drop.

Kopin also achieved success with the project-related technology. By September 2003, Kopin was selling more than 400,000 AMLCD units per month, up from 10,000 per month in 1998. Company employment had increased from 80 employees at the beginning of the project to 379 in 2003.

Kopin currently markets several near-eye display products, called CyberDisplay (see illustration below). Products include monochrome and color options with varying resolutions. The CyberDisplay is 1,000 times smaller and consumes 100 times less power than a conventional PC monitor. Kopin sells these displays to a variety of OEMs for applications including viewfinders for digital cameras and camcorders, miniaturized view screens for cellular telephones, personal digital assistants, computerized writing instruments, virtual reality games, belt-wearable computers, and eyewear viewers (the viewer is attached to eyeglasses or a helmet and allows wearers to view the CyberDisplay screen with one eye), as well as low-volume, specialty military products. Demand for these products is driven by consumers' desire for smaller, less expensive, more compact electronic devices, which display ever-increasing amounts of data and visual information.

Examples of OEM products that use the Kopin CyberDisplay. From left: IBM BodyWorn ThinkPad, JVC Camcorder, Oriscape Personal DVD Viewer, and Navitrak Hand-Held GPS.

Also in 2003, Kopin was developing a rear-screen dashboard projector for automobiles, which builds on the ATP-funded technology. This dashboard will include instruments and programmable formats and colors. Prototypes of the dashboard have been used since 2002 in Formula 1 race cars. However, because the dashboard is subjected to engine heat and high environmental temperatures, Kopin must develop methods to permit higher temperature tolerances for the display.

Regulations Stimulate Demand for HDTV

The Federal Communications Commission (FCC) is responsible for regulating and enforcing communications standards; therefore, they are interested in standardizing HDTV broadcasting. In April 1997, the FCC adopted rules for digital television broadcasting. The agency has been trying to accelerate the slow rollout to HDTV. In 2002, Congress set a target date for completing the transition to HDTV signals by December 31, 2006. These requirements encourage more broadcasters to offer HDTV, which stimulates consumer demand. As of May 2003, more than 1,000 U.S. stations were on the air with HDTV signals, including at least one in every major market. (Analog TVs will still receive a signal; however, they will not be able to pick up the HDTV signal.) Philips expects to increase sales of its ATP-funded projection HDTVs as a result of increased consumer demand.

U.S. Manufacturing Gains Entry into Display Market

Philips provided an entry for U.S. manufacturing into a market that was previously dominated 100 percent by foreign manufacturers. Philips manufactures key components and assembles the HDTV units in the United States. Kopin designs and manufactures its miniature displays in the United States and is the largest exporter of displays to Japan.

The ATP-funded technology was successfully applied to other markets.

By early 2003, more than 5 million U.S. consumers owned HDTV sets (less than 5 percent of U.S. homes). It is estimated that the market for projection HDTV will reach $6 to $10 billion by 2005. Worldwide shipments of electronic display materials were estimated at $8.5 billion in 2000 and $66 billion in 2002, with sales projected to continue to grow by 12 percent per year and to reach $115 billion by 2007. In addition to HDTVs, LCD projection technology advances from this ATP-funded project have contributed to improved resolution, speed, and color, as well as reduced prices in cellular phones, camcorders, and digital cameras.

Conclusion

This pioneering technology facilitated a paradigm shift in high-definition display technology. From 1995 to 1998, Kopin and Philips combined existing monochrome liquid crystal displays (LCDs), which were used in watches and radios, with color, signal processing, and high-definition technology. During the project, the team accomplished 95 percent of its technical goals, received two patents, and shared knowledge with the industry through presentations and publications. The team members independently continued their development efforts after the conclusion of the project and achieved all of the project goals. Philips successfully developed and commercialized a liquid-crystal-on-silicon-based high-definition projection technology for high-definition televisions (HDTVs), providing prototypes by January 2003 and retail products by August 2003. Screens are now lighter, with improved color and speed, and consume less power. Projection HDTVs have lowered the entry price for consumers into the HDTV market. They are priced 50 to 70 percent less than comparable-sized plasma HDTVs, which is stimulating sales. The market for projection HDTVs is anticipated to expand to $6 to $10 billion by 2005, growing at approximately 11 percent per year. Philips expects to benefit from this sales increase.

After the conclusion of the ATP-funded project, Kopin further developed LCD technology and provided the foundation for enhanced miniature color screens for multiple uses. Original equipment manufacturers use the screens in cellular phones, personal digital assistants, camcorder and still digital camera viewfinders, virtual reality games, wearable computers, and military applications. Kopin’s monthly sales increased from 10,000 active matrix liquid crystal displays in October 1998 to more than 400,000 units in September 2003. The outlook for additional new applications as well as growth in sales is excellent.

PROJECT HIGHLIGHTS
Kopin Corporation

Project Title: Miniature LCDs Enhance High-Definition Displays (High-Information Content Display Technology)

Project: To develop next-generation liquid-crystal projection display technology capable of producing the high-quality, high-resolution images needed for monitors, multimedia applications, and high-definition TV.

Duration: 4/15/1995–6/14/1998
ATP Number: 94-01-0304

Funding (in thousands):

ATP Final Cost	$6,097	49%
Participant Final Cost	6,407	51%
Total	$12,504	

Accomplishments: Kopin and Philips accomplished 95 percent of their technical goals:

- Developed and demonstrated high-speed image microprocessors using TM-1000 chips
- Designed and developed the optical and color system
- Designed the display drive electronics to take television-format video signals and display a picture
- Demonstrated a prototype system to evaluate image quality

Philips continued research and ultimately developed and successfully commercialized high-definition projection televisions (HDTVs) in 2003, which relied on liquid-crystal-on-silicon (LCoS) displays. Philips manufactures components and assembles the HDTV units in the United States.

ATP support allowed Kopin to develop a knowledge base that later made its CyberDisplay product series possible; CyberDisplay's color sequential display is based on this technology. Kopin produces U.S.-made liquid crystal displays (LCDs) for miniaturized color screens used in cellular phones, personal digital assistants, camcorder and still digital camera viewfinders, virtual reality games, wearable computers, and military applications. Kopin was selling more than 400,000 units per month by September 2003 and was the largest exporter of displays to Japan.

In addition, Philips and Kopin received patents and awards, and they disseminated knowledge through presentations and publications.

Philips filed and was awarded the following two patents resulting from this project:

- "Rear projection screen with reduced speckle" (No. 6,147,801: filed August 18, 1997, granted November 14, 2000)
- "Dichroic filters with low nm per degree sensitivity" (No. 5,999,321: filed June 19, 1998, granted December 7, 1999)

The Philips projection HDTV won an award for innovation:

- "Best Innovation for Consumer Electronics Show 2003" for the 44-inch LCoS HDTV

The ATP-funded project contributed to the knowledge base that made development of Kopin's CyberDisplay product series possible in an accelerated timeframe. Kopin's CyberDisplay won the following awards for innovation:

- "Product of the Year," for expanding functionality of portable devices including PDAs, cell phones, and pagers, 1998, Electronic Products magazine
- "25 Technologies of the Year," 1998, IndustryWeek magazine
- "25 Most Technically Innovative Products," 1999, for the CyberDisplay 320C, Photonics Spectra magazine

Commercialization Status: Philips successfully brought the short-depth, low-weight projection HDTVs to market in August 2003. The award-winning LCoS picture provides "the next level…[of] unsurpassed natural colors and picture sharpness," according to the Consumer Electronics Show 2003. Philips was able to price the models 50 to 70 percent lower than comparable-sized plasma HDTVs and anticipates that production costs will become even more cost competitive as LCoS production increases. Sales are expected to be brisk.

Kopin's projection display products are being marketed for many applications. Kopin products include the CyberDisplay 320 Monochrome, CyberDisplay 320 Color, CyberDisplay 640 Color, CyberDisplay 1280 Monochrome, and custom displays. These are used by original equipment manufacturers for many applications, including camcorder viewfinders, digital still camera viewfinders, hand-held global positioning system devices, wireless cellular telephones, personal digital assistants and pagers, personal computers, wearable computers, and military applications. Near-to-eye head-mounted displays (attached to eye glasses or a helmet) connect with any device that provides video output (e.g., digital camera, camcorder, portable TV, or laptop).

Outlook: The outlook for this technology is excellent. Worldwide sales of electronic display products were estimated at $66 billion in 2002. Shipments were projected to continue to grow by 12 percent per year to reach $115 billion by 2007. The market for projection HDTVs is anticipated to reach $6 to $10 billion in 2005. In addition, sales of miniature near-to-eye applications (e.g., viewfinders for camcorders and digital cameras, wearable computers, and military applications) are growing.

Composite Performance Score: * * * *

Number of Employees: 80 at project start, 379 as of September 2003

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Subcontractor:
Massachusetts Institute of Technology
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Publications and Presentations:

Philips and Kopin's presentations and publications include the following:

- Stanton, D. A., J. A. Shimizu, and J. E. Dean. "Three-Lamp Single-Device Projector." Proceedings of SID 1996, San Diego, CA, pp. 839-42, May 12-17, 1996.
- Goldenberg, J. F., H. Qiang, and J. A. Shimizu. "Rear Projection Screens for Light Valve Projection Systems." Projection Displays III, San Jose, CA, Sponsors: SPIE and IS&T, Proceedings of the International Society for Optical Engineering (SPIE), vol. 3013, pp. 49-59, Feb. 10-12, 1997.
- Woodard, O., F. P. Herrmann, H. E. Kim, and F. P. Cuomo. "Development of a 2560 x 2048 AMLCD Display for HMD Applications." Helmet- and Head-Mounted Displays III, Proceedings of the SPIE, vol. 3362, pp. 311-321, August 1998.
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- Gale, R. P., F. Herrmann, J. Lo, M. Metras, B-Y. Tsaur, A. Richard, D. Ellertson, et al. "Miniature 1280 by 1024 Active Matrix Liquid Crystal Displays." Helmet- and Head-Mounted Displays IV, Proceedings of the SPIE, vol. 3689, pp. 231-237, July 1999.
- Woodard, O., R. P. Gale, H. L. Ong, and M. J. Presz. "Developing the 1280 by 1024 AMLCD for the RAH-66 Comanche." Helmet- and Head-Mounted Displays V, Proceedings of the SPIE, vol. 4021, pp. 203-213, June 2000.
- Shimizu, J. A. "Philips' Scrolling-Color LCoS Engine for HDTV Rear Projection." Information-Display, vol. 17, no. 11, pp.14-19, Nov. 2001, published by Palisades Inst. Res. Services.
- Janssen, P., J. A. Shimizu, J. Dean, and R. Albu. "Design Aspects of a Scrolling Color LCoS Display." Displays (UK), vol. 23, no. 3, pp. 99-108, June 2002, published by Elsevier.
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Research and data for Status Report 94-01-0304 were collected during June - September 2003.

Planar Systems, Inc. (American Display Consortium)

Patterning Technology for Color Flat-Panel Displays

In 1992, monochrome flat-panel displays (FPDs) for viewing essential data were becoming a key product differentiator for most electronics products, such as mobile phones and navigational devices. Analysts believed that color FPDs were the next advancement and would be a vital component of electronics products in the next decade. The worldwide market was forecasted to grow from $3.5 billion in 1992 to $14 billion in 1999. Color displays demanded much higher resolution than existing monochrome panels, and higher resolution required new methods for applying electrical conductors in minute, intricate patterns on glass plates. Grid patterns that had been greater than 100 micrometers on monochrome displays had to shrink to 2 to 50 micrometers (a micrometer is 1/1000 of a millimeter).

The American Display Consortium (ADC) formed in 1992 to explore enhancements to color FPD technology. The leading members were five small U.S. FPD manufacturers: Planar Systems, Inc., Plasmaco, Electro-Plasma, Inc., Photonics Imaging (now Photonics Systems, Inc.), and Tektronix, Inc. (an instrumentation company interested in flat panel technology). This group agreed to focus on developing mutually beneficial micropatterning technology (minute, intricate patterns for the electronic circuits) to support color FPDs. Because none of the companies were large enough to fund this research independently, they applied to the Advanced Technology Program (ATP) in early 1993. They believed their pre-competitive research would stimulate U.S. competition in a Japanese-dominated market.

Through their ATP-funded project, which began in 1994, the consortium made advances in micropatterning circuits, achieving a resolution down to 5 micrometers. Moreover, they increased panel size to meet consumer demand (up to 24 x 24 inches) and ultimately commercialized large, color FPDs. By the end of the three-year collaborative research project, the remaining active companies were Planar Systems, Kent Digital Science (now Kent Displays), Three-Five Systems, Inc., and FED Corp. (now eMagin Corp.). These FPD manufacturers continue to supply niche markets in the electronics industry (for example, avionics, medical, and global positioning system displays). Spillover applications of this research include computer chips, high-end printers, calibration plates, and x-ray systems. In 2003, U.S. manufacturers accounted for less than 1 percent of the $50 billion worldwide FPD market.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

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Research and data for Status Report 93-01-0054 were collected during January - March 2004.

Flat-Panel Displays Require Multiple Layers of Electro-Optical Material

Many flat-panel displays (FPDs) consist of layers of glass substrates with minute, complex-patterned electro-optical material between the layers in order to light up pixels to create images. Rows and columns of electrical conductors form an intricate grid pattern. FPDs consist of four basic types: liquid crystal displays (LCDs), electroluminescent (EL), plasma, and field emitter displays (FEDs).

By 1994, U.S. FPD manufacturers had developed adequate processes for making monochrome displays. The electrodes typically had dimensions greater than 100 micrometers (a micrometer is 1/1000 of a millimeter). However, as FPD technology was moving toward color, the requirement for patterning resolution increased significantly to 2 to 50 micrometers. Detailed color images required much finer patterning of the electrical conductors on the multilayered grid patterns, called wafers. Wafers could have up to 16 layers of metal, semiconductors, and dialectrics (nonconductors) to make the patterns. However, existing methods for applying the conductive material were inadequate. Furthermore, visual inspection methods being used at the time could not adequately characterize the color issues of chromaticity (quality), brightness, and gray scale (definition).

American Display Consortium Applies to ATP for Research Funding

The American Display Consortium (ADC), formed in 1992, was a group of U.S. FPD manufacturers focused on making patterning technology advances that would benefit all the members. The consortium initially included Planar Systems, Inc., Plasmaco (now part of Matsushita), Electro-Plasma, Inc. (now EPI), Tektronix, Inc., and Photonics Imaging (now Photonics Systems, Inc.). Their common FPD needs included in-process inspection and repair tools and high-density interconnects (chip on glass and silicon on glass). Individually, the companies were too small to pursue this fundamental micropatterning technology research. Therefore, in 1993, the consortium submitted a proposal to ATP to pursue a group of projects that would address the generic technology and infrastructure requirements for the patterning of color FPDs. Beginning in 1994, the projects initially included the following seven areas of research:

- Large-area photo-exposure tools
- Large-area photo masks
- Wet-etching tools
- Dry-etching tools
- Printing tools
- Panel alignment methods
- Final inspection tool

Changes within companies as well as lessons learned from these seven areas of research led to changes in research efforts. This included the addition of the following three new research areas:

- Patterning process for dielectric barrier layers
- Laser lithography endpoint monitors
- Low-cost color filter processes

ADC planned to expand membership to include suppliers to the flat-panel industry as well as manufacturers. It proposed to provide quarterly meetings, internal publishing, technical reports, and on-site visits to facilitate knowledge sharing, collaboration, consensus building, and technology transfer among all formal and informal members of the consortium (some members did not actively participate in the ATP-funded research and development).

FPD Advancement Could Benefit the U.S. Electronics Industry

ATP granted funding to the ADC in part because industry analysts had identified FPDs as a strategic technology for the growing U.S. electronics industry. While Japan already enjoyed a manufacturing lead, it was critical for the United States to regain market share. Semiconductors were a key component of the electronics products, receiving research and investments from the public and private sectors in the 1980s. Similarly, it was believed that FPDs would be a vital component of the electronics products in the 1990s, and that the display would become the key product differentiator for most electronic products (for example, personal digital assistants, cell phones, and computers). The worldwide market for FPDs was expected to grow from $3.5 billion in 1992 to $14 billion in 1999. Some of the process technology developed for FPDs would likely also apply to the semiconductor industry and the electro-optics industry (for example, image digitizers, copiers, sensors, scanners, hybrids, and multichip modules).

Consortium Develops Foundational, Pre-Competitive Research Steps

During the ATP-funded project, the ADC ultimately researched 10 supporting technologies that could advance U.S. competitiveness in the FPD industry. At its peak in terms of membership, the ADC included 13 U.S. FPD manufacturers: Planar Systems, Photonics Imaging, Optical Imaging Systems (OIS), Electro

Plasma, Inc., Norden Systems, Plasmaco, Standish Industries, Inc., Kent Displays, Inc., Silicon Video Corp., Three-Five Systems, Inc., AT&T Xerox, Coloray Display Corp., and Tektronix. Some actively collaborated and conducted research, while others only participated in quarterly meetings to gain knowledge. While Planar led the project, joint venture members divided up the tasks, relying heavily on six subcontractors: Microphase, Solid State Equipment Co. (SSEC), Plasma-Therm, Inc. (now part of Oerlikon-Buehrle), Photronics (now Infinite Graphics, Inc.), Tamarack Scientific, and YieldUp International (now FSI International). A summary of their ATP-funded research efforts in all 10 areas and their results upon the conclusion of the project follow:

1. **Photo Exposure Tools:** Photonics Imaging worked with a subcontractor, Pacific Infrared, to design contact printing exposure equipment intended to produce large-area printed circuit boards with resolutions down to 4 micrometers over a 40- x 40-inch area (phase 1) and then over a 60- x 60-inch area phase 2), while offering high yields of printed circuit boards.
   Results: This portion of the project was terminated in 1997. Approximately 70 percent of the effort was complete, but the final milestones could not be met because Photonics Imaging was unable to continue funding the effort. While the prototype did not lead to a commercially viable piece of equipment for manufacturing, the project participants advanced their knowledge in the areas of registration, scanning, and uniformity of exposure and tool size aspects.

2. **Large-Area Photo Masks:** This work was started by Tektronix and later was transferred to Planar (Tektronix shifted its business focus away from FPDs). Researchers intended to directly pattern chrome on glass, using a photo mask in sizes larger than 6 x 9 inches. Researchers intended to develop the tool set needed to establish the full mask processing capability (such as cleaning, developing, and etching) for these large-area chrome masks with resolution down to 5 micrometers. The integrity of the photomaster is a key factor in determining process yield and quality of the intricate patterns. Damage to the pattern or contamination on the photo tool were serious problems in the high-resolution, large-area artwork used in making FPDs.
   Results: Photronics, a subcontractor, achieved speed goals and improved dimension uniformity by 400 percent. Although not an original design goal, the new photo masks reduced chemical use by 70 percent, a significant environmental benefit. Tamarack Scientific, a subcontractor, scaled up its existing exposure equipment to expose the substrates through Photronics' masks (up to 840 x 1025 mm). Researchers optimized processes for individual glass vendors and effectively collected and analyzed data as an ongoing process.

3. **Wet-Etching Tools:** Researchers at Kent Digital Science (now Kent Displays) and Planar planned to develop wet-etching production tools and processes to produce reflective Cholesteric LCDs and EL displays with plastic substrates. Wet etching is the most widely used technique to define the substrate structures, the electrode patterns, and the color sub-pixels of FPDs. While the etcher would be intended for glass etching, the tools could be applied to other etching processes used in the manufacture of FPDs, such as the etching of indium tin oxide (ITO, a transparent plastic that conducts electricity), electrode metals, or other materials.
   Results, Wet-Etching Process: Kent researched plastic materials such as acrylic, polycarbonate, and polyester. Acrylic and polycarbonate's strengths were that they absorb ultraviolet radiation (protecting the liquid crystal) and were rigid substrates (requiring no special handling techniques). However, they were brittle and slightly bowed, making registration difficult. Polyester's strength was that it was easy to shape to final dimensions; however, it was flexible and required special tooling, and its air bubbles interfered with quality.
   Results, Wet-Etching Tool: Planar identified and designed cost-effective automated tools that addressed the critical handling steps in its immersion process line. Planar relied on two subcontractors: SSEC to design the faster automated system and YieldUp International to dry the glass substrates after wet etching. Operators no longer directly touched the glass. The new system provided a throughput of one substrate per minute. SSEC developed a method to load plates up to 500 x 550 mm into a chamber and spray the chemicals instead of immersing them. YieldUp received 10 patents for its automated processing technologies.

4. **Dry-Etching Tools:** Dry etching is expensive compared to wet etching. It is used for high resolution or deep etchings in the substrate. Dry etching is also advantageous when patterning water-sensitive materials (such as color phosphors). This research used dry etching to define high-resolution patterns (5 micrometers or less), such as those found in active-matrix LCDs. Planar researchers intended to design a machine with at least a 100-percent improvement in the ratio of the capital cost to the throughput (process speed). Plasma-Therm, a subcontractor, had developed a unique square plasma process chamber concept, which maximized the useful area for processing rectangular FPD substrates.
   Results: The team developed and implemented a dry-etch tool. Etchers were installed and were operational at Planar on 6-inch wafers. The team developed, characterized, and implemented an ITO etch process in a pilot run of high-resolution, active-matrix displays.

5. **Printing Tools:** Existing screen printing tools were limited to resolutions of 100 micrometers, and most equipment was designed for relatively small substrates. Plasmaco intended to develop printing equipment with advanced resolution capabilities of 50 micrometers for large-area substrates (20 x 20 inches).
   Results: Plasmaco evaluated the process and implemented a pilot for screen-printing evaluation. Initial screen-printing results far exceeded expectations. However, Plasmaco was purchased by Japanese manufacturer, Matsushita, in early 1996, and this research was discontinued.

6. **Panel Alignment Methods:** Color FPD production requires precise registration of multiple micropatterned images from one film layer, or substrate, to the next. This is difficult, because subsequent processing steps, such as heating and cooling, distort substrates. Electro Plasma focused on developing methods to compensate for substrate distortions, so that precise layer-to-layer registrations could be obtained on the order of 0.025 mm. Researchers intended to create unique per-plate masks on auxiliary plates, which are keys from the electrode patterns already processed into the glass, because it was doubtful that all distortions could be eliminated. They intended to adapt to process-induced distortions.
   Results: Electro Plasma attempted to align panels using a phosphor deposition process and found that high-resolution alignment was not practical. An electrophoretic method (using current to move phosphor particles) provided potential for high-volume manufacturing and for achieving a superior image. However, additional research was needed.

7. **Final Inspection Tool:** The prevailing practice for final testing relied on operators who made a visual inspection and took measurements. Planar Systems intended to provide an automated, objective inspection tool to test and evaluate the color flat-panel performance and to provide feedback for process improvement. Manufacturers needed to characterize the chromacity (quality and purity of color), brightness, and gray scale performance of full-color panels. Besides measuring the optical performance, the inspection tool needed to detect any defective pixels and then accept or reject the panel. The throughput goal was to characterize 50 to 100 video-graphics-array (VGA)-sized panels per day. Final inspection meant developing nondestructive testing and evaluation techniques for the quality inspection process.
   Results: Initial results were positive and appeared to apply to all emissive displays. Subcontractor Photronics found a solution that solved the alignment problem for 30-inch plasma color displays by using an etching groove structure. The company achieved minimum specifications for metrology and defect detection, which they verified on VGA-color displays. They implemented automated device handling and test-data logging for a miniature display product. They successfully measured chromacity, image retention and flicker, and automated substrate handling for miniature displays.

Three research areas were added over the course of the project:

8. **Patterning Process for Dielectric Barrier Layers:** Three-Five Systems researched producing micropatterns on dielectric layers of silicon dioxide.
   Results: Researchers found that film hardness varies in different materials. They produced a

uniform film over 14- x 16-inch substrates. They were continuing research upon conclusion of the ATP-funded project.

9. **Laser Lithography Endpoint Monitors:** FED Corp. (now eMagin Corp.) researchers intended to develop and characterize a technique to develop in-process photoresist laser endpoints (putting down a pattern where the circuits would not be applied) for FED applications. The goals were to achieve lithography performance improvement with low voltage, low cost, and increased volume. Micropatterns should have resolutions down to 0.1 micrometers, with tight tolerance and real-time process control.
   Results: Actual display substrates gave reasonable signals to be able to determine a reference point. Endpoint detection is feasible for manufacturing FEDs patterned by laser interference lithography. Research was ongoing at the end of this project.

10. **Low-Cost Color Filter Processes:** Standish Industries researchers studied the color filter process. They examined screen printing approaches (direct print images, print blocks, and photolithographical pattern images), as well as changing materials from photoresists to inks.
   Results: Standish established materials for the first evaluation, where chromacity was close to requirements, thickness was acceptable, and resolution was achieved. They procured equipment, to include a printer, an emulsion coater, and a screen expose unit, and established a prototype low-cost color filter process. Further testing was needed to demonstrate repeatability.

The ADC membership changed during the project. Tektronix left the group in 1995, when it stopped pursuing FPD manufacturing. Plasmaco left after it was purchased by Matsushita in 1996. Upon conclusion of the project in 1997, the remaining four active consortium members were Planar Systems, Kent Displays, Standish Industries, and Three-Five Systems.

ATP Research Yields Mixed Results

While the project made reasonable technical advances, the ATP-funded FPD research yielded mixed results. In late 1997, Planar Systems and Three-Five Systems were doing well. Both had successfully broadened the number and scope of their niches, such as high-resolution medical displays. The EL work of Planar and the LCD work of Standish Industries and Three-Five Systems appeared to be the most synergistic and to have the most significant market opportunities for these firms.

Color FPD production requires precise registration of multiple micropatterned images from one film layer to the next.

Photronics (now Infinite Graphics, Inc. or IGI) successfully commercialized large-area photo masks using Tamarack Scientific's scanning and exposure tools. They had processed 280 large-area plates using the process developed during this ATP-funded project (at $2,000 per plate as of September 1997). Three-Five Systems was using Photronics' photo mask process, which allowed them to use a U.S. rather than a foreign manufacturer. Planar Systems scheduled the mask cleaner for production in their new EL expansion line, anticipated in 1998, and increased productivity by 60 percent. Photronics was becoming an important supplier to the semiconductor industry, as well as to the FPD industry (which was only 5 percent of Photronics' total sales). Their enhancement laser pattern generator wrote high-resolution patterns on glass substrates up to 24 x 24 inches.

SSEC used the wet-etching work developed during this project to support both FPD and semiconductor manufacturers. This project provided one of SSEC's first orders for spraying wet-etching chemicals and enabled the company to refine its technology. SSEC successfully commercialized its spray wet-etching machines.

Standish Industries further developed color filtering, but was unable to build color displays with high enough yields to enter commercial production. Standish was purchased by Planar in 1998. SSEC, Tamarack Scientific, and YieldUp International were expected to have marketing opportunities elsewhere as well as for ongoing FPD development and manufacturing.

After project conclusion, Kent Displays continued research into wet-etching processes on plastic substrates and developed large plastic prototypes by 1998. Planar also continued developing wet-etching tools.

Other company achievements resulting from this ATP-funded project included the following:

- Plasma-Therm successfully commercialized dry-etching processes in its Clusterlock 7000 on 6-inch wafers. Planar used the Plasma-Therm etcher to produce active-matrix EL microdisplays.

- After project conclusion, the FED Corporation received significant additional funding from investors and government agencies in order to further develop high-definition field emission display technology.

- Three-Five Systems continued developing dielectric barrier layers.

U.S. FPD Manufacturing Shrinks in 1999

Asian competition hit U.S. FPD manufacturing hard in 1999. The production capacity in China for monochrome small LCDs increased significantly. High-performance active matrix LCDs were becoming a commodity item, leading to lower prices, in much the same way as the dynamic random-access memory (DRAM) chip and the bare silicon wafer had become commodity items in the computer industry. Retail prices dropped for electronics such as laptop computers. When global demand temporarily shrank, Asian suppliers were prepared to reduce prices lower than the cost of production in the United States. The cost to develop and manufacture color FPDs was too high to compete, and, as a result, U.S. firms increased their FPD outsourcing from Asian manufacturers. OIS went out of business, and Plasma-Therm was sold to a Swiss company, Oerlikon-Buehrle. Three-Five Systems was able to outsource dielectric barrier layers for less and discontinued its ATP-funded research.

Kent Displays found that using wet etching during manufacturing was too expensive and discontinued its use. As of 2004, they still produced FPDs using glass and have moved on to using conducting polymer substrates, where circuits are printed rather than etched. The Planar EL manufacturing plant, which opened in 2000 but closed in 2003, used several of the processes developed during this project.

Planar continued developing its final inspection tool and used it for miniature display products based on EL. The company was not able to develop a high-volume business for these products, and the program was shut down in 2002.

The worldwide market for FPDs was expected to grow from $3.5 billion in 1992 to $14 billion in 1999.

FED continued developing its laser lithography endpoint monitor. Ultimately, the company gave up FPD production and in 1999 changed its technology focus to active matrix organic light-emitting diode (OLED) microdisplay technology. The company changed its name to eMagin in 2000.

The future of U.S. FPD manufacturing is uncertain. Only four ADC niche players remain in the business: Planar Systems, Three-Five Systems, Kent Displays, and eMagin. They provide specialty applications, such as medical instrument displays, "ruggedized" military displays, automated teller machines and outdoor kiosks, and navigation instruments, such as for global positioning systems for trucking and avionics.[1]

Electronics Manufacturing Spillover Provides a Bright Spot

Some of the ATP-funded research has been commercialized through spillover electronics applications. The manufacturing processes for FPDs, such as micropatterning and producing multi-layered integrated circuit wafers, also apply to other high-resolution manufacturing.

IGI continues to lead the market, using its enhancement laser generator developed for large-area photo masks. Resolutions have increased from micrometers to nanometers (a nanometer is 1/1000 of a micrometer). By 2004, IGI was able to work on panels up to 32 x 28

[1] Freedonia Group, *Electronic Displays,* March 2004.

inches. It continues to sell customized large-area masks for use in high-end printer circuits, calibration plates, and x-ray systems, as well as for use in FPDs account for 5 to 10 percent of their business, or $500,000 to $900,000 annually (based on $8.8 million in 2002 sales). The global market for photo masks was expected to reach $3 billion in 2003 (up from $2.4 billion in 2001).[2]

SSEC still sells its wafer wet chemistry systems as of 2004, which represents approximately 10 to 15 percent of the company's business. Tamarack Scientific continues to sell large-area scanning and exposure tools, with resolution down to 3 micrometers.

YieldUp sold its patented wet-etch processing tools to several FPD manufacturers. These processes are key components of a larger system, which the company still uses for integrated circuits (on glass substrates) and computer chips (on silicon wafers) of up to 12-inch diameter (their primary business as of 2004). Other applications include hard disk drive cleaning and photo mask cleaning. The company had sales of $88.8 million in 2003. Wet-etching tools are a critical area in semiconductor manufacturing, which is also experiencing extreme pricing pressure. The wet-etch-clean market shrank 40 percent from 2002 to 2003 but is expected to grow again to $1.5 billion in 2005.

Conclusion

In 1994, at the time the ATP-funded color flat-panel display (FPD) research began, the technology was still in its infancy. U.S. manufacturers had competed effectively in the market with their monochrome displays and hoped to continue this success in the high-resolution color environment. Displays were recognized as a key differentiator in numerous electronic products, such as mobile phones and navigation instruments. Existing photo exposure equipment was no longer adequate for producing high-resolution circuit micropatterns for color FPDs, in which critical dimensions were as small as 2 to 50 micrometers (down from 100 micrometers) on panels as large as 24 x 24 inches (up from 6 x 9 inches). Thirteen U.S. manufacturers participated in the American Display Consortium from 1994 to 1997. The consortium members, relying substantially on subcontractors to develop the tools, achieved higher resolutions and larger dimensions by making improvements in technologies for etching, printing, alignment, and inspection. They shared knowledge and received 10 patents, but research into FPDs achieved mixed results. U.S. flat-panel manufacturers made a strong showing on the global market until 1999. At that time, price-competitive Asian manufacturers drove prices so low that U.S. manufacturers had to focus on niche markets, such as automated teller machines and outdoor kiosks, "ruggedized" military applications, microdisplays, and avionics and other navigation instruments. They captured less than one percent of the global $50 billion FPD market in 2003, but new innovations keep surfacing. U.S. manufacturers of high-resolution printers, x-ray systems, and computer chips have also benefited from the high-resolution tools developed during the ATP-funded research.

[2] *Solid State Technology,* August 2002.

PROJECT HIGHLIGHTS
Planar Systems, Inc. (American Display Consortium)

Project Title: Patterning Technology for Color Flat-Panel Displays (FPDs)

Project: To develop patterning technologies necessary to manufacture color FPDs, including large-area photo exposure tools, large-area masks, wet- and dry-etching tools, printing tools, panel alignment methods, and a final inspection tool.

Duration: 4/18/1994-10/17/1997
ATP Number: 93-01-0054

Funding (in thousands):

ATP Final Cost	$5,670	49%
Participant Final Cost	5,901	51%
Total	$11,571	

Accomplishments: With ATP funding, researchers made the following technology advancements, which benefit the FPD and semiconductor industries.

Implemented methods to produce large-area photo masks up to 24 x 24 inches (up from 6 x 9 inches), increasing dimensional uniformity by 400 percent and reducing chemical use by 70 percent

- Implemented automated wet-etching processes and tools and achieved a throughput of one substrate per minute
- Implemented a dry-etching process for 6-inch wafers
- Implemented a final inspection process for miniature displays, measuring chromacity, image retention and flicker, and test data logging
- Developed a patterning process for dielectric barrier layers
- Determined that endpoint detection is feasible for laser interference lithography; pursued additional funding to continue research

Research and development into wet etching led to 10 key technology patents that aid in processing silicon wafers for multiple uses, including manufacturing FPDs and computing chips. These were awarded to subcontractor YieldUP International (now FSI International, Inc.).

- "Ultra-low particle semiconductor method" (No. 5,634,978: filed November 14, 1994; granted June 3, 1997)
- "Method for cleaning and drying a semiconductor wafer" (No. 5,571,337: filed May 9, 1995; granted November 5, 1996)
- "Ultra-low particle semiconductor cleaner" (No. 5,772,784: filed November 8, 1995; granted June 30, 1998)
- "Ultra-low particle semiconductor apparatus" (No. 5,685,327: filed August 8, 1996; granted November 11, 1997)
- "Method and apparatus for cleaning wafers using multiple tanks" (No. 5,849,104: filed September 19, 1996; granted December 15, 1998)
- "Ultra-low particle semiconductor cleaner" (No. 5,868,150: filed May 22, 1997; granted February 9, 1999)
- "Ultra-low particle semiconductor cleaner" (No. 5,878,760: filed May 22, 1997; granted March 9, 1999)
- "Ultra-low particle disk cleaner" (No. 5,873,947: filed August 6, 1997; granted February 23, 1999)
- "Ultra-low particle semiconductor cleaner" (No. 5,891,256: filed December 29, 1997; granted April 6, 1999)
- "Cleaning and drying photoresist coated wafers" (No. 5,932,027: filed January 12, 1998; granted August 3, 1999)

Commercialization Status: Research led to some near-term commercial successes, which did not last, as well as several long-term commercial successes.

- Subcontractor Plasma-Therm successfully commercialized dry-etching processes in its Clusterlock 7000 for 6-inch wafers. Planar used this etcher to produce active-matrix electroluminescent microdisplays until 2002. Plasma-Therm was sold to a Swiss company, Oerlikon-Buehrle, in 1999.

- Subcontractor Photronics (now Infinite Graphics, Inc.) provides commercialized customized large-area photo masks for use in high-end printer circuits, calibration plates, x-ray systems, and FPDs (this work accounts for 5 to 10 percent of their business). This technology relies on two processes that were developed during this ATP-funded project: mask cleaning and laser pattern generating.

PROJECT HIGHLIGHTS
Planar Systems, Inc. (American Display Consortium)

- Subcontractor YieldUp (now FSI) developed automated wet-etch processing tools. These are now used for FPDs, but primarily for computer chip manufacturing. They are also used in hard disk drive cleaning and photo mask cleaning. Currently, the company markets the following larger processing systems, for which the ATP-funded technology was key: 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.

Outlook: The outlook for U.S. FPD manufacturing is poor, with U.S. manufacturers' share of this $50 billion global market at less than one percent in 2003. The foundational manufacturing technologies developed during this project apply to other electronics applications, primarily computer chip manufacturing. The large-area, high-resolution photo mask processes contribute to a $3 billion industry. The automated wet-etch tools were commercialized in wafer-processing machines, which improved throughput in semiconductor manufacturing. Wafer processing has also endured extreme pricing pressures, and the market shrank 40 percent in 2002.

Composite Performance Score: * *

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Research and data for Status Report 93-01-0054 were collected during January - March 2004.

Superconductor Technologies Inc. (formerly Conductus)

A Superconducting Hybrid Switch

By the early 1990s, more and more researchers were searching for ways to use a phenomenon that occurs at ultra-low temperatures, known as superconductivity, to address the limitations of conventional integrated circuits (ICs) at normal operating temperatures. The complexity of computation and communications circuits, coupled with the increasing demands on speed, will ultimately exceed the capabilities of semiconductor-based technology. Researchers believe that superconductivity, along with cryogenic operation of semiconductor circuits, could ultimately be used to produce electronic systems with unprecedented performance.

Research in superconductivity, which was a new, challenging, complex, and barely tested technology in electronic applications, was considered extremely risky for commercial applications. As a result, firms who sought to study superconductivity found it difficult to obtain private venture capital. In 1991, a joint venture led by Conductus applied for Advanced Technology Program (ATP) funds to pursue this research, and funding was awarded in 1992. The joint venture, which comprised several private companies and universities, defined the purpose of the project as twofold: 1) to design, build, and test a hybrid-technology switch to demonstrate high-throughput communication switching using components based upon several technologies operating at different temperatures; and 2) to demonstrate the ability to integrate these disparate technologies into a single system. If the project were successful, it would demonstrate that ICs based on superconducting technology could be integrated into a high-speed electronic system, along with other high-performance technologies, to create a viable approach to future communications systems.

Although the joint venture met most of its project goals, their prototype superconducting switch did not demonstrate potential performance sufficiently superior to competing technologies to warrant near-term commercialization. Conductus ceased its efforts in high-speed electronic circuits in 1998 to focus entirely upon microwave communications applications. The company was acquired by its competitor Superconductor Technologies Incorporated in 2002.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

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Research and data for Status Report 91-01-0134 were collected during February - May 2004.

Superconductivity: A New Solution for Excess Resistance in Semiconductors?

Superconductivity is a property exhibited by a wide variety of electrical conductors that results in the complete cessation of electrical resistance at extremelylow temperatures, typically not many degrees above absolute zero (0 K on the kelvin scale). Superconductors have been widely used commercially to produce high-powered magnets for magnetic resonance imaging (MRI) medical scanners and to a lesser extent in other applications. Superconducting materials with higher operating temperatures (77 K and above), which are known as “high-temperature superconductors,” were discovered in the 1980s and have enabled additional applications such as the use of superconducting filters for cellular communications.

Since the 1960s, researchers have been developing integrated circuits (ICs) based on superconducting switching devices known as Josephson junctions. These devices have extraordinarily fast switching speeds and use only 1/1000 the electrical power of semiconductor transistors. However, because of limited resources devoted to developing the technology, as well as the intrinsic complexities associated with operating circuits at ultra-low temperatures, superconducting IC technology has never reached a mature enough level of development to successfully compete with conventional approaches. The expectation of the superconducting research community has been that conventional technology would ultimately reach its performance limits and then superconducting technology could take over.

The challenge of increasing speed in electronic circuits is chiefly affected by three limitations:

- The intrinsic speed of the device itself depends on the circuit design, materials, and ultimately the underlying physics by which the device operates.
- The time required for signals to travel through the device circuits drives the increasing miniaturization of the circuits.
- The inability to dissipate the heat generated by the circuits as they become denser causes the highly dense circuits to literally cook themselves to death.

Superconducting circuits can theoretically address these limitations because they are intrinsically faster than semiconductor circuits. They can carry currents in much narrower conductors and can dissipate far less energy than semiconductor circuits. High-speed network switching, a rapidly growing technology requirement in the modern Internet-enabled world, provided the ideal challenge for advanced electronic circuits and appeared to be the area where superconducting circuits could have the greatest impact.

Joint Venture Proposes a Superconducting Prototype Test Switch

In 1991, a joint venture proposed to build and test a multiple-temperature prototype test switch to demonstrate a circuit using high-capacity fiber optic data inputs and superconducting memory and logic circuits. The team consisted of project leader Conductus (now part of Superconductor Technologies), TRW (now Northrop Grumman Space Technology),

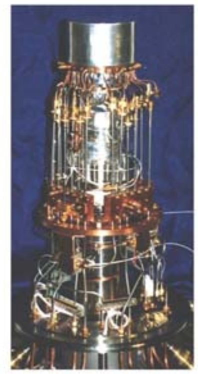

Figure 1. The top cylinder is the shielding can that holds the 4 K circuits (DSP chip). The rigid coaxial cables coming down from the perimeter of the top cylinder are the high-speed fiber optic data lines from the 4 K compartment to the 77 K compartment below. Everything shown in the illustration was then encased in an outer vacuum jacket (not shown). The interior of the vacuum jacket was cooled to maintain the temperatures of the components inside.

Hewlett Packard, the University of California at Berkeley, and Stanford University.

Conductus received Small Business Innovation Research funding, but the monies were only sufficient to support rudimentary research into high-speed circuits. The complex design and testing of a prototype device required additional funding. The joint venture partners were unable to obtain private funding because of the high risk of building a test switch, so they applied to ATP in 1991 and received an award for a five-year project in 1992.

The joint venture partners proposed to design and construct a prototype signal processing system. The goal of the prototype was to demonstrate that a system using standard IC technologies, semiconducting random access memory (RAM), and a digital signal processor (DSP) chip could operate with greater speed and less power loss at three operating temperatures. The prototype's components would operate at the following temperatures: the DSP at 4 K, the memory chips at 77 K, and a supervisory room-temperature workstation at 300 K, or 20°C (these components are shown in Figure 1). The target throughput speed of each port on the DSP was 10 gigabits per second (Gb/s), and the target power loss was 1/1000 that of a conventional semiconductor operating at room temperature. (Power loss is normally caused in room temperature switches by resistance.) More broadly, the switch designers hoped to demonstrate a generic technology that would have a wide range of applications, including memory circuits equivalent to medium-scale integration (MSI, or hundreds of transistors on a chip) and large-scale integration (LSI, or thousands of transistors on a chip).

Difficulties Force the Team to Modify Technical Goals

Over the five-year project, the partners pursued several goals in order to build the prototype system, such as developing the capability to manufacture superconducting large scale integration (LSI) logic circuits and to build a DSP chip based on five generic chip types. However, the team encountered technical difficulties; therefore, starting in late 1992, they began to modify several of their goals. In 1993, after the completion of its first-year activities, Hewlett Packard withdrew from the joint venture. The company had brought computational expertise to the project, so their withdrawal led the venture leader, Conductus, to reevaluate the design and goals of the project. Primarily, Conductus redirected the demonstration focus of the program from computation circuits to communications circuits and, hence, the network switch became the central goal of the program. Subsequently, the team amended the project's goals in minor ways several more times before the project ended.

The hybrid switch designers hoped to demonstrate a generic technology that would have a wide range of applications.

Over the next few years, the partners made steady progress in building the prototype hybrid switch. During this time, Conductus kept current with developments in the field of superconductivity and solicited expertise from the University of California at Santa Barbara and the Lawrence Livermore National Laboratory.

Team Demonstrates Prototype Hybrid Switch

Despite the numerous technical difficulties that the team encountered on this extremely complex project, they demonstrated a prototype hybrid switch in July 1997. Data were transmitted to the four input channels and from the four output channels in the DSP component of the switch via a 10 Gb/s supercooled optical interface for each channel. However, the maximum data rate demonstrated was 8 Gb/s per channel, not the 10 Gb/s intended. According to the lead project engineer, Randy Simon, this lower rate was probably due to the limitations of the so-called driver circuits that amplify the low signal levels of the superconducting circuits to the higher signal levels required by the other components of the switch. The superconducting switch IC itself and these driver circuits operated at 5 K, while the circuits that directly interfaced with the optical components operated at 77 K .The switch system demonstrated that a multiple-temperature design could successfully combine superconducting circuits with cooled semiconductors and room-temperature optical components using a variety of input and processing technologies. Simon noted that falling short of the 10 Gb/s speed goal was not a factor in determining the commercialization prospects of the technology. The partners did not pursue commercialization because of the advancing progress of conventional technology, coupled with the magnitude of resources that would be required to make the superconducting approach viable.

The switch system demonstrated that a multiple-temperature design could successfully combine superconducting circuits with cooled semiconductors and room-temperature optical components.

After the successful switch demonstration, project partners attempted to solicit funding from telecommunications companies, but none were interested in funding additional research efforts. This forestalled the joint commercialization that Conductus had originally planned to pursue with other companies. Conductus, therefore, focused its business on short-term applications of superconducting filter technology, thereby ending all its efforts on high-speed circuit technology. The company was subsequently acquired by its primary competitor, Superconductor Technologies Inc. in 2002. Although no commercialization resulted from this project, Conductus was awarded three patents, one during the project and two after project completion. Moreover, the joint venture members published 17 articles and made one presentation related to the technologies.

One of the project's subcontractors, High Precision Devices, Inc. (HPD) of Boulder, Colorado, has been able to apply knowledge it gained on the ATP-funded project to its work in cryogenic technology for superconducting electronics. The company originally provided the joint venture partners with cryoprobes, multichip modules, chip mounts, and other superconducting hardware. As of 2004, HPD has built cryogenic sample holders, chip mounts, voltage probes, cryostats, and liquefied gas storage containers for government and university research labs, as well as for private companies located in the United States and in many foreign countries. According to company founder and President Bill Hollander, this work is increasingly important to HPD and accounted for about 25 percent of its $1.5 million in sales for 2004. HPD was founded in 1993 with two employees and had sales of $200,000 that year. HPD now employs 15 engineers, instrument makers, and technicians.

Conclusion

A joint venture consisting of Conductus (now part of Superconductor Technologies), TRW (now Northrop Grumman Space Technology), Hewlett Packard, the University of California at Berkeley, and Stanford University successfully built a prototype high-speed network switch that incorporated disparate technologies that were able to operate at several different temperatures. The project team’s demonstration of the switch met the original project goals to successfully combine superconducting integrated circuit technology, cryogenically cooled semiconductor circuits, and optical components in an integrated system.

According to Conductus project lead Randy Simon, this diverse joint venture would not have formed without ATP funding. In addition, ATP business and technical contacts at Federal Labs provided oversight to the project that helped Conductus reevaluate its goals after the team experienced major technical failures, such as difficulty in designing and manufacturing the logic switch for the prototype demonstration. Technologies used in the project, such as the ultra-low temperature digital signal processor circuits, have not shown much progress. More research is needed in all aspects of superconductivity. The team shared its project knowledge through three patents, 17 published articles, and one presentation. In addition, the project’s requirements assisted High Precision Devices of Boulder, Colorado, in establishing itself as a leading supplier of test devices to the global superconductor industry.

PROJECT HIGHLIGHTS
Superconductor Technologies Inc. (formerly Conductus)

Project Title: A Superconducting Hybrid Switch (Hybrid Superconducting Digital System)

Project: To develop manufacturing, packaging, and multiple temperature environments to combine superconducting logic chips, optical fibers, and room-temperature hardware in a single operating switch system.

Duration: 8/1/1992-7/31/1997 (the project was extended to 5/1998)
ATP Number: 91-01-0134

Funding (in thousands):

ATP Final Cost	$7,391	50%
Participant Final Cost	7,426	50%
Total	$14,817	

Accomplishments: The joint venture team led by Conductus developed and successfully tested the first hybrid technology and temperature test switch at superconducting temperatures.

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

- "Ultrahigh speed laser"
  (No. 5,651,016: filed May 30,1996; granted July 22,1997)
- "Digital optical receiver with instantaneous Josephson clock recovery circuit"
  (No. 5,963,351: filed April 29, 1997; granted October 5, 1999)
- "On-chip long Josephson junction (LJJ) clock technology"
  (No. 6,331,805: filed June 22, 2000; granted December 18, 2001)

Commercialization Status:
Commercialization of the technology developed and tested during this ATP-funded project was not pursued by Superconductor Technologies Inc. (STI), the company that acquired Conductus. According to Randy Simon, formerly of STI, this was probably due to a lack of interest in the technology on the part of the semiconductor and communications industries. However, one the project's subcontractors, High Precision Devices, which manufactured prototype high-temperature superconductivity (HTS) devices, currently earns about $375,000 a year that is attributable to its involvement in the ATP-funded project. The company started in 1993 with 2 employees and now has 15.

Outlook: The outlook for this technology is poor. HTS-integrated circuit research and development remains uncertain due to a lack of funding.

Composite Performance Score: *

Number of Employees: 133 at project start; 275 as of December 2004.

Company:
Superconductor Technologies Inc.
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Contact: Dr. Randy Simon
Phone: (518) 355-3999

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- Hewlett Packard
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  Palo Alto, CA 94304
- University of California
  Berkeley, CA 84720
- Stanford University
  Palo Alto, CA 94301

Subcontractors:
High Precision Devices
Boulder, CO

Publications:

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PROJECT HIGHLIGHTS
Superconductor Technologies Inc. (formerly Conductus)

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Presentations:

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Research and data for Status Report 91-01-0134 were collected during February - May 2004.

Texas Instruments Inc.

New Materials to Speed Signal Transfer in Integrated Circuits

In the mid-1990s, the U.S. semiconductor industry needed new manufacturing materials and techniques to keep pace with the trend toward miniaturization. Integrated circuits (ICs) had become so small that performance inefficiencies resulted because the aluminum interconnects had to be placed too closely together. A commonly used insulator that was placed between the interconnects was becoming ineffective as the miniaturization trend continued.

In 1994, Texas Instruments applied for and received Advanced Technology Program (ATP) funding to research two new materials, a polymer Teflon, and a special insulating material nanoporous silica, also known as aerogel, that could be used as interconnect materials. The goal of the project was to integrate these materials adjacent to on-chip interconnects in order to overcome problems with interconnect delay as a result of the continuing trend toward miniaturization. The project work started in 1995 when Texas Instruments subcontracted with a small company, NanoPore Corporation.

After three years of research funded by ATP, the two companies showed that aerogels held significant promise as an insulator for aluminum interconnect wiring. Furthermore, Texas Instruments and NanoPore developed the world's first fully automated manufacturing process to dry an aerogel quickly. The companies 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 IC 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.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

* *

Research and data for Status Report 94-01-0221 were collected during January - February 2004.

Semiconductor Materials Reaching the Limit of Their Capabilities

In 1994, the U.S. semiconductor industry faced a crisis as the speed of signaling between different components within integrated circuits (ICs) approached the maximum speed enabled by IC materials. For a number of years, semiconductor transistors had been getting smaller without losing energy in the form of heat or power dissipation or without incurring "cross-talk" between different circuits as a result of capacitive "coupling" (signal merging). However, as semiconductor parts continued to get even smaller, signal delays between components on ICs were becoming greater. Furthermore, this technical problem was impeding improvements in devices such as digital signal processors, cell phones, and laptop computers.

On a semiconductor, metal interconnects of about 0.25-µm thickness conduct the signal/data between IC components. These interconnects need to be insulated from each other by materials called dielectrics. In the mid-1990s, the industry commonly used silicon dioxide (SiO_2) as the dielectric. However, as IC miniaturization progressed, increasing capacitance and resistance in the interconnect caused excessive signal delay.

(Resistance is a measure of how strongly an interconnect, such as one made of aluminum, supports electron or current flow. Capacitance is a measure of how much electrical charge a conducting material stores.) If there is too much resistance in an IC interconnect, then the circuit operation speed is too slow. If there is too much capacitance, then an unacceptable level of crosstalk occurs. Excessive resistance and capacitance are expressed as the "k" constant in the dielectric rating assigned by the industry standard. A lower k insulator material with a k ≤ 2 was needed for semiconductors if miniaturization were to continue successfully. SiO_2 has a k of approximately 4, which translates to a serious performance bottleneck for the transmission speeds required in ICs. A new material with a k constant far lower than SiO_2's needed to be developed.

Improved Dielectrics Would Mitigate the Signal Delay in ICs

Historically, the implementation of new materials in semiconductor processing has taken approximately a decade from concept to production. Texas Instruments subcontracted with NanoPore Corporation in 1995 to begin research into a new interconnect material; however, they faced difficulties in securing either internal or external funding. Therefore, Texas Instruments sought funding from ATP to develop and test two new dielectrics for aluminum leads, with the goal of determining which was better. Texas Instruments expected a reduction of up to 50 percent in power loss between components on ICs if a superior dielectric were found to replace SiO_2. Although copper is a better conductor, in the mid-1990s, aluminum was cheaper and less difficult to integrate with other IC components. If a lower k dielectric material could be developed, it would be another step in interconnect evolution towards the goal of approaching copper's performance, without the difficulty of actually incorporating copper into semiconductor manufacturing.

Texas Instruments selected a special insulating material, silica aerogel, and an amorphous Teflon by DuPont, a polytetrafluoroethylene (PTFE) polymer, to test in separate testing regimens. These two materials were the lowest k materials available at the time. As dielectrics, both materials presented challenges in IC manufacturing. The aerogel required too much time to dry after application. The PTFE polymer would not adhere properly to other substances, which presented a problem in composing the multilayer design that is used in manufacturing ICs.

Aerogels or PTFEs: Which is Better?

Developed in 1931, an aerogel is a solid substance with air embedded in minute "pores" (in diameters of 10 to 20 nanometers, or 10 to 20 billionths of a meter). Air is the best dielectric known, but it must be encapsulated in another substance to be useful as a dielectric for IC interconnects. One of the lightest weight solids known, silica aerogel offers the following low-k dielectric properties:

- Thermal stability to 900ºC
- Small internal air pore size of 10 to 20 nanometers
- Controllable aerogel density during application (to vary the dielectric constant)
- Manufactured from silica, a substance widely used in the industry

Because the integration of aerogel with semiconductor components required extensive customization during the manufacturing process, it was more expensive to test than the Dupont Teflon material, PTFE. For example, a disadvantage of using an aerogel is its hydrophilic (water-absorbing) nature during and after deposition on a semiconductor. If it absorbs water, its pores collapse and the insulating properties are lost.

Furthermore, in 1994, the semiconductor industry was not capable of commercial mass-production of aerogel. The material required days to produce, which was significantly longer than the seconds or minutes required for commercial acceptance. Aerogel production also required that scientists spend significant time in a wet lab to complete production. Moreover, modeling showed that aerogels would not adhere to aluminum semiconductor circuits. A new type of aerogel would need to be developed before the material could be used in semiconductors.

The other dielectric that was tested, the polymer Teflon, has the lowest dielectric constant of any plastic material (1.9 to 3.9). It is chemically inert and is compatible with most IC manufacturing techniques. Teflon is applied using a dry application technique (dry etch), a procedure that is different from the wet application used with aerogel. When the application is complete, a Teflon-coated surface is hydrophobic (water-resistant).

However, this hydrophobic property often presents adhesion problems when other materials need to be added on top of the Teflon layer.

Aerogels Demonstrate Early Superiority

The improved properties that NanoPore and Texas Instruments sought for aerogels included the following: higher mechanical strength, better dimensional stability, higher thermal stability, better ability to etch small circuits onto the materials, lower degree of moisture absorption, better adhesion, higher thermal conductivity, lower leakage of current, and lower overall cost. No dielectric has all these properties, so achieving the desired improvements required radical rethinking of aerogel's manufacturing and use. The biggest drawback of aerogels was the long drying time needed. ATP funding enabled the test team to start with the technically riskier aerogel materials. As the PTFE was easier to work with, the team decided to do the more difficult task first (the aerogels).

Texas Instruments and NanoPore identified four tasks for this three-year project:

- Evaluating a thin-film aerogel
- Designing tests for the amorphous Teflon and the silica aerogel
- Testing Teflon with several layers of IC structures
- Device modeling at Texas Instrument's Semiconductor Process and Device Center

The team achieved early success with aerogel and discovered that aerogel adhesion layer combinations could insulate aluminum semiconductor wiring. The aerogel tests went so well that the companies were able to shorten their original test schedule by three years. However, less success was achieved with Teflon. Texas Instruments determined that Teflon was a poor choice as an interlevel dielectric material; adhering it to the semiconductor made overlaying additional circuits extremely difficult. Subsequently, Texas Instruments switched to a different PTFE supplied by W.L. Gore. Even though Gore's PTFE showed promising results, it failed to demonstrate the ability to reduce capacitance. Moreover, it had leakage, delamination, and dispersion problems. Therefore, in the final year of the project, Texas Instruments decided, on the basis of test results, not to pursue PTFE development unless W.L. Gore improved the material.

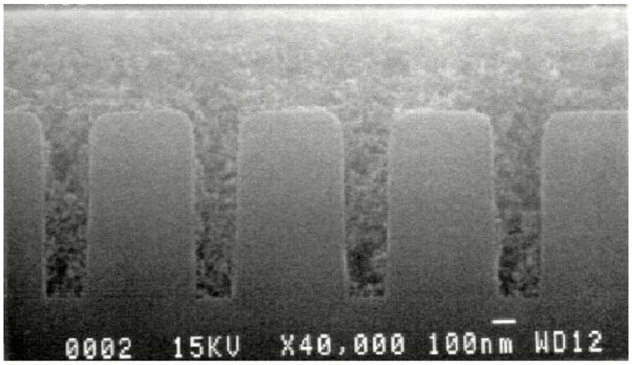
Aerogel Deposition Problems Solved

During the first year of the ATP-funded project, the team was able to reduce aerogel production time from 90 to 20 minutes; however, 20 minutes was still 10 times too long for commercial acceptance. Later the team discovered that by using ethylene glycol in the aging phase of the gel processing, they could reduce the production process to 1 to 2 minutes, which was acceptable for competitive manufacturing. As the aerogel was drying much faster, engineers called it an "xerogel," (literally, a "dried" gel). Texas Instruments and NanoPore worked with two vendors to develop the world's first fully automated xerogel processing tool, which used a new solvent that quickened the drying time. The tool, which Texas Instruments paid approximately $1 million of its own funds to create, was installed in 1997. As a result, the processing tool enabled 1- to 2-minute xerogel production and replaced the previous 20-minute process.

During the first year of the ATP-funded project, the team was able to reduce aerogel production time from 90 to 20 minutes.

The companies continued working to bring xerogels into the market. They also worked with SEMATECH, the semiconductor industry trade association, to make xerogels available for all American semiconductor industry participants. However, at the same time, in late 1997, IBM introduced copper wiring into semiconductor circuits by developing a process that prevented the copper from leaching into the silicon layer; before this, copper had been too difficult to use. This breakthrough caused Texas Instruments to change its focus from xerogels with aluminum circuits to developing copper wiring. The company transferred its knowledge about xerogels for aluminum wiring to NanoPore.

At the conclusion of the ATP-funded project, xerogel was a pre-commercial prototype and would still require years of development. NanoPore and AlliedSignal formed a 50/50 joint venture called Nanoglass LLC and worked together to further develop the material into a product they called NANOGLASS (see Figure 1). Then AlliedSignal and Honeywell merged, and Honeywell bought NanoPore's stake in the product. AlliedSignal changed the name of the xerogel to NANOGLASS E and entered into research collaboration with General Electric and Armstrong to explore the use of xerogels as a heat insulator in other, non-semiconductor applications.



NANOGLASS™ gapfill: 0.15 micron, 6:1 aspect ratio

Figure 1. Cross section scanning electron micrograph of the dielectric insulator NANOGLASS filling the gaps between aluminum interconnects. The “bubbly” appearance of the NANOGLASS is due to embedded air.

Currently, as market pressures dictate that circuits continue to grow smaller and faster, copper wiring is the clear choice for use in semiconductors. At some point in the near future, however, the dielectrics in use today will be obsolete due to the trend toward miniaturization. To address this eventuality, many in the semiconductor industry, including Honeywell, Texas Instruments, NanoPore, and other semiconductor companies, have refocused on xerogels to try to adapt them for use with copper wiring. As of 2004, due to poor sales, Honeywell abandoned the NANOGLASS E material that it sold briefly as a manufacturing material for semiconductor insulators.

Team Shared Project Knowledge

Texas Instruments and NanoPore published their project-related information in two professional journals, gave presentations at a number of industry conferences, and disclosed knowledge they learned from this ATP-funded project in 24 patents. In addition, some knowledge from the project was disseminated to suppliers such as AlliedSignal, DuPont, and W.L. Gore.

Conclusion

Texas Instruments and NanoPore tested polymers and aerogels in order to develop a new material that could be used in semiconductors to reduce crosstalk and to improve transmission speed. The aerogel product demonstrated early superiority, while the polymer development process for use in semiconductors was fraught with problems and was eventually abandoned.

After the partners discovered a process to apply and dry aerogel at a commercially acceptable speed, a new aerogel called xerogel was created. At the conclusion of the ATP-funded project, their teaming arrangement grew into a joint venture that produced a product, NANOGLASS, which was later purchased and refined into NANOGLASS E by Honeywell. The company sold this product briefly for use as a dielectric with copper interconnects and nonsemiconductor applications. By 2004, however, Honeywell discontinued selling the material due to poor sales.

PROJECT HIGHLIGHTS
Texas Instruments Inc.

Project Title: New Materials to Speed Signal Transfer in Integrated Circuits

Project: To integrate new dielectric materials (amorphous Teflon or silicon-dioxide-based xerogel) adjacent to on-chip interconnects in order to overcome problems with interconnect delay as a result of the continuing trend toward miniaturization.

Duration: 3/1/1995 - 2/28/1998
ATP Number: 94-01-0221

Funding (in thousands):**

ATP Final Cost	$1,629	37%
Participant Final Cost	$2,742	63%
Total	$4,371	

Accomplishments: With ATP funding, Texas Instruments accomplished the following:

- Generated a large amount of information on the use of aerogels to insulate aluminum semiconductor wiring.

- Developed and put in production the world's first fully automated aerogel processing system. The system enabled certain types of aerogels, known as xerogels, to be produced in 1 to 2 minutes rather than the typical 90 minutes.

NanoPore continued to develop xerogels for use with aluminum semiconductor wiring, first through a agreement with Texas Instruments and then by teaming with AlliedSignal. Currently, several semiconductor companies are selling xerogel materials for integrated circuits (IC) dielectrics. Even though the semiconductor industry is moving toward copper wiring, Texas Instruments and NanoPore's xerogel research will have future applications.

Texas Instruments and NanoPore representatives delivered presentations on the ATP-funded technology at a number of conferences between 1995 and 1997 and published two papers in the MRS Bulletin in 1997. In addition, Texas Instruments received the following 24 patents for technologies related to the ATP-funded project:

- "Porous dielectric material with improved pore surface properties for electronics applications"
(No. 5,523,615: filed June 7, 1995, granted June 4, 1996)

- "Porous composites as a low dielectric constant material for electronics applications"
(No. 5,561,318: filed June 7, 1995, granted October 1, 1996)

- "Porous dielectric material with improved pore surface properties for electronics applications"
(No. 5,723,368: filed June 7, 1995, granted March 3, 1998)

- "Low dielectric constant material for electronics applications"
(No. 5,789,819: filed June 7, 1995, granted August 4, 1998)

- "Method of making a low dielectric constant material for electronics"
(No. 5,804,508: filed October 23, 1996, granted September 8, 1998)

- "Glycol-based method for forming a thin-film nanoporous dielectric"
(No. 5,736,425: filed November 14, 1996, granted April 7, 1998)

- "Rapid aging technique for aerogel thin films"
(No. 5,753,305: filed November 14, 1996, granted May 19, 1998)

- "Polyol-based method for forming thin film aerogels on semiconductor substrates"
(No. 5,807,607: filed November 14, 1996, granted September 15, 1998)

- "Porous dielectric material with improved pore surface properties for electronics applications"
(No. 5,847,443: filed November 14, 1996, granted December 8, 1998)

- "Low volatility solvent-based method for forming thin film nanoporous aerogels on semiconductor substrates"
(No. 5,955,140: filed November 14, 1996, granted September 21, 1999)

- "Limited-volume apparatus and method for forming thin film aerogels on semiconductor substrates"
(No. 6,037,277: filed November 14, 1996, granted March 14, 2000)

** 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
Texas Instruments Inc.

- "Nanoporous dielectric thin film surface modification"
(No. 6,063,714: filed November 14, 1996, granted May 16, 2000)

- "Aerogel thin film formation from multi-solvent systems"
(No. 6,130,152: filed November 14, 1996, granted October 10, 2000)

- "Stress relief matrix for integrated circuit packaging"
(No. 5,894,173: filed November 5, 1997, granted April 13, 1999)

- "Metallization method for porous dielectrics"
(No. 6,156,651: filed December 10, 1997, granted December 5, 2000)

- "Integrated circuit dielectrics"
(No. 6,059,553: filed December 17, 1997, granted May 9, 2000)

- "Porous dielectric material with improved pore surface properties for electronics applications"
(No. 6,140,252: filed May 5, 1998, granted October 31, 2000)

- "Integrated circuit dielectric and method"
(No. 6,008,540: filed May 28, 1998, granted December 28, 1999)

- "Integrated circuit dielectric and method"
(No. 6,351,039: filed May 28, 1998, granted February 26, 2002)

- "Polyol-based method for forming thin film aerogels on semiconductor substrates"
(No. 6,171,645: filed July 15, 1998, granted January 9, 2001)

- "Stress relief matrix for integrated circuit packaging"
(No. 6,096,578: filed January 21, 1999, granted August 1, 2000)

- "Integrated circuit dielectric and method"
(No. 6,265,303: filed November 9, 1999, granted July 24, 2001)

- "Nanoporous dielectric thin film formation using a post-deposition catalyst"
(No. 6,319,852: filed January 20, 2000, granted November 20, 2001)

- "Aerogel thin film formation from multi-solvent systems"
(No. 6,437,007: filed April 14, 2000, granted August 20, 2002)

Commercialization Status: In 2001, NANOGLASS LLC, a subsidiary of Honeywell and formerly a 50/50 joint venture between Honeywell/AlliedSignal and NanoPore, successfully integrated copper and NANOGLASS xerogel. This material for manufacturing was sold briefly as NANOGLASS E. Its development is directly traceable to the ATP-funded research performed during this project. As of 2004, the product is no longer offered due to poor sales.

Outlook: The outlook for the product developed during this project remains weak. Although the project succeeded technically, the technology was surpassed in the second year of the project by competing technology that uses copper instead of aluminum. The ATP-funded technology has been transferred to Honeywell, which sold it briefly as a dielectric material for use with manufacturing semiconductor interconnects of copper.

Composite Performance Score: * *

Company:
Texas Instruments Inc.
13536 N. Central Expressway
MS 147
Dallas, TX 75265

Contact: David Denker
Phone: (972) 995-3333

Subcontractor:
NanoPore Corporation
Albuquerque, NM

Publications: Company representatives published the following articles related to the project research:

- Jin, Changming, J.D. Luttmer, Douglas M. Smith, and Teresa A. Ramos. "Nanoporous Silica As An Ultralow-k Dielectric," MRS Bulletin, 22:10, 61, 1997.

- List, R. Scott, Abha Singh, Andrew Ralston, and Girish Dixit. "Integration of Low-k Dielectric Materials Into Sub-0.25-μm Interconnects," MRS Bulletin, 22:10, 61, 1997.

Research and data for Status Report 94-01-0221 were collected during January - February 2004.

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	-