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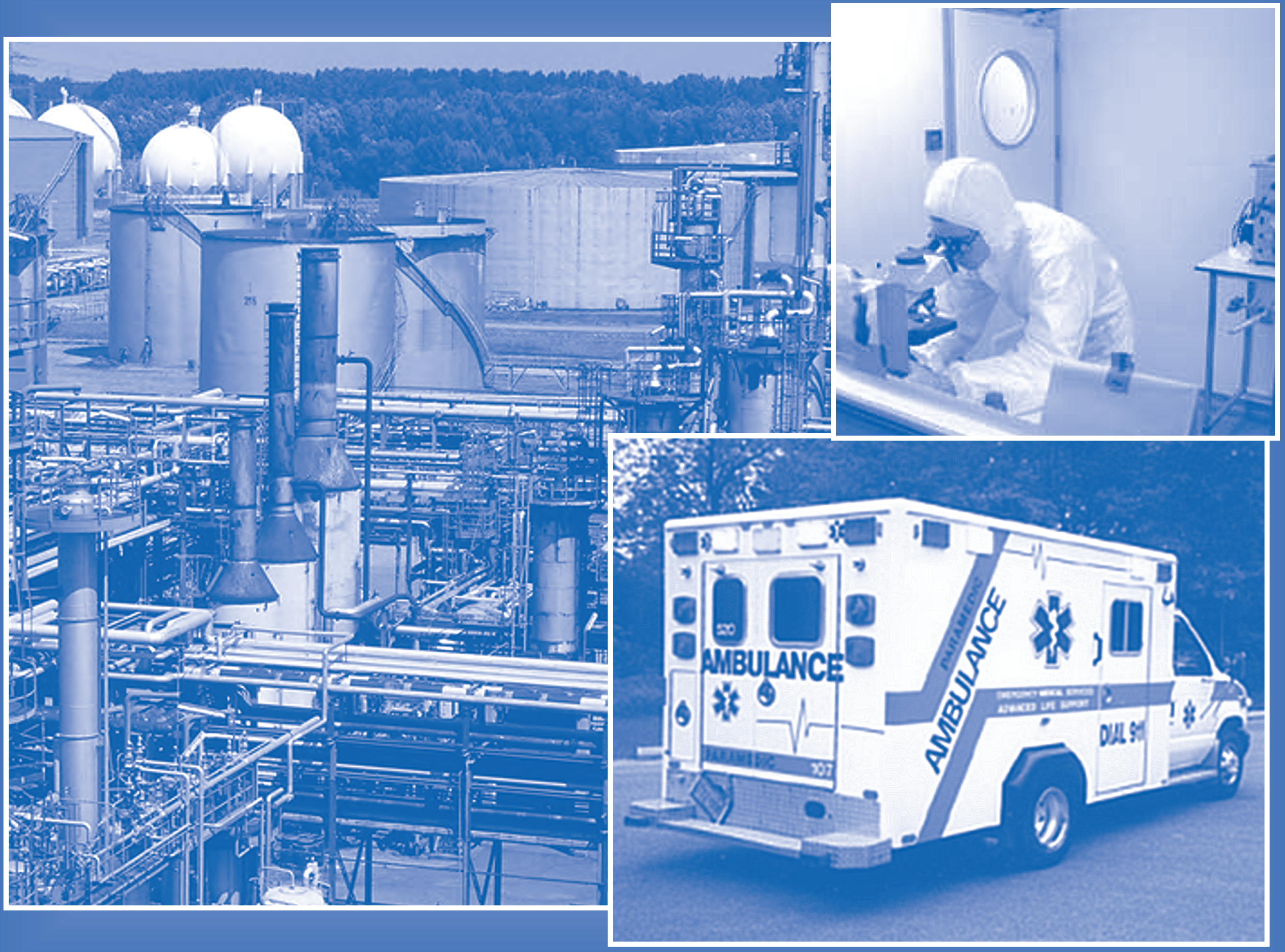
Photonics Technologies:

Applications in Petroleum Refining, Building Controls, Emergency Medicine, and Industrial Materials Analysis

Thomas M. Pelsoci



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Photonics Technologies:
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Economic Analysis of a Cluster of ATP-Funded Projects

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Abstract

Photonics technologies bring together advances from optics and electronics to enhance U.S. competitiveness through high-performance manufacturing processes, metrologies, and new products. As an enabling technology, photonics facilitates new capabilities and cost savings with broad implications for future growth in manufacturing, energy, medicine, and other sectors.

While U.S. photonics companies tend to be successful in specialized, high-performance, niche markets, they have been less successful in markets requiring mass production. The Advanced Technology Program (ATP), recognizing the potential for broad-based economic benefits from enhancing the manufacturing capabilities of U.S. photonics companies, has provided cost-sharing funding for photonics projects since its inception in 1990. Projects focused on new design tools, metrologies, and fabrication methods for mass production.

To assess the economic benefits from the ATP-funded photonics projects, a cluster study approach was used to combine the methodological advantages of detailed case studies and of higher level overview studies. Five projects were selected for analysis, spanning applications in such sectors as industrial materials analysis, petroleum refining and distribution, medicine, and building controls. Two projects with the best near-term commercial prospects were selected for detailed case studies.

The cluster study was based on primary research and analysis and identified important benefits from ATP's investment in the five photonics projects. One important benefit includes preventing an estimated 112,000 deaths of trauma victims and of critically ill patients in transit to emergency rooms over a 10-year period. Other benefits include increasingly efficient industrial materials analysis, facilitating accelerated development of advanced materials for new industrial products, the near real-time detection of trace-level sulfur contaminants in petroleum refining and distribution, cost savings from avoided post-emergency medical treatment, and energy savings in commercial office buildings.

Performance metrics based on projected benefit cash flows are:

- Benefit-to-cost ratios on ATP's investment ranging from 33:1 to 41:1
- Net present value of ATP's investment ranging from $276 to $345 million
- Public (internal) rates of return on ATP's investment ranging from 48 to 51 percent

These measures reflect estimated benefits to industry users and the general public, excluding benefits to direct recipients of ATP funding.

There were additional qualitative benefits, including reduced risk of emergency room infections, reduced harmful diesel emissions, and improved occupant productivity in commercial office buildings.

It is clear from this research that ATP's industry partners would not have developed high-risk, low-cost photonics technologies without the ATP cost-share, and technological advances, associated market opportunities, and resultant public benefits would not have been realized.

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Executive Summary

Photonics is a class of enabling infrastructure technologies that promises broad economic benefits by bringing together technical advances from optics and electronics to develop high-performance manufacturing processes, ultra-high-sensitivity metrologies, and new products.

Historically, U.S. photonics companies, despite a strong base in fundamental research and basic photonics technologies, tended to be financially successful when exceptional performance was critical and where market sizes were small. U.S. photonics companies are apt to be less successful when efficient mass production is required.

Recognizing the potential for broad-based economic impact from reversing these tendencies, the Advanced Technology Program (ATP) has provided cost-sharing funding for more than 120 photonics projects from the time of its inception in the early 1990s, focusing on:

- Developing photonics design tools
- Miniaturizing and integrating opto-electronic macrosystems
- Developing photonics-based metrologies for ultra-sensitive measurements
- Progressing toward cost-efficient, high-quality photonics fabrication, at scales approaching mass production

To assess the economic benefits from a portion of ATP-funded photonics projects, a cluster study approach was used to combine the methodological advantages of detailed case studies and of higher level overview studies. By using this hybrid analytical approach, the following five projects were selected for analysis:

- Capillary Optics for X-Ray Focusing and Collimating (X-Ray Optical Systems, Inc.)
- MEMS-Based Infrared (Photonic Crystal) Micro-Sensor for Gas Detection (Ion Optics, Inc.)
- Infrared Cavity Ring-Down Spectroscopy (Picarro, Inc.)

- Optical Maximum Entropy Verification (Physical Optics Corporation)
- Integrated Micro-Optical Systems (Digital Optics Corporation)

Though the five projects were not intended to be representative of ATP's total investment in photonics technologies, they did span a broad range of applications including industrial materials analysis, petroleum refining and distribution, medicine, and building controls. From initial examination, these projects appeared to have achieved important technical accomplishments and made considerable progress toward full commercialization.

Two projects that showed actual commercial deployment or highly probable, near-term prospects for commercial deployment and substantial associated economic benefits were singled out for case studies: Capillary Optics for X-Ray Focusing and Collimating, with application in the petroleum, materials analysis, and semiconductor sectors; and MEMS-Based Infrared (Photonic Crystal) Micro-Sensor for Gas Detection, with initial application in measuring CO_2 levels in emergency medicine and commercial building controls.

Detailed case studies for these two projects were conducted to identify key technical accomplishments, to identify pathways to market, and to quantify clinical benefits, energy saving benefits, and efficiency benefits.

This report describes the results of those two case studies and the results of higher level analyses for three additional photonics projects. Data collection and analysis were started in 2004 and completed in early 2005.

Case Study: Capillary Optics for X-Ray Focusing and Collimating

X-Ray Optical Systems, Inc., of East Greenbush, NY, used ATP cost-share to develop high transmission efficiency optics using tiny capillary glass tubes to guide and focus X-rays. The project led to fully commercial optical products used as performance-enhancing components in industrial materials analysis as well as optical components in industrial process sensors to detect trace-level contaminants in petroleum refining and distribution.

Public benefits to industry users and the general public from this ATP cost-shared project were quantified on the basis of conservatively estimated unit sales estimates of up to 300 performance-enhancing X-ray optics and process sensors each year. Private benefits to X-Ray Optical Systems were excluded.

Public returns from this project on ATP's investment over a 20-year period (1994–2014) indicate net present values ranging from $184 to $233 million and benefits of $75 to $94 for every dollar invested. Retrospective benefit analysis alone, over the 1994–2003 period, indicates a realized net present value of $7.40 million and realized benefit-to-cost ratio of $4 of public benefits for every dollar invested by ATP.

These economic performance metrics reflect cost savings from the use of X-ray optics in industrial materials analysis, as well as in energy savings and corresponding cost savings at U.S. petroleum refineries and distribution systems.

Case Study: MEMS-Based Infrared Micro-Sensor for Gas Detection

Ion Optics, Inc., of Waltham, MA, used ATP cost-share to develop photonic crystal sensors that could be tuned to accurately, reliably, and inexpensively measure CO_2 levels (the first target gas for which this technology is commercially viable) in the expired breath of emergency room patients and in commercial office buildings.

Commercial production of photonic crystal CO_2 sensors is targeted for 2006 with annual sales over the next 10 years expected to ramp up to 400,000 units for emergency medicine and up to 290,000 units for commercial building controls.

Medical use of photonic crystal CO_2 sensors over the next 10 years has the potential to prevent an estimated 112,000 deaths of trauma victims and of critically ill patients on their way to U.S. emergency rooms.

In addition, cost savings from avoided medical treatments, as well as energy savings (and associated cost savings) from commercial building control systems, are projected to result in net present values ranging from \$143 to \$175 million and public benefits of \$174 to \$212 for every dollar invested.

CLUSTER ANALYSIS

Based on primary research and analysis, quantitative economic benefits from the two case study projects alone as compared to ATP investments in the cluster of five photonics projects point to high public returns, including:

- Benefit-to-cost ratios on ATP's cluster investment ranging from 33:1 to 41:1 (base case versus step-out scenarios in 2004 dollars)
- Net present value of ATP's cluster investment ranging from \$276 to \$345 million
- Public (internal) rates of return on ATP's cluster investment ranging from 48 to 51 percent

- 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.
- Some benefits from ATP technology investments have already been realized, with \$1.90 of realized public benefits having been generated for every dollar of ATP's investment in the cluster of five projects.

In addition, the cluster study identified a number of qualitative public benefits (some of which may also be quantified at some future date), including reduced risk of post–emergency room infections, reduced harmful diesel emissions, improved occupant productivity in commercial office buildings, and accelerated development of advanced materials for new industrial products.

The social rate of return is an alternative, broader performance measure of the combined public and private returns. Estimates range from 43 to 51 percent and point to significant spillover gaps (the difference between the social rate of return and private returns), indicating that the value of the projects to the general public is significantly greater than their value to the companies receiving public cost-share funding.

CONCLUSIONS

It is clear from the research performed for this study that ATP's industry partners would not have developed high-risk, low-cost photonics technologies without the ATP cost-share. Technological advances, associated market opportunities, and resultant public benefits would not have been realized.

The analysis also took into account other public investments, notably from the National Science Foundation, in one of the two case study projects. Appropriate attribution for public benefits from other federal science and technology funding sources was made.

The resulting performance metrics presented in this Executive Summary and summarized in Table ES-1 specifically show the exceptional performance of ATP's investment in selected photonics projects, demonstrated via high public rates of return, quantified medical benefits, and important qualitative benefits. As other ATP-funded photonics technologies reach the marketplace, further benefits from this project cluster and from other photonics projects are expected, and improvements in performance metrics can be anticipated.

Table ES-1: Public Benefits from ATP's Investment in Cluster of Five Photonics Projects

Quantitative Benefits

- Preventing an estimated 112,000 deaths of trauma victims and critically ill patients on their way to U.S. emergency rooms during the next 10 years

- Public benefits of $1.90 realized to date for every dollar of ATP's $7.47 million cost-share

- Public benefits of $33 for every dollar of ATP's $7.47 million cost-share (from additional efficiencies in laboratory materials analysis, petroleum refining and distribution, emergency health care services, and commercial heating and air conditioning systems) are expected to be realized during the 1994 through 2014 study period.

Qualitative Benefits

Capillary Optics for X-Ray Focusing and Collimating

- Improved U.S. petroleum refinery and pipeline compliance with challenging EPA ultra-low sulfur diesel regulations and decreasing harmful diesel emissions
- Accelerated development of advanced materials for new industrial products

MEMS-Based Infrared Micro-Sensor for Gas Detection

- Reduced patient risk from post–emergency room infections
- Improved commercial office space internal air quality and occupant productivity

Other ATP-funded photonics projects in cluster

- Reduced product counterfeiting and identity theft through low-cost optical authentication
- Increased manufacturing efficiencies from miniaturizing and integrating optical macrosystems

Cross-Industry Knowledge Diffusion

The implementation of new infrastructure, metrology, and product technologies, in combination with licensing and other forms of industrial cooperation, will continue to diffuse new knowledge to other economic agents.

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Abbreviations, Acronyms, and Definitions

ATP	Advanced Technology Program, National Institute of Standards and Technology
BTU	British Thermal Unit
Building ventilation	System of electric fans and ductwork for air circulation
Capillary	Glass tubes with extremely small (micron-scale) diameters and precisely engineered curvature along longitudinal axis
Capnometry	Direct measurement of the maximum expired CO_2 concentration during patient respiratory cycle
Cavity-ring down spectroscopy	Highly sensitive technique for measuring very low levels of contaminant concentrations
Chip	Small piece of semiconducting material with embedded integrated circuit
Collimating	Making parallel beams, such as in parallel X-rays
Colorimetric	Detectors using chemically treated paper that changes color when exposed to agents, such as CO_2 in respired gases
CO_2	Carbon dioxide
CRDS	Cavity ring-down spectroscopy
Critical angle	Angle at which X-rays are reflected from the inside surface of a capillary tube rather than refracted through the surface
Desaturation	Blood oxygen levels dropping below critical levels, potentially leading to brain damage and other fatal complications
Detector	Instrument for the sensing of elements and compounds, without the capability of measuring concentrations
DOE	U.S. Department of Energy

Elemental analysis	Accurate measurement to characterize chemical elements in a sample under investigation
Endotracheal intubation	Placement of a breathing tube into a patient's trachea
Esophagal intubation	Incorrect placement of breathing tube into a patient's esophagus
EPA	U.S. Environmental Protection Agency
ETI	Endotracheal intubation
HVAC	Heating, ventilating, and air conditioning (system)
Hydro-treatment	Petroleum refining process that uses hydrogen and catalysts, under high pressure, to capture and extract sulfur molecules in the form of hydrogen sulfide
IMOS	Integration of miniaturized micro-optical systems
Intubation	Inserting a breathing tube into a patient's esophagus
IOI	Ion Optics, Inc., recipient of ATP cost-share
IR	Infrared
IMOS	Integrated micro-optical systems
Kwh	Kilowatt hour
Mechanical ventilation	Placing patient into a mechanical breathing apparatus to remedy lung damage from misintubation
Metrology	Science of measurement
MEMS	Micro-electromechanical system
Micro-bolometer	Instrument for detecting and measuring small levels of radiation (e.g., visible light, infrared, and ultraviolet radiation)
NDIR	Nondispersive infrared absorption spectroscopy
NIST	National Institute of Standards and Technology
NSF	U.S. National Science Foundation
OEM	Original equipment manufacturer
OIT	Office of Industrial Technologies, U.S. Department of Energy
OMB	U.S. Office of Management and Budget
OMEV	Optical maximum entropy verification
ppb	Parts per billion
ppm	Parts per million

Photonic crystal	Artificially engineered material with a lattice structure (lattice of holes) that repeats itself at regular intervals within a dielectric; photonic crystals can have a photonic bandgap (defined below)
Photonic bandgap	In periodic dielectric structures or photonic crystals, the propagation of electromagnetic waves is blocked over a certain frequency range
Photonics	Integrates technical advances in electronics and optics to generate and control photons (electromagnetic radiation) and use photons to carry information
Sensor	Device that detects and measures a signal or physical condition
Sensor engine	Integrated sensor system, including laser source, X-ray optics, detectors, and read-out electronics for detection of trace amounts of contaminants in industrial processes
SOC	Sensor on a chip
Spectroscopy	Study of electromagnetic spectrum, used in physical and analytical chemistry for the accurate identification of substances
Surface plasmon	Quantum name of an electron density wave
Therm	100,000 BTUs
Transmix	Limited mixing of adjacent batches at the interface between different petroleum products moving through distribution pipelines; specifically, transmix are off-spec products that require reprocessing or downgrading
ULSD	Ultra-low sulfur diesel with less than 15 ppm sulfur content
VAV	Variable air volume HVAC system
Wafer	Thin, circular slice of single-crystal semiconductor materials used in manufacturing of semiconductor devices and integrated circuits
Wheatstone bridge	Instrument used to measure unknown electrical resistance
XRD	X-ray diffraction
XRF	X-ray fluorescence
XOS	X-Ray Optical Systems, Inc., recipient of ATP cost-share
Yield	Ratio of functionally working devices to the total number of devices produced

1. Introduction

The Advanced Technology Program (ATP), National Institute of Standards and Technology (NIST), fosters partnerships among government, industry, and academia by co-funding innovative, high-risk research to develop enabling technologies that promise broad economic benefits for the nation.

Photonics (opto-electronics) comprises a class of enabling infrastructure technologies that bring together technical advances from optics and electronics with significant potential for fostering economic growth and increased societal well being.

Photonic devices are used for generating, modulating, guiding, amplifying, and detecting optical radiation across the electromagnetic spectrum and have broad implications for industrial growth and productivity across the U.S. economy, including manufacturing, health care, entertainment, information technology, telecommunications, and homeland security.

U.S. photonics companies, despite a strong base in fundamental research and basic photonics technologies, have historically tended to be financially successful when exceptional performance was critical (military and other high-performance applications) and where market sizes were small. U.S. photonics companies are apt to be less successful when efficient mass production is required.

Given the characteristic limitations of U.S. photonics firms and a potential for broad-based economic impact, the ATP has funded more than 120 photonics-related projects from the time of its inception in the early 1990s through 2004. To enhance U.S. competitiveness, ATP funded projects have tended to focus on:

- Developing advanced simulation and modeling tools for the design of high-performance photonics products
- Miniaturizing and integrating opto-electronic macrosystems
- Developing advanced metrologies for trace-level detection on a near-real-time basis

- Progressing toward cost-efficient, high-quality fabrication methods at scales approaching mass production

CLUSTER STUDY OBJECTIVES AND SCOPE

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

To assess the economic benefits from the ATP-funded photonics projects, a cluster study approach was used to combine some of the methodological advantages of detailed case studies and of higher level overview studies.

A cluster of five projects was selected for analysis:

- Capillary Optics for X-Ray Focusing and Collimating (X-Ray Optical Systems, Inc.)
- MEMS-Based Infrared (Photonic Crystal) Micro-Sensor for Gas Detection (Ion Optics, Inc.)
- Infrared Cavity Ring-Down Spectroscopy (Picarro, Inc.)
- Optical Maximum Entropy Verification (Physical Optics Corporation)
- Integrated Micro-Optical Systems (Digital Optics Corporation)

This cluster of projects spanned applications in industrial materials analysis, petroleum refining and distribution, semiconductor fabrication, emergency medicine, and building controls and included only projects where ATP-funded technical tasks were completed. Data collection and analysis were started in 2004 and completed in early 2005. One project, Capillary Optics for X-Ray Focusing and Collimating, with application in the petroleum, materials analysis, and semiconductor sectors, has realized economic benefits to date, with more significant benefits yet to come. A second project, MEMS-Based Infrared Micro-Sensor for Gas Detection, has near-term commercial prospects with identifiable economic benefits for U.S. industry and society. The remaining three projects are at varying stages of commercial development, and benefits at this time are somewhat less certain and less quantifiable. These three projects were assessed on a qualitative basis. Future economic analysis may determine that their benefits may also be captured and quantified.

FIVE PROJECTS IN THE CLUSTER STUDY

Each of the five projects in the cluster involved a single-company awardee that was either a startup or operated as a standalone small business. One ATP partner had important informal relationships with a regional university. None of the projects included an industrial joint venture or formal collaborative structure.

In addition to high-risk technology and product development, the companies engaged in contract research to generate some revenue. After the successful completion of ATP-funded high-risk technology development projects, in some instances, significant financial resources were raised from venture capital groups and from industry investors.

Capillary Optics for X-Ray Focusing and Collimating

X-Ray Optical Systems, Inc., of East Greenbush, NY, used its ATP cost-share to develop high-performance computational and design methods and efficient, high-quality fabrication methods for tiny capillary glass tubes to guide X-rays with high transmission efficiencies. The project was based on the physical principles of special optics for guiding X-rays that were discovered in the Soviet Union during the early 1960s.

Research resulted in transitioning X-ray focusing and collimating optical lenses from the status of laboratory curiosity to performance-enhancing components for industrial materials analysis and for the detection of trace-level contaminants in industrial processes.

Commercial production of capillary optics for laboratory materials analysis started in the late 1990s. Economic benefits have been realized by downstream industries and by consumers of products incorporating advanced materials. In addition, newly designed integrated sensor engines incorporating X-ray optics were being deployed as of late 2004 and are expected to result in substantial economic benefits and reduced environmental pollution from lower diesel emissions.

MEMS-Based Infrared (Photonic Crystal) Micro-Sensor for Gas Detection

Ion Optics, Inc., of Waltham, MA, cost-shared with ATP to develop photonic crystal sensors that could be tuned to accurately, reliably, and inexpensively measure CO_2 levels in the expired breath of emergency room patients and in commercial office buildings. The ATP award built upon the results of prior National Science Foundation (NSF)–funded research.

Subsequent to the successful completion of the ATP-funded project, Ion Optics obtained three rounds of venture capital financing totaling $8.2 million.

Production of photonic crystal CO_2 sensors is targeted for 2006, and the commercial-scale use of CO_2 sensors is expected to result in preventing in-transit mortalities and leading to emergency room treatment savings. This same technology will also reduce energy use and increase occupant productivity in commercial office buildings.

Infrared Cavity Ring-Down Spectroscopy

With ATP cost-share as well as with U.S. Department of Energy (DOE) funding (subsequent to the ATP award), Picarro, Inc., developed a high-performance near-infrared cavity ring-down spectroscopy system for ultra-sensitive contaminant detection (in the parts per billion range) for clean room applications, for petrochemical processing, and for the development of advanced, ultra-clean diesel engines. The ATP-funded project also led to a sixfold size reduction of large and cumbersome laboratory instrumentation.

The successful completion of the ATP- and DOE-funded projects was followed by several rounds of private equity financing (in 2003 and 2004) that will be used to support an effective marketing program to gain customer acceptance and to implement manufacturing ramp-up to commercial production levels by the end of 2007.

Optical Maximum Entropy Verification

Physical Optics Corporation of Torrance, CA, cost-shared with ATP to develop a laser-based system to generate random optical patterns to be affixed to product labels. The authenticity of product labels could then be verified by comparing labels with a reference mask in an optical reader with randomized optical signatures, in real time, without the need for human interaction or a centralized database.

The project was successfully completed and then licensed to OptiKey LLC, which is currently marketing the technology under the brand name of OptiKey Optical Authenticity Verification System. OptiKey LLC expects to complete commercial proof of concept in 2006.

Integrated Micro-Optical Systems

Digital Optics Corporation of Charlotte, NC, developed processes for wafer-scale integration of miniaturized micro-optical systems (IMOS) consisting of lasers, optics, detectors, and electronics to be aligned and assembled into a complex, three-dimensional microsystem. The project positions the IMOS technology toward becoming an optical counterpart of integrated circuits, shrinking down from expensive macroscopic optical systems to inexpensive and compact photonic chips.

Digital Optics is currently developing IMOS-based commercial products for various industry applications, including telecommunications and data storage. Subsequent to the ATP award, the company received two venture capital equity infusions totaling $45 million, some of which was used to build a 100,000 square foot manufacturing facility.

2. Analytical Framework and Methodology

ANALYTICAL FRAMEWORK

This study uses microeconomic, cash flow-based case study methodology to generate an objective assessment of broad-based economic benefits relative to investment costs. The framework includes both in-depth case study evaluation of individual ATP-funded projects and a broader, higher level, multi-project portfolio, or cluster approach. This hybrid approach yields quantitative measures of project and portfolio performance familiar to the financial and economic communities—net present value, benefit-to-cost ratio, and internal rate of return—as well as qualitative descriptions of other non-quantified benefits.

Cluster Approach: Case Studies and Overview Studies

The cluster approach used in this study is a hybrid of two traditional approaches for evaluating the benefits of publicly funded science and technology programs: detailed case studies of individual projects and overview studies of many projects.

- *Detailed case studies* are used to generate rich insights into complex causal chains from innovation to market pathways to public benefits. Based on an understanding of causal chains and industry dynamics, case studies can be used to develop cash flow estimates of the value of technology innovations.

- *Overview studies* of many projects identify observable trends in the flow of public benefits from technology innovations, without developing detailed information about specific technologies, industry, and market factors. While overview studies can provide useful general information about the benefits of technology innovation, they do not generally lend themselves to developing quantitative benefit time series.

The hybrid approach helps to realize the advantages of both detailed case studies and multi-project overview studies while avoiding their limitations.

Public and Private Benefits

For purposes of evaluating the performance of publicly funded science and technology projects, the benefits of technology innovation can be segmented with reference to different classes of beneficiaries.

- *Private benefits*: Economic benefits enjoyed by the innovating firms funded on a cost-share basis with the ATP (or another public agency) are considered private benefits. The innovating firm's expectation that these private benefits (profit contribution from new technologies) will be realized is a necessary precondition for completing remaining technical development tasks (after the successful completion of the ATP-funded project phase) and for undertaking subsequent commercialization to facilitate economic and social benefits from ATP-funded technology projects.

- *Public benefits*: Economic and social benefits arising from the ATP-funded technologies and enjoyed by downstream industrial firms and end users of industrial products are considered public benefits. In microeconomic terms, public benefits represent spillover phenomena, where the degree of spillover represents that portion of total benefits that the innovating firm is unable to capture for itself (Jaffe, 1996). As suggested by both the theoretical and empirical economics literature, public benefits, or the extent of spillover from ATP's investment, can be expected to substantially exceed the magnitude of private benefits (Mansfield et al., 1977).

In addition to economic benefits for industrial users (eventually allocated among producers and consumers based on market forces), many important public benefits have a *public goods* quality that society will enjoy directly. Examples include:

- Reduced harmful environmental emissions
- Improved clinical outcomes for medical patients
- Conservation of scarce energy resources
- Knowledge diffusion about new technologies

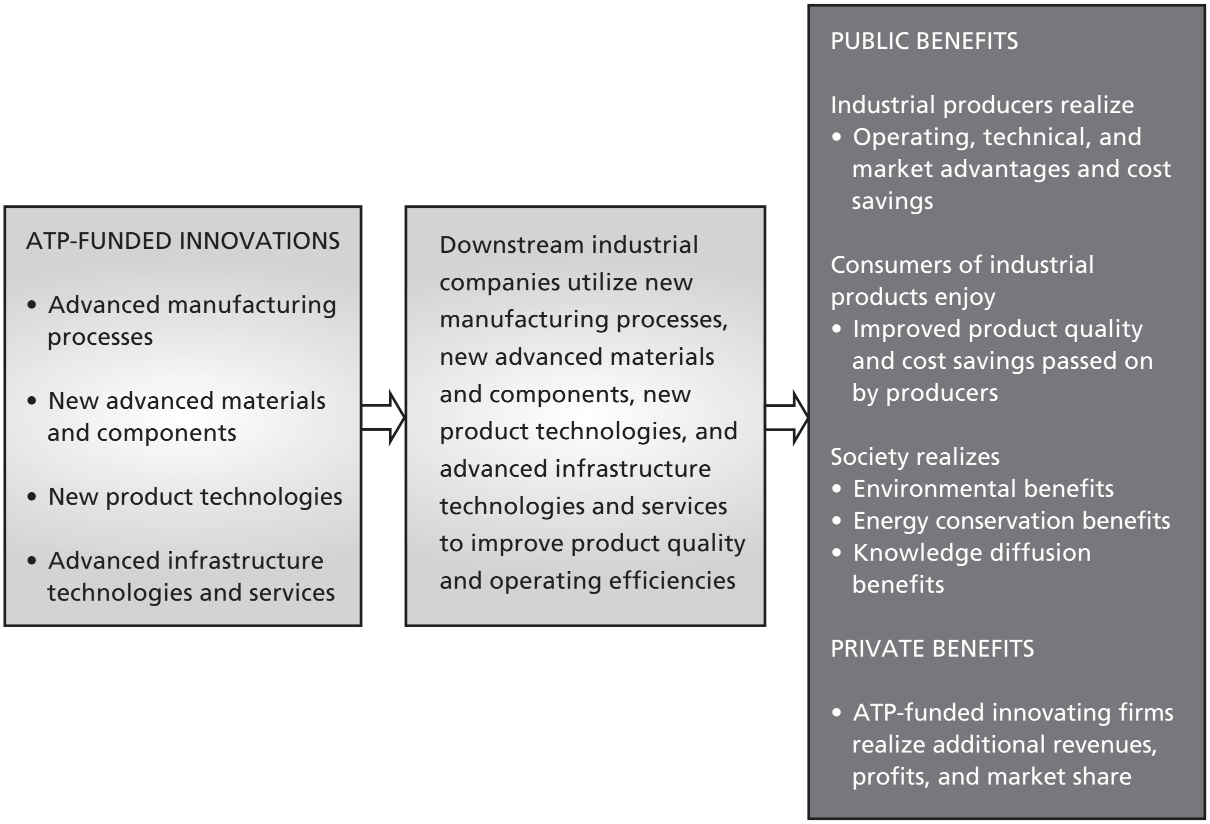
The flow of public and private benefits to different classes of beneficiaries is illustrated in Figure 1. This model is sufficiently general that it could be applied to many federal science and technology evaluation efforts across different agencies operating under a range of science and technology missions.

Retrospective versus Prospective Benefits

The temporal placement of benefits is an additional important variable for science and technology benefit analysis, and the cluster study utilizes retrospective as well as prospective analysis, as appropriate.

- *Retrospective benefits*: Realized benefits (to date), identified on the basis of well-documented analysis, involve less uncertainty and can lead to higher levels of

Figure 1: Flow of Public and Private Benefits from ATP-Funded Technologies



confidence in the analytical results of science and technology impact studies than prospective future benefit estimates.

- *Prospective benefits*: Expected future benefits are typically associated with a variety of risks and uncertainties, including market introduction, consumer acceptance, and manufacturing ramp-up. While these risks and uncertainties may be mitigated through various means, including documented expressions of interest from potential customers, prototype sales, rigorous market studies, as well as reasonable expectations of near-term commercialization, the inherent uncertainties of prospective analysis necessitate the use of expected value constructs, where first-order benefit estimates are scaled down with consensus-based probability estimates.

Benefits Resulting from ATP Investments

The central objective of this cluster study is to gauge the programmatic impact of rigorously screened and well-timed ATP investments. This requires a fair assessment of the portion of public returns attributable to the ATP.

To this end, benefit analysis includes a consideration of the contributions of other sources of public and private funding to ultimate benefits. As an example, ATP-funded high-risk technology projects may be preceded by basic and applied research projects funded through the NSF or other U.S. agencies. Alternatively, agency funding for subsequent technology and product development may be put in place after an ATP cost-shared project is completed. In either case, a series of sequential investments by the ATP and other agencies will tend to enhance the value of prior investments relative to the technology's potential to generate economic and social benefits.

The appropriate attribution to ATP will depend on specific circumstances of each case, reflecting the relative importance as well as the size and timing of ATP and other investments. In general, benefits attributable to ATP represent the increment over the counterfactual situation where ATP funds were not made available to support the specific project.

BENEFIT-COST ANALYSIS METHODOLOGY

Two projects were selected for in-depth case studies to document project history, including an account of the need for ATP funding, the characterization of technical challenges and accomplishments, opportunities for commercial applications, pathways to markets, and an identification of all expected benefits, both public and private.

For those benefits that can be meaningfully quantified, cash flow estimates are generated for a conservative base-case scenario and for a more optimistic step-out scenario, incorporating higher unit sales projections and higher per unit benefit estimates, as appropriate. Economic losses to defender technologies being displaced by new ATP-funded photonics technologies are estimated and subtracted from cash flow benefit estimates to arrive at net benefits.

The focus in this report is to gauge ATP's impact and effectiveness through performance metrics that capture the value of public benefits attributable to ATP's investment. Benefit cash flow estimates are compared to investment costs to compute *public benefit performance metrics*, including benefit-to-cost ratios, net present values, and internal rates of return.

Benefit cash flow analysis can also be expanded to include private benefits to the innovating firm as well as all public and private investments to yield a more inclusive and broader measure of *social rate of return*, as described in the box below.

Mini-studies for three additional ATP-funded projects were completed and resulted in the identification of qualitative benefits.

Performance metrics for public returns were computed on the basis of benefit cash flow estimates from the two case study projects against public investments in the five projects. Metrics are conservatively estimated and represent expected lower bounds.

Future economic studies may document and estimate benefit cash flows from the other three projects in the cluster and result in substantial upward adjustments of performance metrics.

In addition, a broader social rate of return was computed for the two individual case study projects.

- *Benefit-to-cost ratio* is computed by dividing the present value of public benefits attributable to ATP (enjoyed by U.S. beneficiaries except the ATP-funded innovator) by the present value of ATP's investment. This measure estimates the benefit to the nation for every dollar of ATP's investment.
- *Net present value* is calculated by subtracting the present value of ATP's investment from the present value of public benefits attributable to ATP from new photonics technologies. Cash flows are normalized to 2004 dollars and discounted at the 7 percent OMB-designated rate (OMB Circular A-94). This measure describes the net total benefit to the nation, in 2004 dollars.
- *Public (internal) rate of return* is calculated by iterative solution for a rate at which the discounted value of ATP's investment equals the discounted value of cash flows attributable to ATP, thus indicating the rate of return to the nation on ATP's investment.
- *Social (internal) rate of return* is a broader, all-inclusive measure of economic and social impact and is calculated by iterative solution for a rate at which the discounted value of all public and private investments equals the discounted value of all cash flows to the innovating firm, to downstream industrial companies, to end-use consumers, and to society.

3. Case Study: Capillary Optics for X-Ray Focusing and Collimating

Accurate, timely analytical information about the chemical composition and crystalline structure of engineering materials is increasingly important for their manufacturability and commercial use. Near-real-time analytical information is also essential for the cost-effective detection of increasingly low concentrations of contaminants in process industries.

In 1992, ATP funded a high-risk technology project to develop capillary optical lenses for hard-to-focus X-rays and neutrons. The successful completion of this project, involving only the focusing and collimating of X-rays, enhanced the analytical performance of laboratory instruments and process control metrology, leading to more effective engineering design practices and improved industrial process controls.

PROJECT HISTORY

More than 50,000 engineering materials are in industrial use, and advanced materials are continually being developed for new product applications. Accurate information about the chemical composition and crystalline structures of engineering materials is critical to their manufacturability and technical performance.

Accurate information about composition and structure can be obtained through X-ray spectroscopy, which measures the absorbed or emitted electromagnetic radiation from material samples. X-ray wavelengths are similar to distances at the atomic scale, leading to ultra-high levels of measurement accuracy.

X-ray diffraction (XRD) and X-ray fluorescence (XRF) are important spectroscopic methods for investigating materials composition and structure. XRD is used for structural analysis, as in degrees of crystallinity, crystal orientation, and material stress. XRD analysis uses collimated or parallel X-rays. XRF is used for chemical composition and thin-film thickness analysis and the detection of trace contaminants. Incident X-rays for XRF analysis are focused.

Prior to the ATP-funded project, high energy X-rays could not be effectively focused or collimated, which limited the measurement accuracy and speed of XRD and XRF instruments.

The physical principles of special optics for guiding X-rays were discovered in the 1960s at the I.V. Kurchatov Institute of Atomic Energy in Moscow, Russia. Despite an understanding of underlying principles, significant technological uncertainties remained before X-ray optics could be effectively used to increase XRD and XRF measurement accuracy and speed in industrial materials analysis and process control.

In 1990, X-Ray Optical Systems, Inc. (XOS), of East Greenbush, NY, was formed to develop commercially viable X-ray optical lenses based on the physical principles discovered at the Kurchatov Institute. Mr. David Gibson, president of XOS, had professional contacts at the Kurchatov Institute and at the Center for X-Ray Optics at the University at Albany, State University of New York, through his father, Dr. Walter Gibson, who was Director of the Center. Dr. Gibson and staff from the Kurchatov Institute served as technical consultants to XOS.

XOS at the time lacked internal financial resources and access to the venture capital community. In 1991, XOS approached the ATP with a proposal to develop methods for the design, fabrication, and testing of X-ray optics. In early 1992, ATP agreed to fund the proposed project, and XOS proceeded with the project in concert with the following collaborators:

- Center for X-Ray Optics at the University at Albany, State University of New York, which conducted radiation damage studies and assessed the impact of surface roughness and waviness on X-ray optical lens transmission efficiencies
- Oak Ridge National Laboratory, which made its micro-focus X-ray fluorescence test site available for testing XOS focusing optics
- INCOM, which assisted in developing part of the early optic manufacturing process.

The ATP-funded project was successfully completed in 1996. XOS began selling optical lenses for collimating and for focusing X-rays on a commercial basis in 1997. The marketing and sales of integrated sensor engines, combining X-ray sources, X-ray optics, detectors, and software, started in 2004.

According to XOS, the ATP provided essential seed capital for the technical development of the high-risk, innovative X-ray optics technology. “Without the ATP, X-ray optics and related sensor engine products could not have been developed, and the resulting benefits to our company and its commercial and industrial customers would not have been realized” (Gibson, 2004).

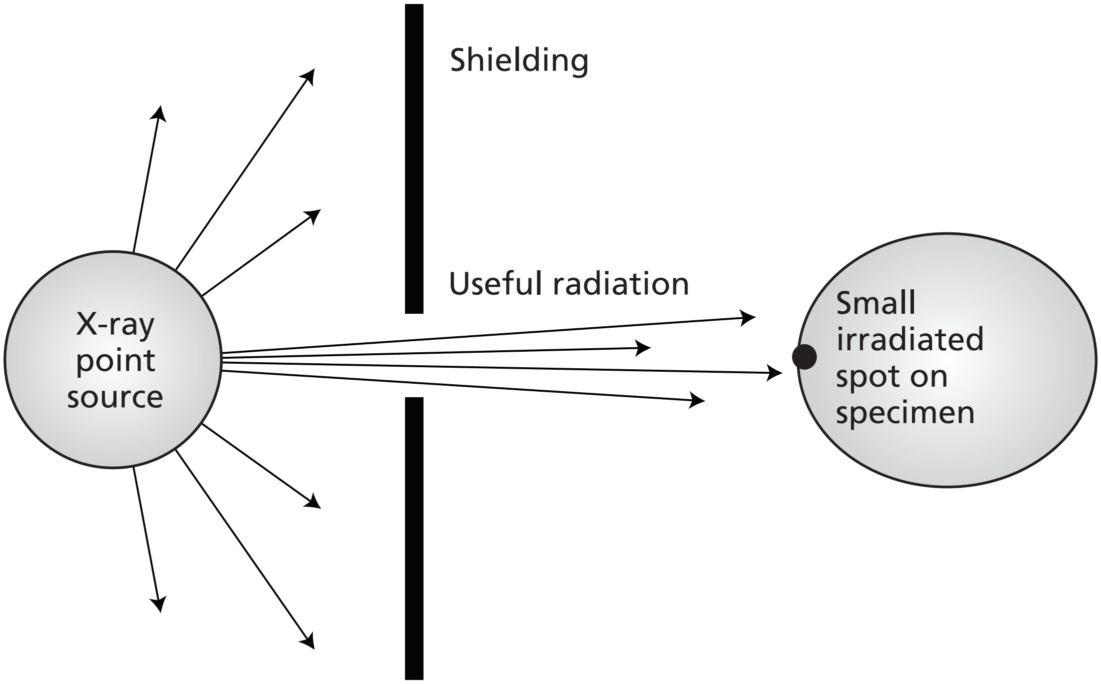
HOW DOES IT WORK?

Metrology systems using X-rays consist of a point source to generate divergent rays over a large angle (Figure 2). The source is enclosed in shielding with apertures allowing the X-rays to pass through and irradiate a small spot on a material specimen.

While beams of visible light can be collimated and focused with optical lenses, X-rays are a penetrating form of electromagnetic radiation and thus cannot be similarly controlled. This property has been an important source of technical limitation for X-ray spectroscopy.

Without X-ray optics, some degree of beam collimation or focusing can still be achieved by varying distances from the X-ray source to the aperture and the sample. However, as beam intensity or the number of X-ray photons that hit their target varies inversely with the square of the distance from the source, an ever decreasing fraction of photons reaches the sample and remains "useful" as distances are increased.

Figure 2: **X-Ray Point Source without Optics**



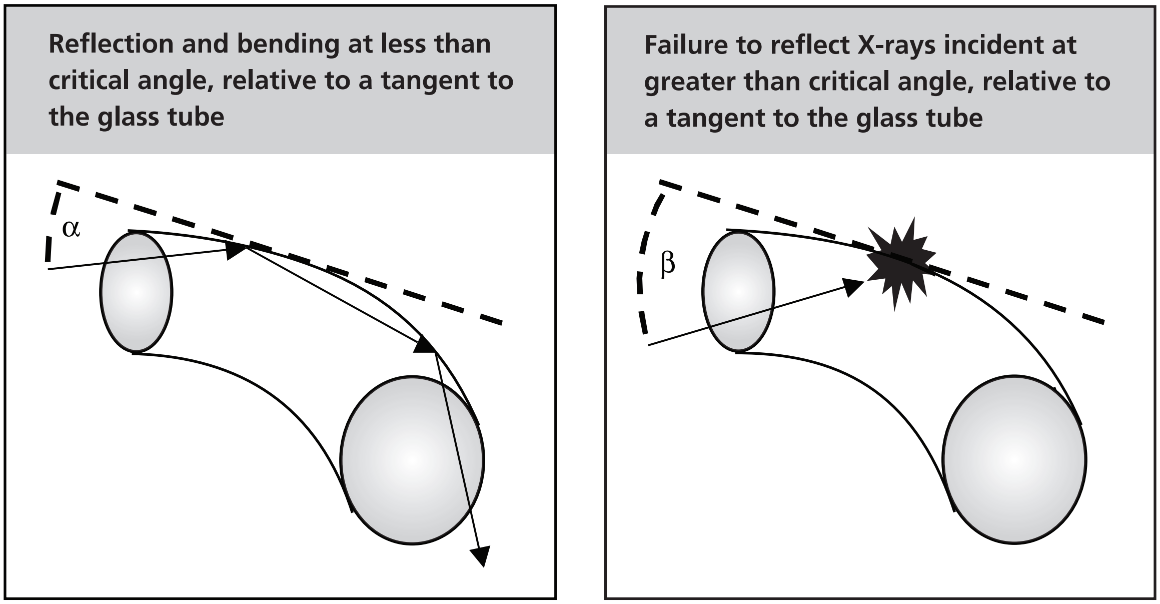
Measurement speed and accuracy are functions of X-ray intensity at the sample. With increasing distances between the source and the sample, X-ray intensity is rapidly degraded, resulting in lower analytical speed and accuracy.

Though many scientists believed that the laws of physics would prevent the more precise collimating and focusing of high energy X-rays, in the late 1980s the I.V. Kurchatov Institute in Moscow developed a laboratory technique for capturing and channeling X-rays utilizing *capillary optics*, or arrays of thin-diameter glass tubes with a slight curvature along the longitudinal axis.

Multiple reflections from the smooth inner walls of capillary tubes can be used to guide X-ray photons. Reflections occur at the boundary between media with different refractive indices (air and glass surfaces) when an X-ray strikes the reflecting glass at a grazing angle smaller than an empirically determined critical angle (α).

If the longitudinal curvature of capillary arrays is kept below a certain limit, many divergent X-rays can be reflected off the inside surface of glass tubes at an angle less than the critical angle (α) and effectively bent and transported along capillary channels (Figure 3). When certain X-rays have an angle of incidence (β) greater than the critical angle, these X-rays will be refracted through the surface of the glass tubes.

Figure 3: **(Left) Internal X-Ray Reflection from Glass Surfaces at Less than Critical Angle and (Right) Incident X-Ray at Greater than Critical Angle**


Reflection and bending at less than critical angle, relative to a tangent to the glass tube

Failure to reflect X-rays incident at greater than critical angle, relative to a tangent to the glass tube

Capillary arrays consist of thousands of tiny, slightly curved glass tubes held together in a frame. Individual glass tubes have varying cross sections over the length of the tube. By arranging the geometry of thousands of capillary channels, X-rays can be collimated. With different geometrical arrangements, X-rays can be focused (Figure 4).

Laboratory research indicated that capillary arrays could potentially:

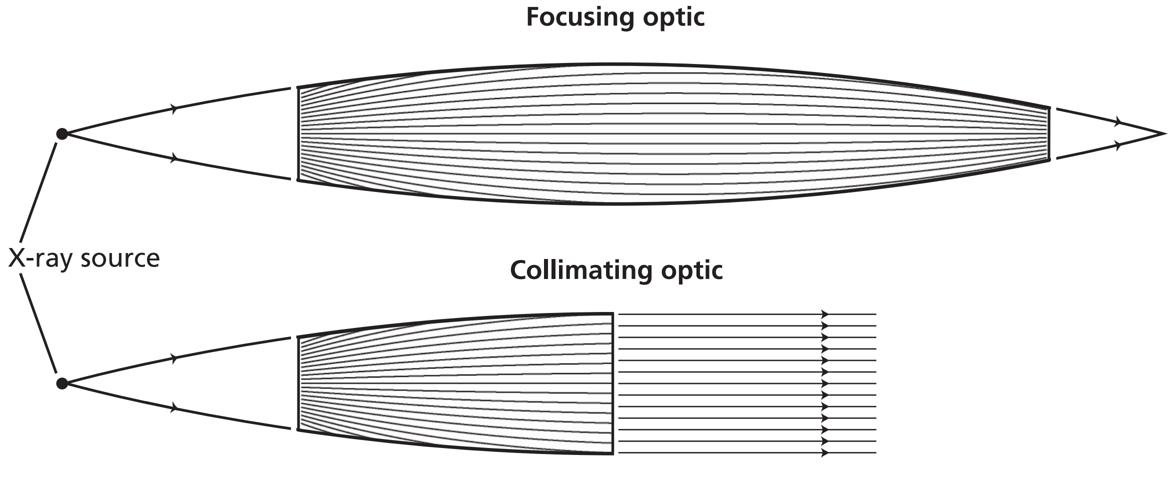
- Capture large angle divergent X-rays from a point source
- Form a convergent beam with orders of magnitude higher intensity
- Form a quasi-parallel beam with low divergence
- Suppress transmission of X-rays at energies above a selected cut-off
- Bend X-ray beams
- Change beam cross sections

If these potential capabilities could be achieved in commercial optical products, the existing design constraints of X-ray spectroscopic instruments could be relaxed and their analytical performance could be substantially improved; that is, new capabilities could facilitate higher throughput, better resolution and sensitivity, increased reliability, and potentially lower cost.

As a practical matter, however, it was expected that capillary optical devices would be very difficult to construct within requisite geometric tolerances and would remain laboratory curiosities, unless significant technical uncertainties could be resolved.

The important remaining technical uncertainties included design procedures, manufacturing control issues, and the long-term reliability of capillary arrays in the presence of ionizing radiation.

Figure 4: **Capillary Optics for Focusing and Collimating X-Rays**



Source: X-Ray Optical Systems, Inc.

To address these issues, XOS proposed a high-risk technology development program to the ATP and obtained ATP funding. The key technology development goals were:

- *Modeling*: Establish engineering design modeling and computational capabilities for effectively working through a large number of computationally challenging, alternative design options, including lens geometries, material properties, and capillary surface roughness, and surface waviness.

- *Alternative lens materials*: Systematically evaluate alternative capillary materials, including borosilicate glass, lead oxide silicate glass, boron oxide glass, and beryllium oxide glass, relative to critical angles for X-ray reflection, transmission efficiencies, glass purity, and use experience with capillary optics.

- *Fabrication*: Develop, test, and refine fabrication methods for drawing high purity, ultra-thin, hollow glass tubes with variable cross sections. Develop assembly and alignment technologies for assembling hundreds of thousands of glass tubes into closely packed capillary arrays, subject to exacting quality standards.

- *Reliability*: Develop an understanding of radiation-related reliability issues; that is, determine the radiation flux limits of capillary optical elements and understand radiation-related processes, such as ionization and beam heating, and their effect on X-ray transmission. Explore methods for controlling or minimizing radiation damage and heating effects to enhance the reliability of capillary optics.

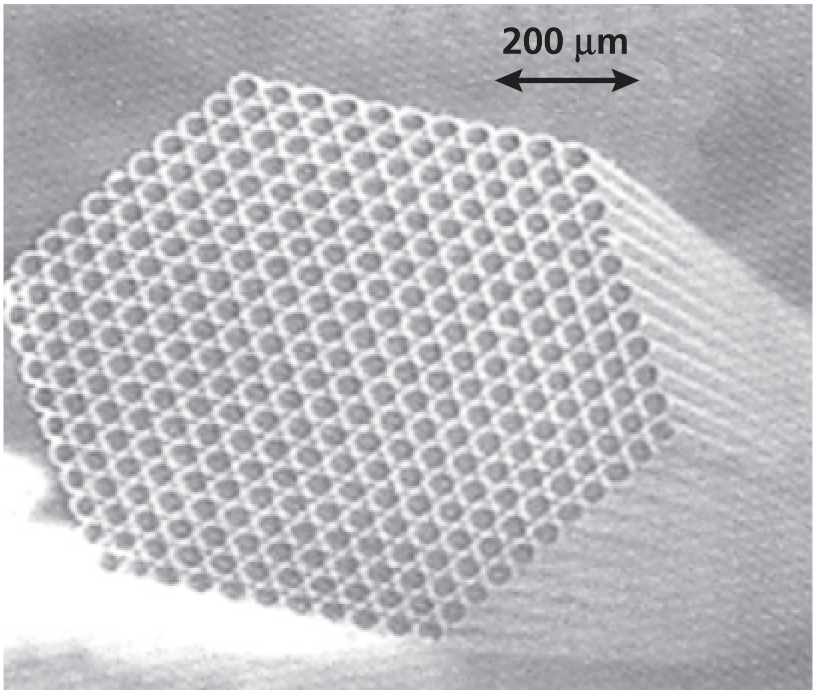
The ATP-funded technology project was successfully completed in 1996 and resulted in the following technical accomplishments:

- *Modeling*: XOS developed a proprietary simulation model to evaluate a wide range of design variables including capillary surface roughness, surface waviness, tapered capillaries, and fiber bending. Models can simulate the performance of complete capillary optical systems and generate detailed fabrication drawings. Actual capillary performance was observed to be closely correlated with model simulation results.

- *Alternative lens materials*: XOS evaluated alternative optical-quality glasses to optimize capillary performance and developed a relationship with U.S. suppliers that could provide 100 percent of capillary materials.

- *Fabrication*: XOS successfully developed glass pulling, multi-capillary fiber construction, array assembly, array alignment, testing, and quality control methodologies to produce high purity and high-efficiency arrays. The smallest of these capillary arrays consists of more than 300,000 channels. “Each capillary is so tiny that over 25 would fit in a single human hair. If the capillary channels of the optic were laid end to end, the length would exceed 10 miles” (X-Ray Optical Systems, Inc., website). (See Figure 5.)

Figure 5: Glass Capillary Optics



- *Reliability*: Radiation damage experiments were conducted on capillary systems at the National Synchrotron Light Source at Brookhaven National Laboratory. Discoloration and some physical damage were observed, but no loss in lens performance could be determined beyond statistical variations.

These technology advances made it possible for XOS to develop commercially viable lenses for collimating X-rays into tight parallel patterns and for focusing X-rays onto micro-sized spots.

When ATP-funded X-ray optical lenses are incorporated into analytical instruments for materials analysis and into sensor engines for industrial process control, more photons are delivered to specimens under investigation, beam intensity is improved several orders of magnitude, and measurement sensitivity is enhanced (Beumer, 2004). As a result, laboratory materials analysis that would take 24 hours can be completed in just 1.5 to 2 hours, without loss of measurement sensitivity, and in-line industrial process metrology can be used to detect trace-level contaminants, on a near-real-time basis (Gibson, 2004). Subsequent product development efforts resulted in further improvements in measurement sensitivity.

In industrial *laboratory applications*, standalone X-ray optics are used as performance-enhancing laboratory instrument components for more accurate and rapid characterization of material composition and crystalline structure.

In industrial *process control applications*, X-ray optics are incorporated into small-footprint, low-power consumption sensor engines along with an X-ray laser source, detectors, hardware, and software.

BENEFIT ASSESSMENT AND MODELING

U.S. *industrial* laboratories need increasingly accurate analytical information about the chemical composition and crystalline structure of advanced materials to support the development and ensure the manufacturability of new industrial products. Analytical information must be obtained in a timely and efficient manner.

U.S. *process* industries need increasingly accurate, near-real-time analytical information about contaminant concentrations to ensure sufficient quality controls and improved process yields.

The ATP-funded X-ray optics technology directly addresses industry needs for increasingly accurate and timely analytical information in three application areas:

- Laboratory materials analysis in a broad range of industries
- Process control metrology in petroleum refining and distribution
- Process control metrology in semiconductor fabrication

LABORATORY MATERIALS ANALYSIS

Laboratory instruments for materials analysis tend to be large-footprint, complex systems offering full analytical range. In the case of elemental composition analysis, full analytical range would include elements from boron to uranium in solids and powders and from sodium to uranium in liquid samples (Uhling et al., 1999).

X-ray diffraction (XRD) and X-ray fluorescence (XRF) are high sensitivity methods for materials analysis:

- XRD systems use highly collimated X-ray beams to study crystalline structure and stress, critical for developing advanced materials for new, high performance industrial applications and for supporting engineering design solutions when utilizing advanced materials.

- XRF systems use highly focused X-ray beams for elemental analysis to detect trace amounts of contaminants and pollutants and to measure thin-film thickness at nano-scales.

Economic Modeling

To quantify cash flow benefits to industry users that can be associated with performance-enhancing X-ray optics for laboratory materials analysis, estimates are developed for average benefits per X-ray optical lens and for retrospective and projected future sales of X-ray optical lenses.

BENEFITS PER X-RAY OPTICAL LENS

For XRD analysis, commercial laboratories tend to charge about $144 per hour as a fully loaded user fee, reflecting such items as equipment depreciation costs, operator salaries, utility costs, equipment maintenance contracts, laboratory consumables, sample preparation, and telecommunications (Morgan, 2001; Pierce, 2004).

For XRF analysis, a fully loaded commercial user fee tends to be around $52.50 per hour, including equipment depreciation costs, operator salaries, and utility costs (Morgan, 2001; Pierce, 2004; Homeny, 2004).

Assuming XOS sales patterns to be 30 percent sales of XRD systems and 70 percent sales of XRF systems, weighted average user fees are computed as $79.95 per hour (Figure 6).

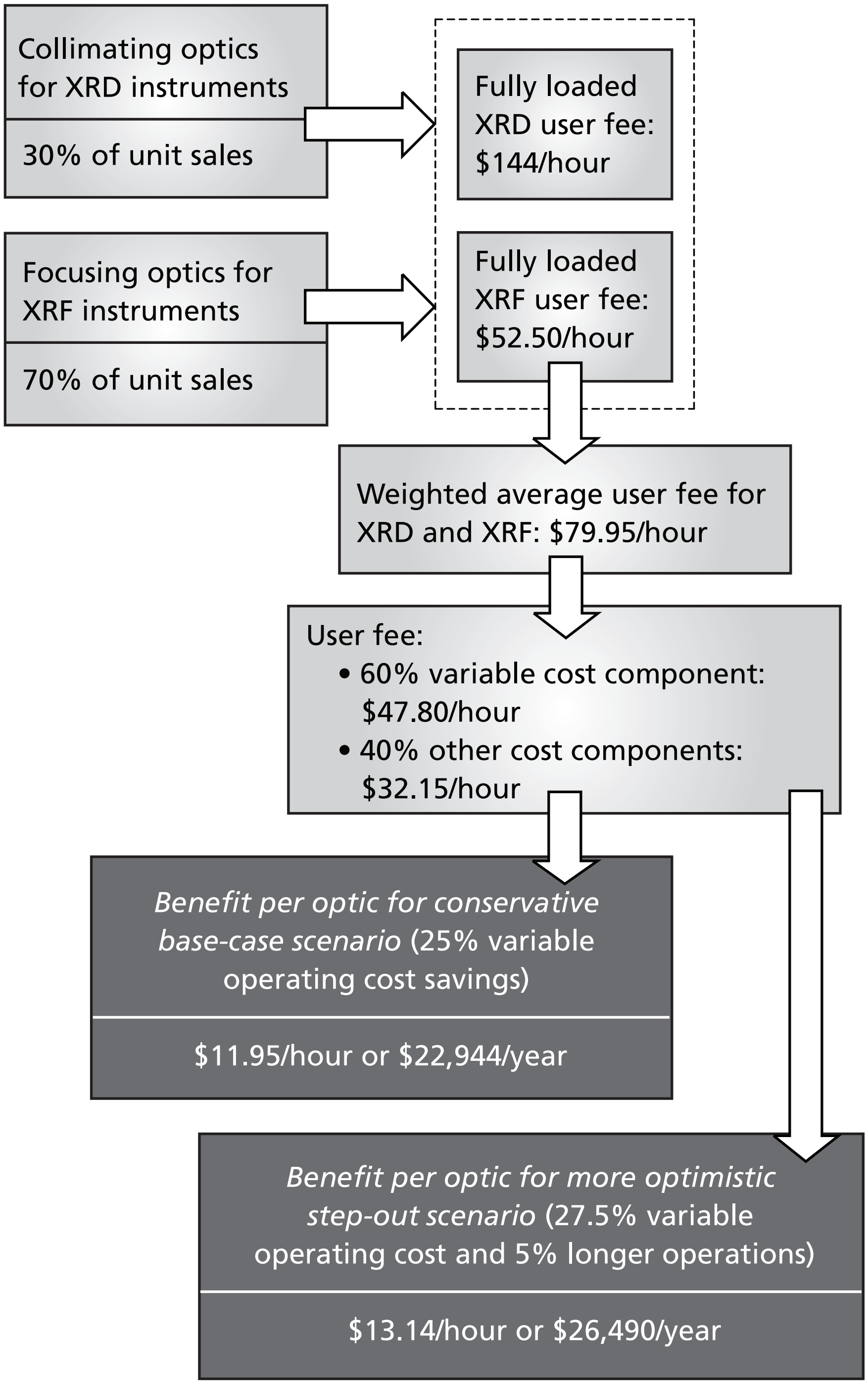
Based on discussions with commercial laboratory operators, it is estimated that 40 percent of the weighted average fees cover such items as equipment depreciation and sample preparation expenses and that 60 percent, or $47.80 per hour, represents the average variable operating cost for the direct use of XRD and XRF analytical instruments.

While multiple orders of magnitude (tenfold to hundredfold) increases in analytical speed were reported from incorporating performance-enhancing X-ray optics, labor, utility, and other variable costs are structurally constrained and only partially variable in commercial operations. In other words, laboratories have fixed salary obligations, and, given less than fully elastic demand for analytical services, laboratories may not always reap economic advantage from increased equipment availability resulting from higher analytical speeds.

To reflect these constraints, we conservatively assume in the base case that tenfold and higher increases in speed will result in only a 25 percent decrease in operating costs. Accordingly, average savings associated with increased analytical speed—at 25 percent of the $47.80 per hour variable costs—yield estimated *savings of $11.95 per hour* from the use of ATP-funded performance-enhancing X-ray optics.

We further assume that a typical laboratory operates for eight hours per day for 240 days per year. Extended by savings of $11.95 per hour, base-case annual savings associated with each X-ray optic in operation is estimated at *$22,944*.

Figure 6: Projected Annual Savings in Laboratory Operating Costs From Use of Standalone X-Ray Optics (2004 Dollars)



For the step-out scenario, hourly savings are increased 10 percent to $13.14, resulting in estimated annual savings of *$26,490.*

Industrial laboratory analysis for new product development, using advanced materials, is often constrained by laboratory equipment availability and cost. Substantially increased analytical speeds at reduced cost can therefore be expected to facilitate new product development with advanced materials.

Though this benefit was not quantified at this time, increased analytical speeds and a more efficient development of advanced materials will provide significant competitive advantage to U.S. companies in a broad spectrum of industries—for example, pharmaceuticals, semiconductors, and other industries using advanced materials.

X-RAY OPTICAL LENS SALES

The analytical instruments industry is highly competitive and technologically advanced. The industry's major segments are laboratory instruments, industrial measuring and controlling instruments, and electrical testing and measurement instruments. The United States is the largest producer in each of the three segments and is a net exporter of analytical instruments for industrial process control and for materials research.

The U.S. laboratory instruments segment is estimated to reach $17.9 billion in sales in 2004 and experience average growth rates of 5 percent. Certain sub-segments, including materials analysis for elemental composition and crystalline structure, are expected to grow at annual rates of 8 percent (Frost & Sullivan, 2003; Business Communication Company, 2004).

XOS has actively marketed X-ray collimating and X-ray focusing optics to original equipment manufacturers (OEMs) of analytical instruments since 1997 and the above industry trends provide a context for XOS's ongoing marketing efforts.

Estimated U.S. annual sales over the 1997–2003 period range from 7 optical lenses to 88 lenses. Going forward, projected sales of standalone X-ray optics gradually increase from 95 units in 2004 to 100 units in 2014 (Table 1).

Projected sales levels represent a highly conservative base case in light of expected industry segment growth rates in excess of 5 percent. For a more optimistic step-out scenario, sales levels for each year (over the 2004–2014 period) are increased by 10 percent over base-case levels.

Given seven years of successful commercial experience and only modestly increasing projections of future sales, the probability of realizing future sales projections is estimated to be 90 percent.

Table 1: Estimated Sales of X-Ray Optical Lenses Over 1997–2014 Period: Retrospective and Prospective (Number of Units)

Retrospective	1997	1998	1999	2000	2001	2002	2003				
	7	10	15	35	61	85	88				
Prospective	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
	95	95	95	95	95	95	95	95	100	100	100

Benefit Estimates

Based on discussions with XOS and industry experts, we assume that optical lenses will continue to generate benefits for a period of 10 years after the sale of each lens. Annual cash flow benefit estimates are computed by extending estimated economic benefits per X-ray optical lens by the number of optical lenses projected to be deployed in the United States.

Cash flow time series covering the 1997–2014 period are displayed in column 2 of Tables 3 and 4 in the Benefit-Cost Analysis section of this chapter, where cash flows from different X-ray optics applications are shown side by side.

To illustrate how cash flow benefit estimates in Table 3 are arrived at, consider base-case calculations for fiscal year 2005. As shown in Table 1, 491 lenses are sold as performance-enhancing components for industrial laboratory instruments during the 1997–2005 period. Given expected utilization for 10 years, each of the 491 lenses is presumed to be in continued use and generating $22,944 benefits per year (Table 1 and Figure 6). Expected benefits for 2005 are determined by multiplying 491 lenses by $22,944, resulting in $11,266,000 of total economic benefits. Assuming a 90 percent probability of realizing sales projections and benefit estimates, the expected value of economic benefit cash flows (for 2005) is $10,139,000.

PROCESS CONTROL IN PETROLEUM REFINING AND DISTRIBUTION

In 2001, the U.S. Environmental Protection Agency (EPA) adopted rules requiring drastic reductions in the sulfur content of highway-grade diesel fuel to ultra-low levels, from 500 to 15 ppm (parts per million). While the regulation is to be fully implemented over the 2006–2010 period, most diesel fuel must meet the 15 ppm standard by 2008.

The petroleum refining and distribution industry will be significantly challenged to achieve 15 ppm ultra-low sulfur diesel (ULSD) levels in the 2006–2008 timeframe. Keeping sulfur levels to trace amounts will require innovative new technologies to provide orders of magnitude more accurate and near-real-time metrology (National Petroleum Council, 2000).

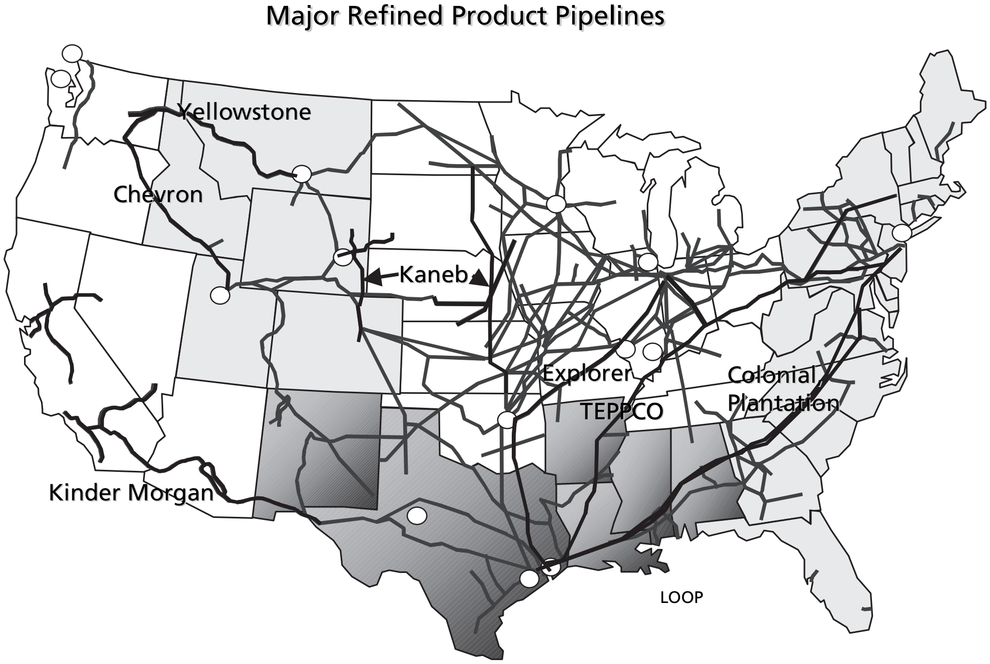
Incorporated into small footprint, low power consumption sensor engines, XOS optics will be deployed in petroleum refining and distribution systems to detect EPA-mandated trace amounts of sulfur, on a near-real-time basis. The use of sensor engines will facilitate regulatory compliance, improved quality control, increased product yield, and reduced highway diesel emissions.

Petroleum Refining and Distribution

The U.S. petroleum refining industry operates 16.7 million barrels per day crude distillation capacity (Energy Information Administration, 2001) to produce motor gasoline, diesel fuel, and other petroleum products. There are 146 petroleum refineries currently operating in 32 states across the United States. Of these, 80 percent, or 117 refineries, process crude oil into diesel fuel (National Petroleum Council, 2000).

Diesel fuel and other petroleum products are distributed through a complex system of storage terminals, pipelines, barges, and tanker trucks to retail outlets and end-users. The U.S. distribution system includes approximately 1,300 storage tanks and 95,000 miles of pipelines (Figure 7).

Figure 7: **U.S. Network of Refined Products Pipelines**



Source: Allegro Energy Group (2001).

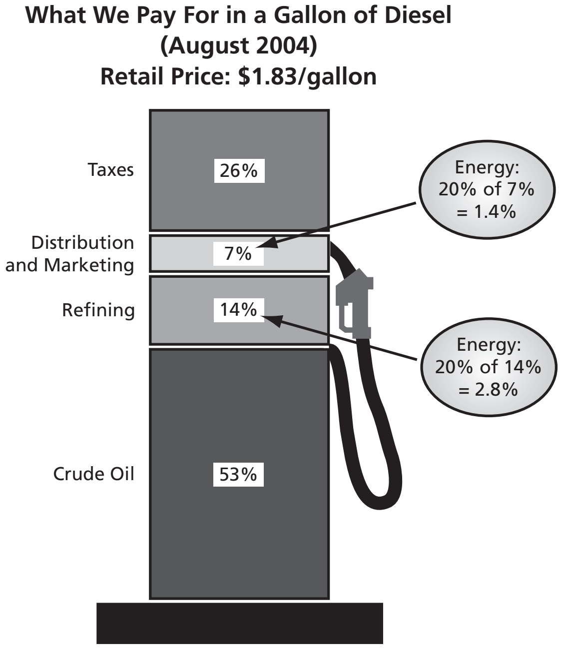
Various grades of motor gasoline, diesel, and other petroleum products are routinely transported in the same physical pipeline as sequential batches.

Batches of petroleum products are pumped through the system and, where adjacent batches come into contact, some mixing occurs between different products. The mixing at the interface is referred to as the *transmix*, and the contents of the transmix are generally off spec relative to motor gasoline or diesel specifications. Off-spec batches are downgraded or reprocessed at additional cost.

Petroleum refining and distribution are highly energy intensive. As indicated in Figure 8, 53 percent of the retail price of a gallon of diesel fuel corresponds to the cost of crude oil. In addition, approximately 20 percent of refinery operating costs and product distribution costs correspond to energy costs related to electricity and steam process use (Energy Information Administration, 2004). Accordingly, more than 57 percent of the retail price of diesel fuel (53% + 2.8% + 1.4%) reflects energy costs for crude oil, electricity, and steam. Without considering taxes, more than 77 percent of production and distribution costs are associated with energy inputs.

Given the highly energy-intensive nature of petroleum refining, industry practice is to express operating efficiency improvements as energy or BTU savings. Since refined product losses in the distribution system must also be made up by reprocessing the

Figure 8: **Cost Components of Average U.S. Diesel Price**



Source: Energy Information Administration (2004).

off-spec transmix, the operating efficiency of storage and pipeline systems tends to be gauged with reference to energy savings as well (Office of Industrial Technologies, 1998).

Transition to Ultra-Low Sulfur Diesel

Diesel is the primary fuel for the U.S. commercial transportation sector. In 2000, the transportation sector used 33.1 billion gallons, and more than 94 percent of all freight was moved using diesel power (*Diesel Fuel News*, 2002). The U.S. refining industry supplies more than 92 percent of domestic diesel consumption (National Petroleum Council, 2000), and the sulfur content in diesel fuel is a major contributor to particulate and sulfur dioxide emissions.

As noted, the 2001 EPA rules require sulfur content reductions in highway grade diesel fuel from 500 to 15 ppm ultra-low sulfur content. "Pipeline operators are expected to require refiners to provide diesel fuel with even lower sulfur content—somewhat below 10 ppm—in order to compensate for possible contamination from higher sulfur products in the distribution system and to provide a tolerance for testing" (Energy Information Administration, 2001). The rule will start to take effect in the fall of 2006, essentially requiring compliance by the end of 2008.

EPA estimates that the cost of reducing sulfur content from 2004 regulated levels to 15 ppm ultra-low levels will be 5.4 cents per gallon, consisting of 4.3 cents in additional refinery costs and 1.1 cents in additional distribution costs (U.S. Environmental Protection Agency, 2000). The American Petroleum Institute projects even higher additional costs, exceeding 15 cents per gallon, consisting of 9 cents in refining costs and 6 cents in distribution costs (Peckhan, 2000). According to the American Trucking Association, the total cost of achieving the ultra-low level is likely to be "someplace in the middle, around 10 cents per gallon" (Thrift, 2003).

Challenges of Achieving Ultra-Low Sulfur Content

The petroleum refining and distribution industry will be significantly challenged to achieve 15 ppm ULSD levels in the 2006–2008 timeframe. ULSD fuels will require not only new processes to extract sulfur from refinery streams but also the utilization of more accurate and near-real-time metrology (National Petroleum Council, 2000).

The optimal blending of crude feedstock with differing sulfur content and the hydro-treating of finished diesel fuel streams will be the two primary methods for achieving ULSD standards in U.S. refineries. Optimal blending and hydro-treating will be technically difficult and high-cost processes (National Petroleum Council, 2000).

Beyond addressing the operational challenges of crude blending and hydro-treating, the lack of precise measurement tools will further exacerbate the difficulty of reliably achieving 15 ppm. Measurement uncertainties of currently available metrology can exceed 16 ppm, “suggesting that without revolutionary improvements in sulfur measurement, refinery blenders will have to produce batches of diesel fuel with zero sulfur content in order to ensure that the refinery is compliant with the 15 ppm standard” (BP America, 2002).

The distribution system for ULSD will also be hampered by limitations in sulfur measurement accuracy and speed. According to the American Petroleum Institute, maintaining product integrity in terminals and pipeline systems and minimizing costly transmix downgrades will be significantly more difficult when transporting 15 ppm ULSD fuel. The American Petroleum Institute projects that interface mixing of fuel batches and sulfur contamination from other fuels will result in up to 17 percent of ULSD fuels being downgraded, requiring costly reprocessing, as compared to less than 1 percent with current higher levels of sulfur content (Peckhan, 2000).

To minimize downgrades and associated economic losses, the flow of refined products should be monitored on a near-real-time basis. According to the National Petroleum Council (2000), “low sulfur fuels are easily contaminated even with a small batch of out-of-spec fuels. Manual sampling takes too long and results in deep interface cuts and significant downgrades. Continuous online monitoring rather than periodic sampling will be essential.”

X-Ray Sensor Engines for Sulfur Monitoring in Refinery Processes

XOS is currently marketing an affordable and innovative measurement technology for monitoring ULSD trace concentration; that is, sensor engines equipped with X-ray optics and with limits of detection as low as 0.4 ppm. These sensor engines can be placed in-line with refinery processes for near-real-time monitoring of sulfur content.

XOS recently concluded an agreement with a major petroleum company (among the top three petroleum companies in the United States) to be its exclusive supplier of in-line sulfur detection sensors for measuring ULSD trace concentration. “In-line sulfur monitoring will provide closed-loop process control so that refiners can quickly detect out-of-spec fuel, take corrective action, identify the root causes of fuel quality problems, and avoid unnecessary operating costs” (Beumer and Radley, 2004). These benefits will be particularly valuable for two refinery processes central to the production of ULSD:

- *Optimal feedstock blending*: Crude supplies vary significantly in sulfur content. Real-time measurement of sulfur content will facilitate the optimal blending of crude oil arriving at distillation columns. Optimal blending will reduce process excursions and downtime due to swings in crude sulfur content. Accordingly, energy savings will be realized as distillation columns are operated at stable sulfur composition levels.

- *Avoiding excessive hydro-treatment*: Achieving ultra-low sulfur levels will be a very expensive process. It will also result in refinery yield losses. If timely and accurate process information from in-line sulfur analyzers is used to prevent over-treating or extracting too much sulfur, then processing costs and yield losses can be reduced, resulting in energy savings.

X-Ray Sensor Engines for Sulfur Monitoring in Distribution Systems

XOS is also actively marketing affordable and innovative in-line sensor engines for monitoring the sulfur content of ULSD fuels moving through the U.S. storage terminal and pipeline distribution system.

After the deployment of in-line sensor engines, expected to start in 2005, pipeline operators will be able to more quickly detect out-of-spec conditions, take corrective action, and minimize costly interface cuts, or intermix, of different batches of refined petroleum products (Beumer, 2004).

Economic Modeling

To quantify cash flow benefits to industry users and the general public from the deployment of X-ray sensor engines in petroleum refineries and in the refined product distribution system, estimates are developed for average benefits per sensor engine and projected sales of sensor engines.

BENEFITS PER SENSOR ENGINE

Removing enough sulfur to meet regulatory requirements, without over-treating refinery streams, and accurately detecting out-of-spec conditions in storage terminals and pipelines will lead to increased operating efficiencies in refineries and distribution.

As a baseline for expressing efficiency gains in terms of energy savings, the U.S. Department of Energy, Office of Industrial Technologies (OIT), conducted a study of energy-use profiles in the U.S. petroleum industry and developed a computer model to estimate energy savings from specific process improvements (Office of Industrial Technologies, 1998).

The OIT model—available as a web-based interactive Project Evaluation Tool on OIT's website (see References)—was used to estimate energy savings resulting from the use of XOS sensor engines in monitoring sulfur content at U.S. petroleum refineries and in the U.S. distribution system. Based on the OIT model results, annual base-case energy savings were estimated as:

- 20,522 million BTUs per sensor engine used for monitoring sulfur levels in refinery crude blending and hydro-treating processes

- 11,543 million BTUs per sensor engine used for monitoring sulfur levels in storage terminals and pipeline systems.

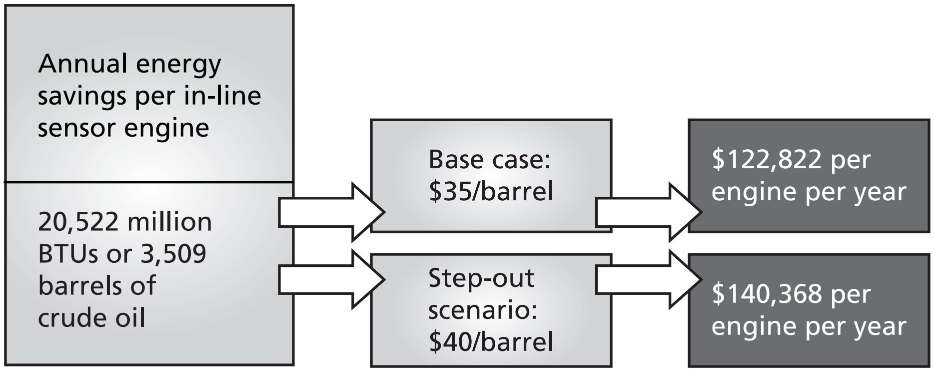
Figures 9 and 10 indicate how refinery and distribution energy savings can be mapped into cost savings. It should be noted that some refinery processes use process waste streams as energy inputs with economic values lower than the market price of crude oil. Other refinery processes use electricity and steam, where the economic values are higher than the market price of crude oil. Given the substantial variability in refinery processes and energy use patterns, we conservatively assume that each BTU of energy saved from more accurate in-line monitoring of the blending and hydro-treating processes and from avoiding over-treating diesel streams can be valued at the market price of crude oil.

In its 2005 *Annual Energy Outlook*, the Energy Information Administration of the U.S. Department of Energy (January 2005) projects crude market prices over the 2005–2025 period to decline at least temporarily from current high levels as new deepwater oil fields are brought into production and projects $24.50 per barrel of crude oil (2003 dollars) by 2010 and $30 per barrel in 2025.

Assuming that Energy Information Administration price projections may be somewhat optimistic, we assumed the market price for crude at $35/barrel ($10.50 above 2005 DOE estimates) over the 2005–2014 planning horizon for benefit analysis in the base case. At this price level, annual savings per sensor engine were estimated at *$122,822*. For a step-out scenario, we assumed crude oil at $40/barrel ($15.50 above 2005 DOE estimates), leading to annual savings of *$140,368* per sensor engine (Figure 9).

Should long-term energy prices exceed DOE projections beyond our adjustments, annual public benefits to be realized from X-ray optics technology will be greater than the above base case and step-out scenario estimates.

Figure 9: **Projected Annual Energy Savings from In-Line Sensor Engines Deployed at U.S. Refineries (2004 Dollars)**



To estimate the economic value of distribution system BTU savings, we used the same assumptions about the market price of crude oil as for refinery energy savings. Over the 2004–2014 planning horizon, we assumed a base-case market price for crude oil at \$35/barrel, leading to estimated annual savings of \$69,085 per sensor engine. For a step-out scenario, we assumed crude oil at \$40/barrel, leading to estimated annual savings of \$78,954 per sensor engine (Figure 10).

Beyond quantitative cash flow benefits from energy savings, the use of in-line sensor engines is expected to result in additional economic benefits, including:

- Reduced hydrogen use in refinery hydro-treating processes from the avoided over-treatment of diesel streams. Approximate value of hydrogen savings is \$1,000 per standard cubic foot (Beumer, 2004).

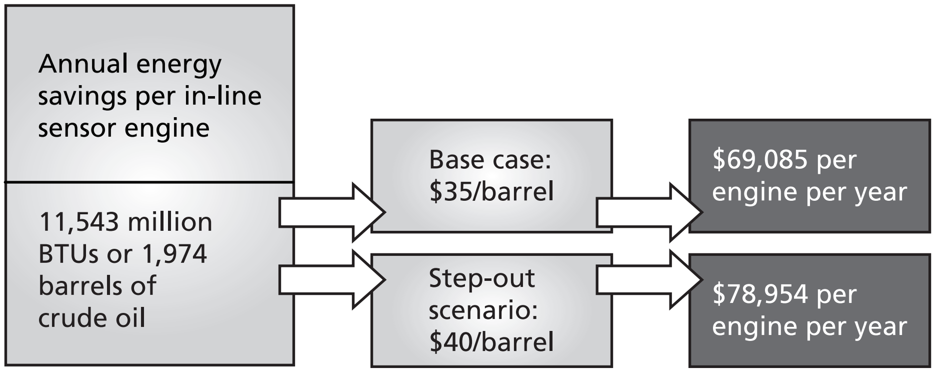
- Reduced environmental pollution from the use of ULSD fuel in commercial transportation. Achieving effective compliance with ULSD regulations, SO_2 and particulate emissions will be reduced. The Office of Management and Budget (2003) estimates that the economic value of avoided SO_2 emissions is \$7,800 per ton.

REFINERY SENSOR ENGINE SALES

Based on input from XOS and discussions with process control OEMs, refinery operators, regulators, and refinery industry associations, we developed the following sales estimates for modeling economic benefits of the ATP-funded X-ray optics project.

For a conservative base case, it is assumed that XOS will deploy 6 sensor engines at each of the 23 refineries that produce diesel fuel over the 2004–2008 period, representing 20 percent of the U.S. diesel market (see Figure 11). The timing of sensor engine sales is projected at 6 engines in 2004, 12 in 2005, 30 in 2006, 42 in 2007, and 48 in 2008, for a total of 138 sensor engines over the 2004–2008 period (Table 2).

Figure 10: **Projected Annual Energy Savings from In-Line Sensor Engines Deployed in U.S. Petroleum Distribution System (2004 Dollars)**



Annual energy savings per in-line sensor engine

11,543 million BTUs or 1,974 barrels of crude oil

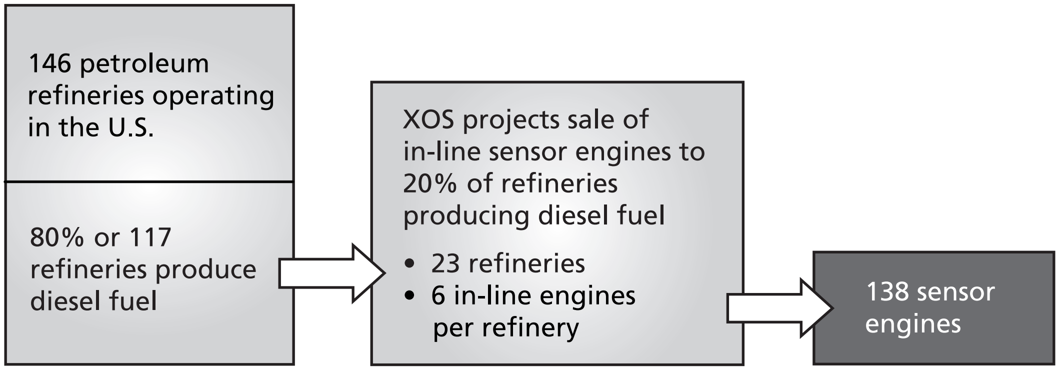
Base case: \$35/barrel

Step-out scenario: \$40/barrel

\$69,085 per engine per year

\$78,954 per engine per year

Figure 11: Projected Deployment of XOS In-Line Sensor Engines in U.S. Petroleum Refineries over 2004–2008 Period



For a more optimistic step-out scenario, sales levels for each year (over the 2004–2008 period) are increased by 10 percent over base-case levels.

Given XOS's agreement with a major U.S. petroleum refining company to be the exclusive supplier of in-line refinery metrology for ULSD, the probability of achieving these plans is estimated to be 90 percent.

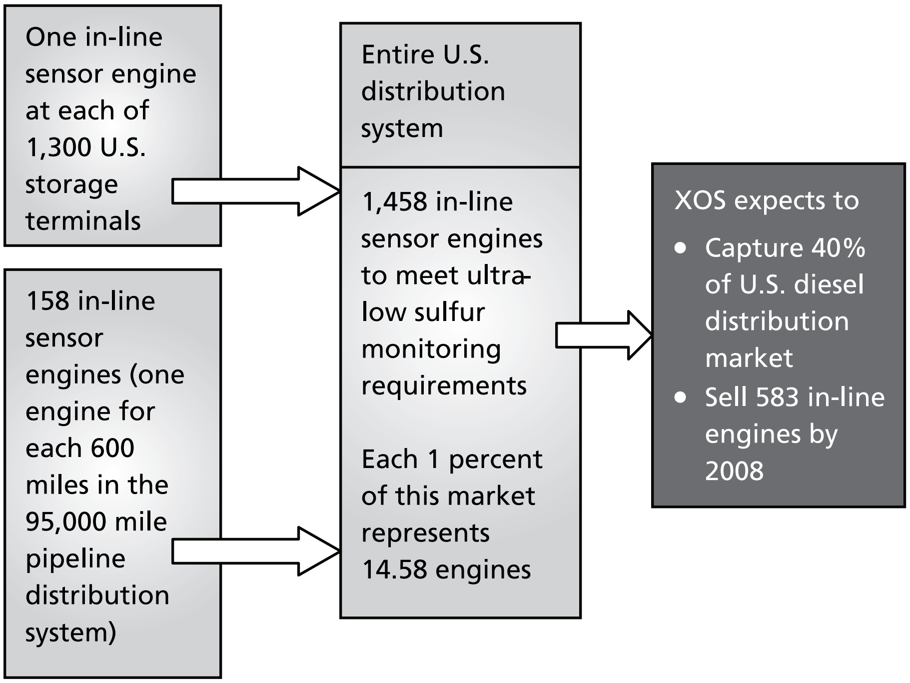
SENSOR ENGINE SALES TO TERMINAL AND PIPELINE OPERATORS

For a conservative base case, one sensor engine will be deployed at each of 520 terminals and one sensor engine for each 600 miles of 38,000 miles of pipeline (63 engines), representing 40 percent of the U.S. petroleum product distribution market. The timing of in-line sensor engine sales is projected at 117 engines in 2005, 146 engines in 2006, 160 engines in 2007, and 160 engines in 2008, for a total of 583 sensor engines over the 2005–2008 period (Figure 12 and Table 2).

Table 2: Projections for Sensor Engine Sales to U.S. Refineries and Pipelines

Year	Units sold to U.S. refineries	Units sold to U.S. pipelines
2004	6	
2005	12	117
2006	30	146
2007	42	160
2008	48	160
Total	138	583

Figure 12: Projected Deployment of XOS In-Line Sensor Engines in U.S. Petroleum Distribution System over 2005–2008 Period



For a more optimistic step-out scenario, sales levels for each year (over the 2005–2008 period) are increased by 10 percent over base-case levels.

The probability of achieving these plans is estimated to be 75 percent.

Benefit Estimates

Based on discussions with XOS and industry experts, we assume that sensor engines will continue to generate benefits for 10 years after the sale and deployment of each engine. Annual cash flow benefit estimates are computed by extending estimated economic benefits per X-ray sensor engine by the number of sensor engines projected to be deployed in the United States.

Annual cash flow estimates of the economic value of projected benefits from using high accuracy in-line sensor engines, and computed on the basis of the above assumptions, are displayed in columns 3 and 4 of Tables 3 and 4 in the Benefit-Cost Analysis section of this chapter, where cash flows for the different X-ray optics applications are shown side by side.

PROCESS CONTROL IN SEMICONDUCTOR FABRICATION

Metrology tools of substantially higher sensitivity are needed to support the implementation of technology advances in semiconductor fabrication to:

- Replace aluminum with copper interconnect metal, in combination with low dielectric constant (low k) insulation
- Facilitate transition from 200 mm to 300 mm wafers

Metrology, including materials characterization in semiconductor fabrication, facilitates the introduction and manufacture of new materials, facilitates miniaturization, enables tool improvements, and can reduce manufacturing costs and time-to-market for new products, through better characterization of processes (International Technology Roadmap for Semiconductors, 2003).

XOS is currently developing metrology products for semiconductor fabrication. In-line sensor engines with X-ray optics will be sold to OEMs of process diagnostic tools and are expected to "add value as metrology sensors for wafer etching, vapor deposition, ion implantation, and chemical mechanical planarization" (Gibson, 2004). In-line sensors will be used to:

- Measure thin-film (copper) thickness and detect iron contamination in silicon wafers
- Characterize wafer crystal lattice orientation and texture, monitor epitaxial growth, and measure thin-film residual stress levels

The use of sensor engines is expected to provide a number of benefits in semiconductor fabrication, including:

- Reduced wafer handling by eliminating the need to transport wafers from a process tool to a laboratory metrology system for critical measurements (Dance et al., 1996).
- Accelerated product development. New chip fabrication facilities, starting with 80 percent test wafers, end up with fewer than 20 percent test wafers after 3–5 years (Gibson, 2004). If ATP-funded X-ray optical technology can accelerate semiconductor fabrication facilities toward a steady state 80 percent yield, waste and manufacturing costs will be reduced.
- Improved quality control with faster detection of out-of-spec process excursions, improved operating yields, and lower cost of quality.

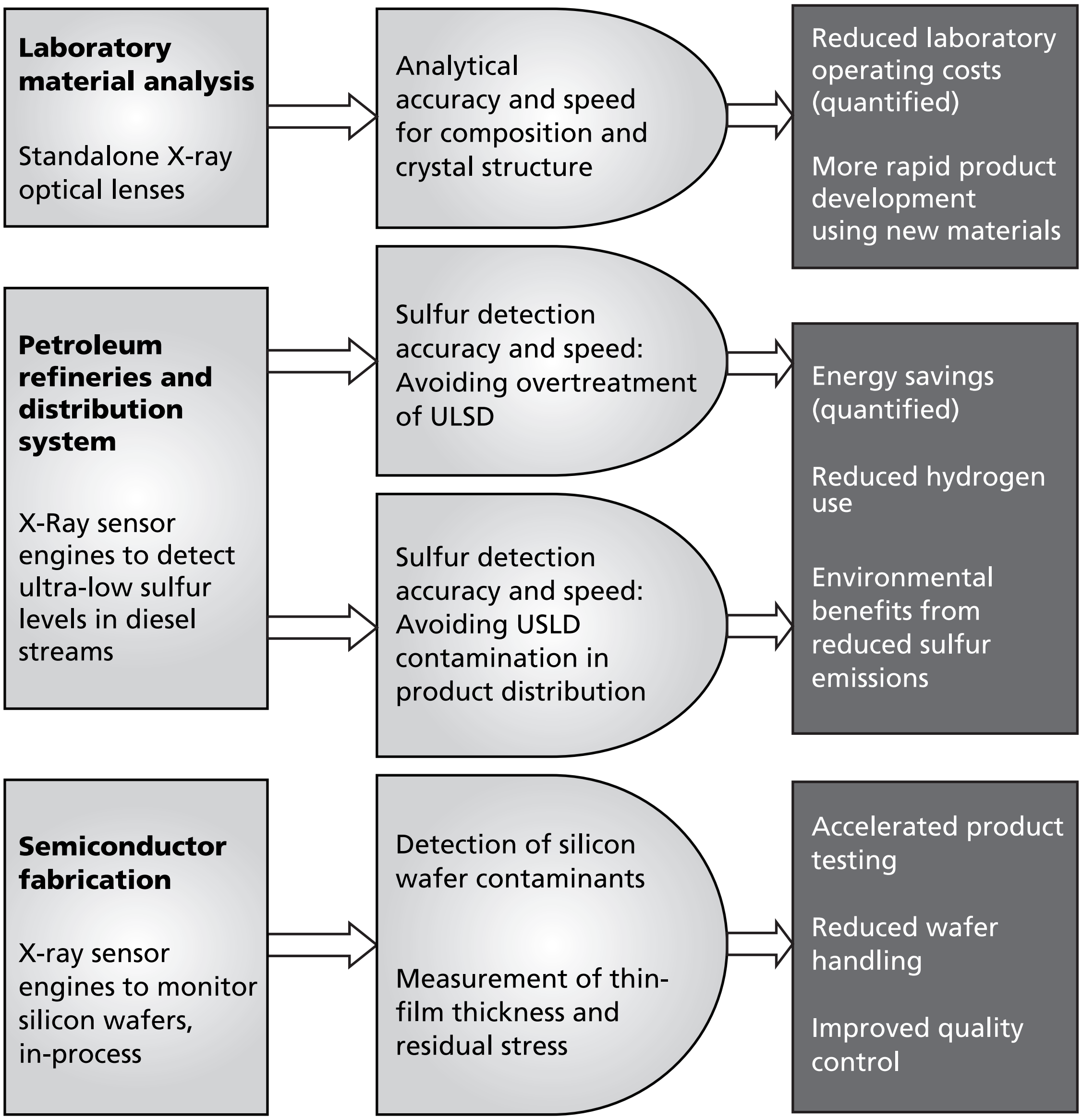
The timing of in-line sensor sales to the semiconductor industry is expected to lag sensor sales for petroleum refinery and distribution applications by several years (Gibson, 2004).

Given the longer time frame and associated commercial uncertainties of benefits of the ATP-funded X-ray optics project to the semiconductor industry, these benefits are not quantified at this time.

BENEFIT-COST ANALYSIS

The commercial utilization of ATP-funded X-ray optics has resulted in actual, realized economic benefits. Even greater future benefits are anticipated from the continued use of standalone optics and from the introduction of new sensor engines incorporating X-ray optics. The flow of these benefits, via four distinct pathways in multiple industries, is summarized in Figure 13.

Figure 13: Flow of Benefits from X-Ray Optics Technology



ATP AND INDUSTRIAL PARTNER INVESTMENTS

During the 1992–1996 period, ATP invested $1.95 million (toward project direct costs) and its industry partner, XOS, invested $371,000 in the development of the X-ray optics technology.

For purposes of cash flow analysis, the ATP investment was normalized to 2004 dollars ($2.496 million) and included as one lump sum investment made in 1994, the midpoint of the four-year investment period.

PERFORMANCE METRICS

Our quantitative analysis was limited to public benefits (to downstream industry, end-users, and society) that could be meaningfully quantified and excluded private benefits to XOS. We estimated benefit cash flows for a conservative base case and for a more optimistic step-out scenario. We compared these benefits to the cash flow representing ATP investment costs.

This comparison resulted in three sets of economic performance measures—net present value, benefit-to-cost ratio, and internal rate of return—that compute directly the impact of the ATP investment.

In this case, all benefits to downstream industrial users and the general public are attributed to the ATP project because it is highly unlikely these benefits would have occurred without ATP.

BASE-CASE ANALYSIS

Laboratory materials analysis savings result from the commercial sale of X-ray optics. In contrast, refinery and distribution savings—associated with the use of sensor engines—are driven by EPA's ULSD regulations, to be implemented by the 2008 regulatory deadline.

As indicated in Table 3, for the base case, the public return (combined retrospective and prospective) on ATP's investment in the X-ray optics technology over the 1994–2014 period can be expressed as a net present value of $184 million. Public benefits are $75 for every dollar invested, and the internal rate of return is estimated at 49 percent.

A purely retrospective analysis of the return on ATP's investment over the 1994–2003 period indicates a *realized* net present value of $7.4 million, a benefit-to-cost ratio of $4 of public benefits for every dollar invested, and an internal rate of return of 30 percent.

Table 3: Base-Case Cash Flows and Performance Metrics from Utilization of X-Ray Optics Technology (2004 Dollars, in Millions)

	Laboratory materials analysis	Refinery process savings	Distribution process savings	Total cash flows
1994				–2.496
1995				
1996				
1997	0.161			0.161
1998	0.390			0.390
1999	0.734			0.734
2000	1.537			1.537
2001	2.937			2.937
2002	4.887			4.887
2003	6.906			6.906
2004	8.177	0.663		8.840
2005	10.139	1.990	6.062	18.191
2006	12.101	5.306	13.627	31.034
2007	13.918	9.949	21.917	45.784
2008	15.673	15.254	30.207	61.135
2009	17.325	15.254	30.207	62.787
2010	18.564	15.254	30.207	64.026
2011	19.266	15.254	30.207	64.728
2012	19.576	15.254	30.207	65.038
2013	19.824	15.254	30.207	65.286
2014	19.927	15.254	30.207	65.389

Retrospective Performance (1994–2003)

Net present value	7.4 million
Benefit-to-cost ratio	4:1
Internal rate of return	30%

Total Performance (1994–2014)

Net present value	184 million
Benefit-to-cost ratio	75:1
Internal rate of return	49%

Note: A 1994 base year and an OMB-designated 7 percent discount rate were used for analysis. Performance metrics were computed from time series assuming ATP investment in 1994 (project midpoint) and cash flow benefits from 1997 to 2014. Positive cash flows represent public benefits attributable to ATP; negative cash flows represent ATP investment costs (assumed to occur at project midpoint).

STEP-OUT SCENARIO ANALYSIS

A step-out scenario analysis was conducted to investigate the sensitivity of performance metrics to more optimistic assumptions about the projected future benefits of X-ray optics installed into laboratory analytical instruments and in-line sensor engines, in combination with a 10 percent increase in projected sales.

As indicated in Table 4, for the step-out scenario, the public return on ATP's investment in X-ray optics technology is associated with a net present value of $233 million. Expected public benefits are $94 for every dollar invested, and the internal rate of return is estimated at 53 percent.

PRIVATE BENEFITS TO ATP INDUSTRY PARTNERS

ATP's industry partners' motivation to continue product development and marketing of the ATP-funded technology is a necessary pre-condition for industrial-scale impact. Only then will the general public come to enjoy the economic and environmental benefits expected to result from ATP's investment in X-ray optics.

XOS's commercial success and continued motivation to actively market and improve in-line sensor engine products are reflected by its growth from 2 employees in 1991 to 35 employees in early 2003. It continues to develop and market new commercial products based on the ATP-funded technology and to enter into joint ventures with instrumentation and process control OEMs. The company is privately held and had positive net income for five years.

SUMMARY

Base-case and step-out scenario performance metrics point to an exceptional performance of ATP's investment in the X-ray optics project, demonstrated by high public rates of returns and important qualitative benefits.

Table 4: Step-Out Scenario Cash Flows and Performance Metrics from Utilization of X-Ray Optics Technology (2004 Dollars, in Millions)

	Laboratory materials analysis	Refinery process savings	Distribution process savings	Total cash flows
1994				–2.496
1995				
1996				
1997	0.204			0.204
1998	0.495			0.495
1999	0.932			0.932
2000	1.952			1.952
2001	3.730			3.730
2002	6.207			6.207
2003	8.771			8.771
2004	10.385	0.834		11.219
2005	12.877	2.501	7.621	22.999
2006	15.368	6.670	17.131	39.169
2007	17.676	12.507	27.553	57.735
2008	19.905	19.177	37.975	77.057
2009	22.003	19.177	37.975	79.155
2010	23.576	19.177	37.975	80.728
2011	24.468	19.177	37.975	81.620
2012	24.861	19.177	37.975	82.013
2013	25.176	19.177	37.975	82.328
2014	25.307	19.177	37.975	82.459

Total Performance over 1994–2014 Period

Net present value	233 million
Benefit-to-cost ratio	94:1
Internal rate of return	53%

Note: A 1994 base year and an OMB-designated 7 percent discount rate were used for analysis. Performance metrics were computed from time series assuming ATP investment in 1994 (project midpoint) and cash flow benefits from 1997 to 2014. Positive cash flows represent public benefits attributable to ATP; negative cash flows represent ATP investment costs (assumed to occur at project midpoint).

4. Case Study: MEMS-Based Infrared Micro-Sensor for Gas Detection

In 1999, the ATP funded a high-risk innovative project to develop photonic crystal sensors to be tuned for the accurate measurement of methane, carbon monoxide, and carbon dioxide concentrations and other common gases. One key outcome was the development of a sensor technology for CO_2 levels, considered to be the best initial target application.

Accurate, reliable, and low-cost detection of trace amounts of CO_2 are needed to meet safety, health, and energy conservation needs in medical and commercial markets.

- Inexpensive catalytic and electrochemical CO_2 detectors in common use only detect the presence of CO_2 without measuring CO_2 levels, are prone to false alarms, and require frequent replacement of sensing elements.

- More expensive infrared (IR) gas sensors—using non-dispersive IR absorption spectroscopy (NDIR)—can provide accurate and reliable measurement of CO_2 levels. Given their high cost, large size, and high power consumption, NDIR systems have not achieved mass-market penetration as CO_2 sensors (Kincaid, 2000).

Simple, standardized, and less expensive sensor technology is needed to lower costs and to bring accurate and reliable CO_2 sensors to mass markets (Johnson, 2004).

The ATP award built upon the results of prior National Science Foundation (NSF)–funded research. Following the successful 2001 completion of the ATP-funded project, Ion Optics, Inc., the recipient of the ATP award, obtained three rounds of venture capital financing ($8.2 million) to commercialize photonics crystals to be tuned to detect CO_2. In the future, Ion Optics may undertake additional technical initiatives to develop photonics crystals tuned to detect methane and other gases.

PROJECT HISTORY

In 1995, Ion Optics, Inc. (IOI), a startup technology company in Waltham, MA, recognized the commercial potential of using photonics crystals for the development of a more accurate, reliable, and inexpensive gas sensor technology.

Prior to receiving an ATP award to develop a photonics crystal technology, IOI obtained several NSF grants totaling \$850,000 to evaluate the overall feasibility of miniaturizing NDIR gas sensors with photonic crystals. IOI matched the NSF award with \$500,000 and succeeded in demonstrating the feasibility of this approach. In addition, IOI gained improved understanding of how crystal surface structures could be used for tuning crystals to wavelengths of specific gases; that is, matching IR energy emissions and absorptions to the absorption line of the target gas.

To move beyond NSF-funded research, IOI proposed to ATP a project to miniaturize the functionalities of NDIR systems onto an integrated sensor chip, using micro-electromechanical system (MEMS) fabrication technologies. One key technical challenge was to develop an IR radiation source that could both emit radiation in a narrow wavelength band and act as a detector of the reflected radiation. In 1999, the ATP agreed to fund this high-risk technology development project, and in 2001 the project was successfully completed.

At the time of ATP funding, IOI's only source of revenue was contract research, which would have been insufficient to fund the photonics crystal technology project. Accordingly, technical development would have been substantially delayed or, most likely, not completed at all (Johnson, 2004).

After receiving the ATP award and achieving initial technical progress, IOI obtained a first round of venture capital financing, with subsequent rounds bringing total venture capital financing to \$8.2 million. Venture capital financing was used to substantially accelerate remaining technical development, to support commercial prototype building, and to facilitate an effective marketing program. Venture capital financing also facilitated an increasingly sharper focus on an initial target gas with the best, near-term commercial prospects, the accurate measurement of CO_2 levels.

Based on technical solutions developed with ATP support, IOI built prototype sensors to measure CO_2 levels in the expired breath of emergency medicine patients. Prototypes were also built for measuring CO_2 levels for air quality control systems of commercial office buildings.

IOI funded extensive independent market research, including bottom-up investigation through discussions with OEMs of CO_2 gas sensors, and extensive top-down market research, to verify aggregate forecasts developed with input from potential customers (Fletcher Spaght, 2001).

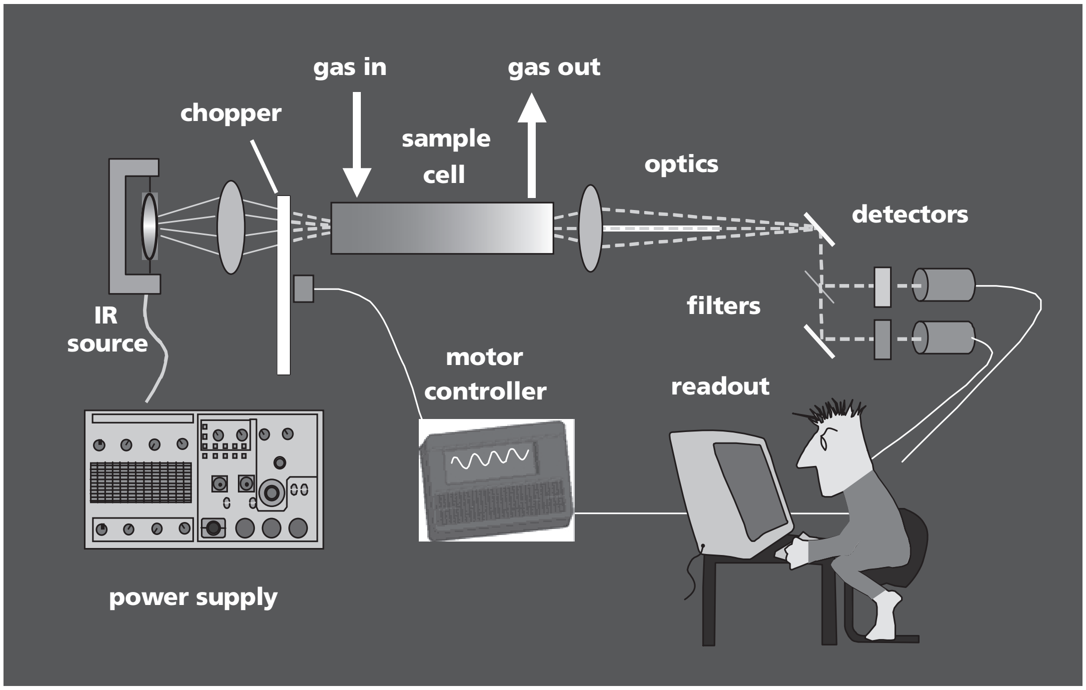
In its marketing efforts, IOI is currently targeting OEMs of CO_2 sensors for emergency medicine and OEMs of commercial building controls. More than 30 letters of interest have been received from potential OEM partners, and prototypes have been shipped for customer evaluation.

In 2004, IOI selected Innovative Micro Technology of Santa Barbara, CA, as its MEMS fabrication partner to bring accurate, reliable, and inexpensive sensor chips to market. Initial production runs are planned to start in 2006.

HOW DOES IT WORK?

Non-dispersive infrared absorption spectroscopy (NDIR) is currently the methodology of choice for the accurate and reliable measurement of gas concentrations. A sensor is used to monitor a specific range of the IR spectrum corresponding to the signature wavelength of the target gas. As shown in Figure 14, when the target gas passes between an IR source and the detectors, the absorption spectrum changes and instrument electronics are used to process this information and determine gas concentration (Puscasu, 2003). While accurate and reliable, NDIR sensors remain expensive and are large units with high power consumption.

Figure 14: **Conventional NDIR (Cabinet Full of Discrete Components)**



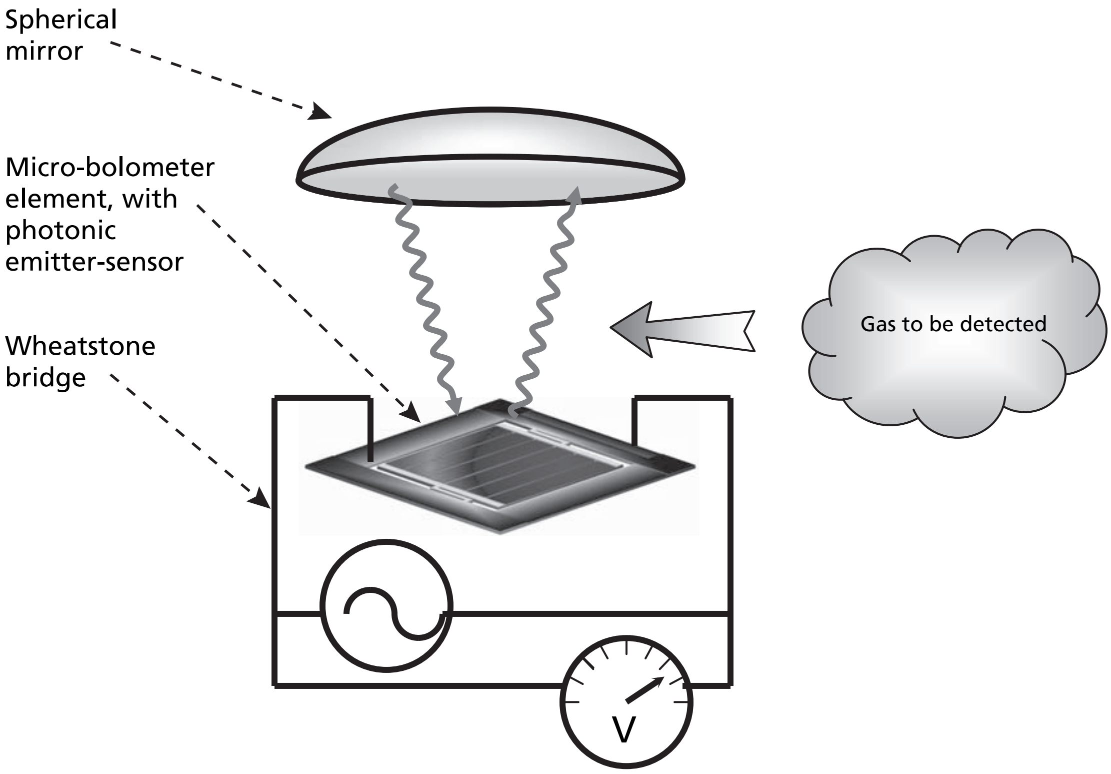
More simple, standardized, and less expensive integrated-circuit technology is needed to lower sensor costs and to bring more accurate and reliable gas sensors to mass markets (Johnson, 2004).

The ATP-funded photonic crystal sensor-on-a-chip (SOC) technology addresses the need for improved accuracy, reliability, and lower cost. As shown in Figure 15, SOC incorporates a micro-bolometer, a radiation-sensitive resistance element in one branch of a Wheatstone bridge. The resistance element is both a source of infrared radiation and a sensor detector of the reflected IR radiation with a spherical mirror reflecting the source signal back to the micro-bolometer element.

In the absence of a target gas to be detected, the micro-bolometer (incorporating the gas SOC) reaches radiative equilibrium with its surroundings. When the target gas is present, it absorbs some of the radiative energy and reduces the amount of light reflected back onto the filament, causing the bolometer to cool off. This temperature change is detected by monitoring filament resistance, or voltage with a constant current source.

Gas SOC is built up as a multi-layer stack. The bottom layer is bulk silicon. Photonic crystal, consisting of an array of holes etched into silicon oxide dielectric, is the

Figure 15: ATP-Funded Gas Sensor on a Chip



intermediate layer. A thin metallic film layer, perforated with apertures approximately the size of the emissions wavelength of the targeted gas, is the top layer.

The IR radiation, or emission process, begins in the bulk silicon where thermal stimulation produces blackbody-like radiation. The pattern of holes in the silicon oxide (photonic crystal) layer reshapes this spectrum of radiation and centers it around a specific wavelength of resonance defined by the lattice spacing in the crystal. As the photons cannot penetrate through the thin metal film (top layer), they excite surface plasmon waves at the photonic crystal/metal interface and generate a resonant interaction of the incident radiation with the surface plasmons on both the bottom and top surfaces of the metal film. The surface plasmons decay into photons and are emitted from the top metal surface toward the spherical mirror, above the bolometer. Using photonic crystal and surface plasmon interactions, the (top) metallic surface efficiently emits and absorbs in a narrow waveband centered on the signature wavelength of the target gas.

- *Photonic crystal*: Artificially engineered material with a lattice structure (lattice of holes) that repeats itself at regular intervals within a dielectric. Photonic crystals can have a photonic bandgap, or a range of forbidden frequencies (S. Johnson, website).
- *Photonic bandgap*: In periodic dielectric structures or photonic crystals, the propagation of electromagnetic waves is blocked over a certain frequency range. Electromagnetic waves (light) in the forbidden frequency range are reflected.
- Surface plasmons coupling or interaction: Surface plasmon is the particle name of an electron density wave. Surface plasmon resonance is a physical process that occurs when linearly polarized light is reflected off thin metal films. The electric field of the reflected photons extends a fraction of the wavelength above the reflecting metal surface and can interact with the free electron constellation in the metal interface, converting some of the photon’s energy into plasmons. The plasmons create a comparable field that extends into the thin metal layer, on either side of the film, with the same wavelength as the incident light reflected off the thin metal film (Puscasu et al., 2005).

The goal of the ATP-funded photonic crystal project was to resolve high-risk technical and fabrication process challenges associated with commercially viable SOC for gas measurement. Key ATP project objectives included:

- Developing a heated filament IR source to emit radiation in a narrow wavelength band, without the use of optical filters, demonstrating that the filament could act as its own detector (by measuring filament temperature or changes in filament resistance), and operating with a high signal-to-noise ratio

- Fabricating MEMS in standard semiconductor foundries to replace NDIR discrete component instruments “in the same way that integrated circuits replaced large electronic systems made from discrete components” (Johnson, 2004)
- Achieving thermal stability (mechanically holding the device together through thermal cycles during fabrication)
- Achieving operational stability subject to ambient temperature and optical conditions as well as environmental insults from interferent gases and operating with low power consumption and high signal-to-noise ratio
- Reaching high production volumes with a gradually declining cost structure

The ATP-funded project was successfully completed in 2001, resulting in:

- Efficient design tools for photonic crystals and frequency selective crystal surfaces
- Five-mask MEMS and e-beam lithographic process by the Jet Propulsion Laboratory, acting as subcontractor
- Thermal testing for IR source and for gas sensing and laboratory experiments confirming the predicted effect of interferent gases
- Cost improvement roadmap for reaching production cost targets
- U.S. patent (US 6,528,792 B2) and 24 published reports in scholarly and industry journals

With these results, the ATP-funded project resolved many technical and fabrication challenges for using photonic crystals to measure CO_2 levels accurately, reliably, and inexpensively in a variety of commercial applications.

When tuned to the signature wavelength of other gases, the ATP-funded photonics crystal technology could also have additional future use for the improved detection of other target gases of industrial and commercial interest.

BENEFIT ASSESSMENT AND MODELING

While accurate and cost-effective measurement of CO_2 levels is important in diverse commercial applications, available CO_2 sensors do not currently deliver both accuracy and low cost. Inexpensive chemical sensors, with low accuracy and reliability, comprise 85 percent of the market. Expensive NDIR sensors with high accuracy and reliability make up 15 percent of the market and their market potential is limited by capital cost, large size, and high power consumption (Frost & Sullivan, 2003).

The ATP-funded photonic crystal technology, developed by IOI to detect trace amounts of CO_2 with high accuracy, high reliability, and at low cost, represents a breakthrough technology that will overcome both performance limitations of chemical detectors and the cost, size, and power consumption limitations of NDIR sensors.

Near-term, high probability applications of the ATP-funded sensor technology are anticipated for:

- *Emergency medicine*: More accurate measurement of CO_2 concentrations in respired gases will reduce in-ambulance mortality (en route to the emergency room) and lead to fewer hospital days and reduced treatment costs for surviving patients.

- *Internal air quality control*: Measuring CO_2 levels in commercial office buildings, to facilitate better control of ventilation systems, will improve internal air quality levels and reduce energy use.

CO_2 SENSORS FOR EMERGENCY MEDICINE

Emergency treatment of trauma and other critically ill patients en route to the emergency room often includes inserting tubes in the trachea to deliver oxygen to the lungs. The insertion process entails considerable risk that the tube will accidentally be misdirected into the esophagus. If the error is not discovered in time, the patient may die.

The ATP-funded CO_2 sensor technology nearly eliminates the possibility that a misdirected oxygen tube will go undetected and result in medical complications or the patient's death.

Endotracheal Intubation

Patients suffering a complex array of injuries and acute medical emergencies, including open wounds from assault and traffic accidents, drug overdoses, strokes, and cardiac arrests, are often brought to the emergency room by ambulance or by air medical evacuation under paramedic care. En route, ambulance paramedics try to stabilize the patient's condition to improve the odds of survival and recovery. However, in trying to stabilize the patient's condition, paramedics must sometimes follow risky procedures.

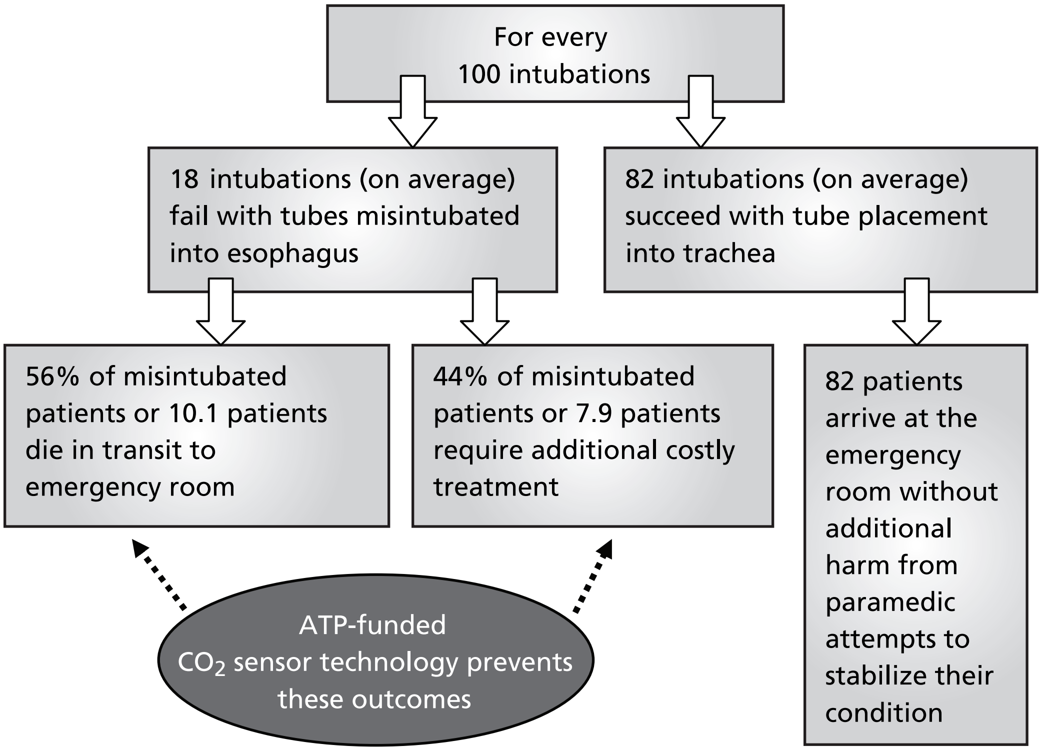
An important step in stabilizing patients involves ensuring that the airway is open and that the patient is not desaturated (i.e., that blood oxygen levels do not drop below critical levels, which could lead to brain damage and other potentially fatal complications). Paramedics will often have to ventilate a patient (provide appropriate levels of oxygen through mechanical ventilation) in transit to the emergency room by inserting a tube into the trachea (endotracheal intubation (ETI)).

Successful ETI may be difficult to achieve when patients are not adequately relaxed, are combative, or if field conditions are unfavorable, such as with flashing lights, snowstorms, and nighttime (Wang et al., 2001). Under these conditions, endotracheal tubes can be accidentally placed into the esophagus.

When endotrachael tubes are placed into the esophagus, and this is detected late or not at all, severe desaturation, medical complications, and even death can result (Fries, 1994; Arabi et al., 2004).

Several studies conducted over the 1994–1998 period indicate a high frequency of failed ETIs in pre-emergency room situations, varying from 14 to 22 percent (Lee et al., 1994; Khan et al., 1996; Epstein and Ciubotaru, 1998). A more recent study of an urban emergency service system indicates that “upon arrival in emergency room, up to 25 percent of patients were found to have improperly placed endotracheal tubes” and faced a 56 percent fatality rate (Katz and Falk, 2001). Relying on the former, more general studies, we assumed that for every 100 intubations under emergency ambulance-type conditions, 14 to 22 intubations fail to achieve proper tracheal tube placement, on average resulting in 18 misintubations, and 10.1 deaths (Figure 16).

Figure 16: **Rates of Emergency Ambulance Misintubation**



Approaches to Detecting Failed ETI

When failed ETI involves esophageal intubation, the result is an absence of expired CO_2. Capnometry is the direct measurement of maximum expired CO_2 concentrations (end-tidal CO_2) during a respiratory cycle and is considered to be an important diagnostic procedure for detecting failed ETI (Grmec, 2002). Two general approaches are currently used for monitoring expired CO_2 levels for the detection and timely correction of failed ETIs under ambulance conditions:

- *Colorimetric detectors*: Chemically treated paper that changes color when exposed to CO_2 in respired gases is the typical procedure for validating ETI. To verify successful intubations, several breaths are sampled and the paramedic then attempts to match detector color to a color chart. These attempts at visual matching often occur at night under, at best, difficult conditions, leading to high rates of false readings. Another source of false reading is gastric acid, which can be misinterpreted as the presence of respired CO_2. Colorimetric disposable detectors are inexpensive, selling at $13 per sensor, but have poor reliability, limited shelf life, and do not provide a quantitative measurement of CO_2 levels (Fletcher Spaght, 2001).

- *Infrared sensors*: These provide accurate quantitative measurements of end-tidal CO_2 levels. An IR beam is passed through a respired gas sample, and CO_2 molecules absorb specific wavelengths of the IR beam energy. The light emerging from the sample is analyzed, and the ratio of CO_2-affected wavelengths to non-affected wavelengths is reported as the end-tidal CO_2. Currently available IR sensors are part of complex NDIR systems composed of discrete components connected by cables. NDIR systems are expensive, selling at $3,000 to $4,000, require considerable space, and have high power consumption (Novametrics website).

The ATP-funded sensor technology is currently being commercialized as an integrated (rather than composed of discrete components) disposable CO_2 sensor that combines the portability and low cost of colorimetric detectors and the accuracy and reliability of NDIR sensor/monitor systems. In contrast to colorimetric paper detectors, disposable IR sensors have a long shelf life.

Economic Modeling

Use of inexpensive, portable IR sensors will facilitate the verification of proper endotracheal tube placement, essentially eliminating false CO_2 readings. Deaths of misintubated patients in transit to the emergency room and the need for subsequent treatment of misintubated patients who survive will thus be prevented.

These benefits are estimated in two stages:

- Expected benefits from use of portable CO_2 sensors in lieu of colorimetric paper for intubations benefits are computed (per 100 intubations for ease of interpretation)
- A sales forecast for portable CO_2 sensors is extended by expected benefits per sensor

EXPECTED BENEFITS PER 100 INTUBATIONS

Colorimetric detectors are used by ambulance paramedics to verify correct endotracheal tube placement and represent the prevailing defender technology. Several studies conducted over the 1994–1998 period, described above, provide a conservative estimate of the failure rate of colorimetric paper under emergency conditions and thus a basis for comparison with the ATP-funded technology.

Based on the observed failure rate of 14 to 22 percent with colorimetric paper documented in these studies, an average 18 percent failure rate is assumed for the defender technology. In contrast, ATP-funded CO_2 sensors are expected to eliminate false CO_2 readings and will provide correct verification of endotracheal placement 99 percent of the time. A 1 percent failure rate is assumed for operator carelessness.

Thus, for every 100 emergency ambulance intubations, 17 of the 18 expected misintubations are assumed to be immediately detected and corrected with ATP-funded CO_2 sensors. Clinical benefits and avoided treatment costs, resulting from preventing 17 failed intubations, are estimated below.

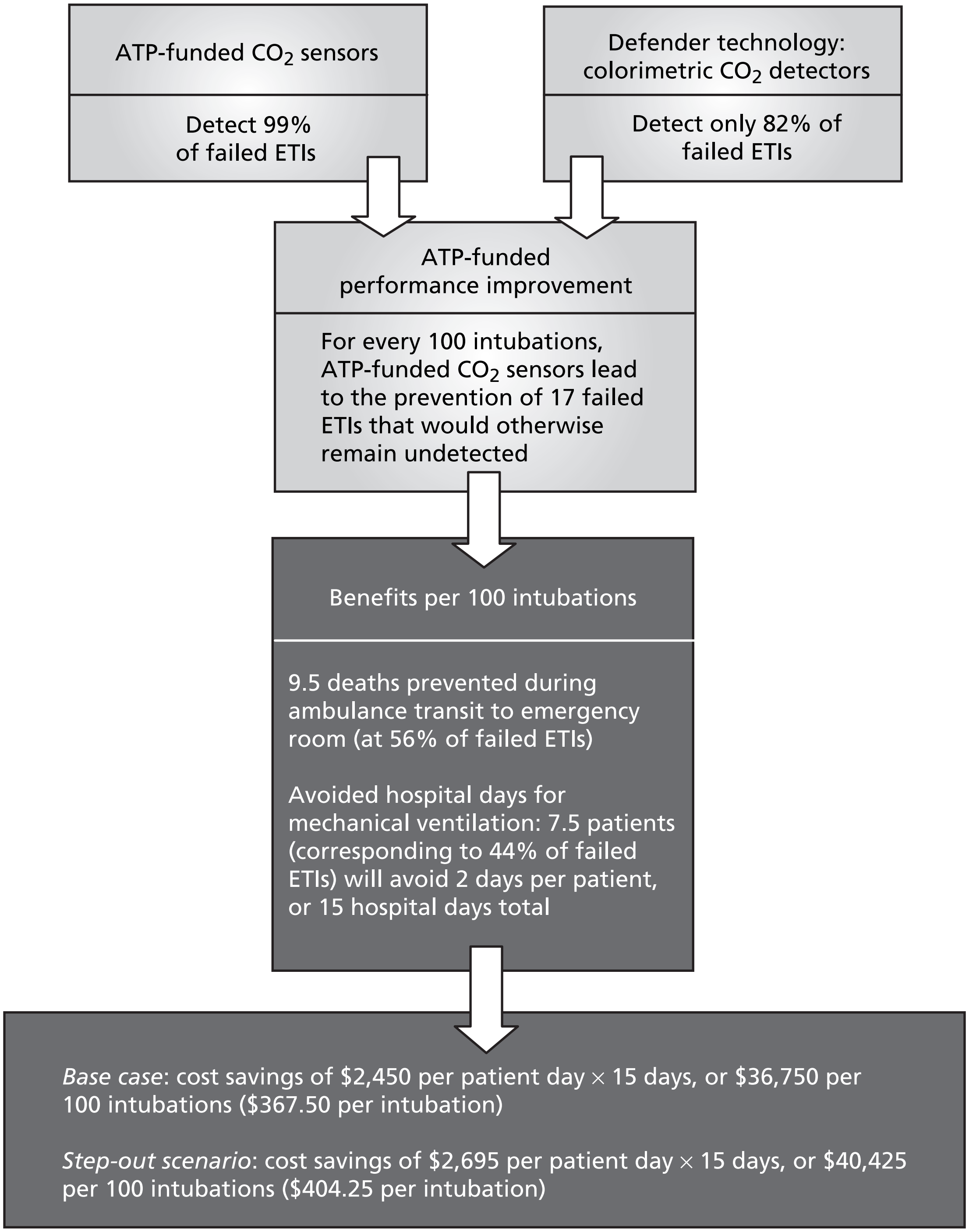
Clinical Benefits: Drawing upon the 2001 Katz study described above, correcting 17 failed intubations will result in the prevention of 9.5 deaths per 100 intubations during ambulance transport to the emergency room (see Figure 17). The reduced mortality rate of misintubated patients is likely to be the most important benefit from ATP-funded CO_2 sensors.

Prevented in-transit mortality does not constitute lives saved, as one usually understands the phrase. Gunshot wounds, drug overdoses, strokes, and heart attacks still remain to be treated upon arrival in the emergency room and in hospital specialty departments, with uncertain clinical results.

Thus, this study does not attempt to value the benefit of preventing in-transit mortality. Nevertheless, a safer ambulance journey to the emergency room should improve the odds of the patient's recovering with appropriate clinical care.

An additional non-quantified clinical benefit of low-cost, accurate CO_2 sensors is their use in predicting patient survival from resuscitative efforts and additional therapy and in determining when cardiopulmonary resuscitation may reasonably be terminated (Levine et al., 1997). As such, CO_2 monitoring could be used to maximize patient outcomes while reducing futile and costly interventions.

Figure 17: Projected Benefits per 100 Intubations from Improved Detection of Failed ETIs, Using ATP-Funded CO_2 Sensors in Lieu of Colorimetric CO_2 Detectors



Detect 99% of failed ETIs

Detect only 82% of failed ETIs

For every 100 intubations, ATP-funded CO_2 sensors lead to the prevention of 17 failed ETIs that would otherwise remain undetected

9.5 deaths prevented during ambulance transit to emergency room (at 56% of failed ETIs)

Avoided hospital days for mechanical ventilation: 7.5 patients (corresponding to 44% of failed ETIs) will avoid 2 days per patient, or 15 hospital days total

Base case: cost savings of \$2,450 per patient day × 15 days, or \$36,750 per 100 intubations (\$367.50 per intubation)

Step-out scenario: cost savings of \$2,695 per patient day × 15 days, or \$40,425 per 100 intubations (\$404.25 per intubation)

Avoided Treatment Costs: Preventing 17 failed intubations will also result in the avoidance of costly treatment (mechanical ventilation) and associated hospital stays for 7.5 patients per 100 intubations (see Figure 17). Risk of pneumonia, infection, and lung injury associated with the use of mechanical ventilation (Meade et al., 2001; Braverman, 2001; Ferrer et al., 2003) will also be avoided.

Conservatively, each patient who survives misintubation during ambulance transport is assumed to avoid two days of treatment and in-hospital days (Ferrer et al., 2003).

For base-case modeling, avoided daily costs are estimated at $2,450, consisting of $1,619 in daily treatment costs and $831 in daily hospital room charges (Cushing, 2004; Epstein and Ciubotaru, 1998). Treatment costs include nursing, respiratory therapist, and mechanical ventilation equipment costs. Hospital costs represent negotiated rates obtained by large health care plans.

For step-out scenario modeling, the avoided daily costs are estimated at $2,695, consisting of $1,719 in daily treatment costs and $976 in daily hospital room charges (American Hospital Association, 2003).

CO_2 SENSOR SALES PROJECTIONS

As was discussed earlier, IOI in 2001 sponsored an independent study to estimate the size of potential markets for disposable CO_2 sensors in emergency medicine applications (Fletcher Spaght, 2001).

The study used a bottom-up approach, relying on extensive direct discussions with nine OEMs of respiratory devices (which collectively represent more than 30 percent of the U.S. market for respiratory devices), emergency room staff at five hospitals, and 10 industry associations and institutions, including the American Ambulance Association, the American Association of Respiratory Care, and the American Hospital Association.

For the near term, extending to 2008, the study estimated the total U.S. market for disposable CO_2 sensors in emergency medicine at 38 million units for 2006, 43 million units for 2007, and 46 million units for 2008 (Table 5, column 1).

Based on direct fact-finding discussions with OEMs, the study estimated accessible levels of sales at 360,000 units in 2006, 4.2 million units in 2007, and 13.3 million units in 2008 (Table 5, column 2), which was considerably less than the total market. Total and accessible unit sales were extended beyond 2008 using a 6 percent long-term growth rate (Fletcher Spaght, 2001).

Going beyond the Fletcher Spaght market research, our case study developed its own bottom-up sales projections to estimate public benefits from ATP-funded CO_2 sensors following discussions with OEMs and industry associations during the early part of 2004.

The resulting unit sales projections used in our analysis (Table 5, column 3) are significantly lower than the accessible market levels Fletcher Spaght reported in its study.

In our study, base-case projected unit sales start at 10,000 units in 2006, compared to 360,000 units in the accessible market for the same year, and top out at 400,000 units per year, compared to an accessible market of 20 million units.

The probability of achieving unit sales projections (Table 5, column 3) is estimated to be 65 percent, reflecting our conservative assessment of marketplace risks facing a new technology company without current sales but very active in marketing a high performance product.

For a more optimistic step-out scenario, sales levels for each year (over the 2006–2015 period) are increased by 10 percent over base-case levels.

A separate top-down analysis is consistent with Table 5, column 3 sales projections. The primary U.S. target market for portable CO_2 sensors is the 24,000 vehicle ground ambulance fleet. A 2005 market estimate of 32 million capnometry procedures per year corresponds to less than four procedures per ambulance vehicle per day (American Ambulance Association, 2002).

Table 5: **Projected U.S. Market for Disposable CO_2 Detectors/Sensors Unit Sales and for IOI CO_2 Sensor Unit Sales (Thousands of Units)**

Year	Total emergency capnometry market (1)	Accessible emergency capnometry market (2)	Projected unit sales (for this study) (3)
2006	38,000	360	10
2007	43,000	4,200	40
2008	46,000	13,300	90
2009	49,000	14,100	130
2010	52,000	14,900	200
2011	55,000	15,800	300
2012	58,000	16,800	400
2013	62,000	17,800	400
2014	65,000	18,900	400
2015	69,000	20,000	400

Sources: Fletcher Spaght 2001 market study for IOI for columns 1 and 2.

Furthermore, an increased use of CO_2 readings in emergency room ambulance situations is anticipated. With growing concerns about malpractice liability lawsuits and adverse court decisions, the American College of Emergency Physicians recently recommended the significantly expanded utilization of capnometry to monitor intubated patients on their way to hospital emergency rooms, both to enhance patient safety and to reduce economic risk to the hospital. Over time, the expected increase in the frequency of ambulance CO_2 readings further suggests that total and accessible emergency capnometry markets are potentially vast.

IOI's ability to secure second and third rounds ($6.5 million) of venture capital financing is additional evidence for the credibility of conservative sales estimates used in this study.

DEFENDER TECHNOLOGY LOSSES

Portable CO_2 sensors that incorporate ATP-funded technology will displace colorimetric detectors. One CO_2 sensor will substitute for two colorimetric procedures given that approximately two colorimetric procedures are required for an acceptable reading while one CO_2 sensor reading can validate proper intubation.

As the cost of a colorimetric reading is about the same as a reading with a CO_2 sensor, defender technology losses can be estimated as two colorimetric sales minus one CO_2 sensor sale, or a net loss of one colorimetric sale. Firms suffering this loss of business to ATP-funded CO_2 sensors will forgo profit contributions from the sale of colorimetric units. This loss is estimated by extending lost sales revenues of $13 per unit by an average U.S. industry profit margin of 8.3 percent, or $1.08 per unit (*Business Week*, 2004).

Benefit Estimates

Mortality reductions during ambulance transport are a key benefit even if not quantified in dollar terms. Table 6, column 2 indicates mortality reductions during ambulance transport corresponding to projected sales of CO_2 sensors. On this basis, over the 2006–2015 period, an estimated 112,000 prevented in-ambulance deaths can be associated with the ATP investment.

Beyond prevented mortalities, cash flow benefits are computed by extending U.S. sales of CO_2 sensors by avoided treatment costs per misintubation. Cash flow benefits are computed for a period of 10 years, the estimated relevant lifespan of the ATP funded CO_2 measurement technology (per IOI).

By way of example, consider the following base-case calculation for 2007: The projected sale of 40,000 CO_2 sensors (from Table 6) corresponds to 40,000

Table 6: Reduced In-Ambulance Mortality (Prevented Deaths)

	Projected unit sales of CO_2 sensors for emergency medicine capnometry (from Table 5) (1)	Estimated prevention of in-ambulance deaths from timely detection of misintubation (2)
2006	10,000	950
2007	40,000	3,800
2008	90,000	8,550
2009	130,000	12,350
2010	200,000	19,000
2011	300,000	28,500
2012	400,000	38,000
2013	400,000	38,000
2014	400,000	38,000
2015	400,000	38,000
Total estimated prevented in-transit deaths (2006–2015)		225,150
Prevented death attribution to ATP		112,575

intubations. Per Figure 17, each intubation is associated with average economic benefits of $367.50. Multiplying $367.50 by 40,000 intubations results in total estimated economic benefits of $14,700,000. Assuming a 65 percent probability of realizing sales projections, the expected value of economic benefits is $9,555,000. Subtracting defender technology losses of $28,054, corresponding to the lost sale of colorimetric detectors as displaced by more accurate CO_2 sensors, yields net benefits of $9,526,946. Reflecting the relative importance and similar size and timing of both ATP and NSF investments, 50 percent of net benefit cash flows are attributed to the NSF for its research investment and 50 percent or $4,763,473 is attributed to the ATP (for 2005).

Base-case and step-out scenario cash flows covering the 2006–2015 period are displayed in Table 8, column 1, and Table 9, column 1, in the Benefit-Cost Analysis section of this chapter, where cash flows for the different photonic crystal applications are shown side by side.

CO_2 SENSORS FOR OFFICE SPACE INTERNAL AIR QUALITY

High building occupancy increases levels of CO_2, which results in stale air and insufficient humidity. Ventilation, where fresh air is exchanged for polluted, stale air, is the standard approach for improving internal air quality. However, ventilation systems in commercial buildings are often wasteful of energy.

Sensors with ATP-funded CO_2 sensor chips, in combination with variable air volume (VAV) systems, can optimize heating, cooling, and ventilation and contribute to improved levels of air quality in commercial buildings at lower energy costs.

According to a U.S. Department of Energy (DOE) survey, there are approximately 50 billion square feet of enclosed and conditioned (heated and/or cooled) commercial space in the United States (U.S. Department of Energy, 1999) with approximately 1.8 billion square feet added annually through new construction (Fletcher Spaght, 2001). This includes 10.2 billion square feet of office space.

Internal Air Quality

Poor internal air quality in commercial office space affects occupant comfort, productivity, and health. The chief sources of poor air quality include CO_2 production from people breathing and combustion contaminants (furnaces and space heaters). Other sources include biological contaminants (from wet or damp materials, filters, and insects and rodents), volatile organic compounds (from paints, waxes, cleansers, sealants, copy machines, and printers), formaldehyde (from furniture, carpeting, and fabrics), disinfectants, rodenticides, printing, and paper handling.

Component factors of poor air quality, individually or in combination, can cause discomfort from lack of air movement and from low humidity, including eye, nose, and throat irritations. Acute and potentially chronic conditions can also develop, including respiratory problems resulting from a buildup of chemical and biological pollutants.

Loss of worker productivity, absenteeism, unhappy tenants, and the threat of litigation can result from poor air quality and can have a negative impact on building owners' return on investment as well as the occupants' health. EPA suggests that average office worker productivity losses from poor indoor air quality can range from 2 to 4 percent, while noting the need for additional studies (U.S. Environmental Protection Agency, website).

Approaches to Building Ventilation and Energy Efficiency

During times of high building occupancy, increased levels of CO_2 can result in stale air and insufficient humidity. Ventilation, or the exchange of polluted, stale air with fresh air from the outside, is considered one of the more effective approaches for adequately controlling CO_2 levels and for providing acceptable overall levels of internal air quality (U.S. Environmental Protection Agency, 1990; Persily and Gorfain, 2004).

Generally, providing air movement through ventilation (using electric motors to run large fans to bring in fresh outside air and to remove stale inside air) is very energy intensive. When ventilation is operated at high constant levels (running large electric fans when air exchange is not needed), unnecessary energy costs will be incurred.

Over-ventilation can also lead to potential buildup of undesirable moisture levels, resulting in the formation of molds and other biological contaminants.

The energy efficiency of ventilation systems is, in large measure, constrained by installed HVAC (heating, ventilation, and air conditioning) system design as well as the system's ability to accurately measure CO_2 levels. In this regard, HVAC systems fall into two broad categories: constant air volume and variable air volume systems.

- *Constant air volume systems*: Many commercial buildings have HVAC systems that operate on the basis of predetermined design occupancy levels for daytime, nighttime, and weekends and do not have the ability to vary air volumes in response to changing levels of occupancy and CO_2.

- *Variable air volume (VAV) systems*: These systems are designed to vary building ventilation rates by tracking detected CO_2 levels. According to a DOE survey, 23 percent, or 2.3 billion square feet, of U.S. commercial office space is equipped with VAV systems that are able to follow CO_2 load and adjust ventilation rates as appropriate for changing levels of occupancy (U.S. Department of Energy, 1999).

To reach and maintain desirable internal air quality levels, without wasteful use of energy, buildings need to have accurate CO_2 sensors as well as VAV systems that can vary ventilation rates in response to detected CO_2 levels.

Commercially available CO_2 sensors fall into two broad categories: chemical detectors, which tend to be small and inexpensive but also inaccurate and unreliable, and discrete IR sensors, which are accurate and reliable but expensive and large. Discrete IR sensors are composed of many separate components including monitors, calibration kits, digital displays, and duct sampling kits, with systems priced at many thousands of dollars per building.

In contrast, the ATP-funded sensor chip, when integrated with an OEM's building control systems, will have comparable accuracy to discrete IR sensors but will be sold at a substantially lower price point, expected to be about \$25 per sensor, or \$250 for a typical building control system (Fletcher Spaght, 2001).

The EPA estimates that accurate and cost-effective CO_2 sensors, in combination with VAV ventilation systems, can reduce commercial office space energy consumption by 10–20 percent through avoided heating, cooling, and fan operations (U.S. Environmental Protection Agency, 1990; Emmerlich and Persily, 2001):

- It is costly to heat cold winter air and to cool hot summer air. Unnecessary air exchange from bringing in excess outside fresh air will increase the volume of air that must be heated and cooled at additional expense.
- Electric power is used to operate ventilation fans, and unnecessary ventilation will result in wasteful electricity consumption.

In combination with VAV systems, sensors with ATP-funded CO_2 sensor chips will contribute to reaching improved levels of internal air quality in commercial buildings, in addition to minimizing unnecessary heating, cooling, and ventilation costs. Better indoor air quality leads to:

- Increased worker productivity—U.S. EPA estimates performance losses from poor indoor air quality at 2 to 4 percent for all buildings (U.S. Environmental Protection Agency, website)
- Reduced incidence of respiratory diseases as well as diseases from other pathogens that can be diluted and removed through properly modulated ventilation (Aries, see website)

Economic Modeling

Energy savings are estimated and projected as quantitative cash flow benefits (Figure 18). Owing to the substantially greater complexity and uncertainty of productivity and health benefits, these benefits are expressed in non-monetary terms at this time.

To arrive at energy savings cash flow estimates, the following assumptions are used for each CO_2 sensor and the projected sales of CO_2 sensors.

EXPECTED BENEFITS PER CO_2 SENSOR

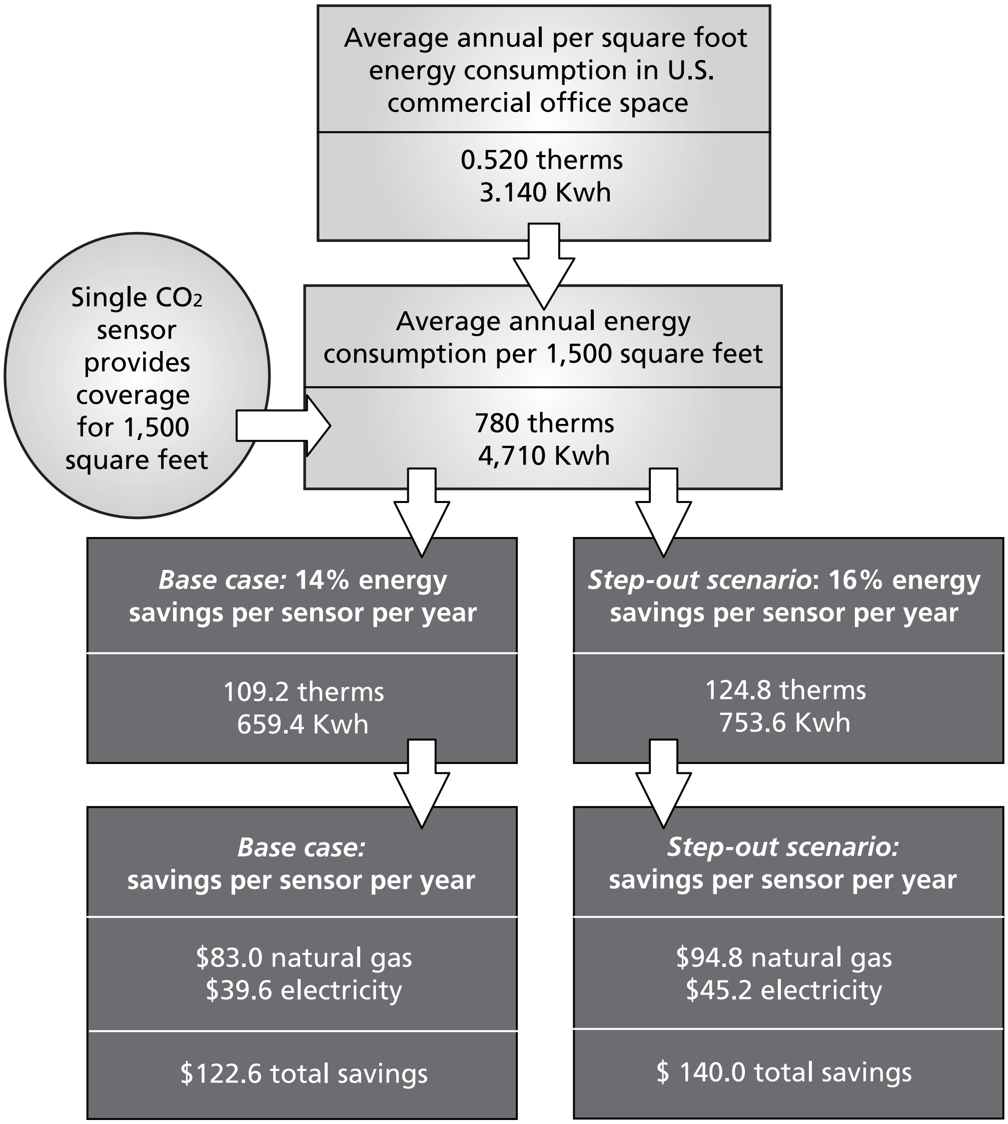
Based on electric and gas utility experience (Madison Gas & Electric, 2005), average energy consumption of commercial office space is estimated at 0.520 therms (520,000 BTUs) per square foot per year for space heating alone and 3.14 Kwh per square foot per year for cooling and ventilation, but excluding interior lighting and office equipment power consumption.

Consistent with IOI's sponsored independent market study (Fletcher Spaght, 2001), it is projected that one CO_2 sensor will be installed per each 1,500 square feet of office space. Extending baseline average energy consumption per square foot by 1,500 square feet, corresponding to one sensor, results in energy savings of 780 therms, or 4,710 Kwhs.

VAV ventilation systems in combination with CO_2 sensors can be expected to reduce HVAC costs by 10–20 percent according to EPA estimates (U.S. Environmental Protection Agency, website).

The base-case analysis assumes annual energy savings of 14 percent of baseline energy use, just below the midpoint of the EPA-estimated range (i.e., 109.2 therms and 659.5 Kwh per sensor). Extended by 2005 retail utility prices (76 cents per therm and 6 cents per Kwh (Madison Gas & Electric, 2005)), annual energy cost savings from ATP-funded CO_2 sensors are estimated at $122.60 per sensor.

Figure 18: Projected Annual Energy Savings from ATP-Funded CO_2 Sensors in Commercial Office Space Building Controls



The step-out scenario assumes annual energy savings of 16 percent of baseline energy use, just above the midpoint of the EPA-estimated range (i.e., 124.8 therms, or 753.6 Kwh per sensor). Extended by 2005 retail utility prices (Madison Gas & Electric, 2005), annual energy cost savings are estimated at $140 per sensor.

CO_2 SENSOR SALES PROJECTIONS

In 2001 IOI sponsored an independent study to estimate the potential U.S. market for CO_2 sensors in commercial buildings (Fletcher Spaght, 2001). Market research used a bottom-up approach, relying on direct discussions with 13 OEMs of building control systems and several industry associations for commercial buildings and building controls.

For the 2006–2007 period, the market study estimated the total U.S. market for CO_2 detectors at 5.2 million units per year. Four million units would be sold each year to retrofit existing commercial buildings and an additional 1.2 million units would be sold for new construction. Going forward, the size of the total market was assumed to remain flat at 5.2 million units (Table 7, column 1).

Based on fact-finding discussions with OEMs, the Fletcher Spaght study estimated accessible levels of sales at 600,000 units in 2006, increasing to 1 million units by 2010 and 1.2 million units by 2015 (Table 7, column 2).

Going beyond the Fletcher Spaght market study, our case study developed its own sales projections to estimate public benefits from ATP-funded CO_2 sensors through discussions with OEMs and industry associations during the early part of 2004. The resulting sales projections, indicated in Table 7, column 3, are significantly lower than accessible market levels, reflecting our conservatism concerning financial, manufacturing, and marketing limitations of new technology companies.

Our base-case sales projections start at 1,000 units in 2006, compared to 600,000 units in the accessible market for the same year, and top out at 292,000 units per year, compared to an accessible market of 1.2 million units.

Table 7: Projected U.S. Market for CO_2 Sensors in Commercial Buildings and IOI Unit Sales (Thousands of Units)

Year	Total market (1)	Accessible market (2)	Projected unit sales (for this study) (3)
2006	5,200	600	1
2007	5,200	700	48
2008	5,200	800	96
2009	5,200	900	144
2010	5,200	1,000	192
2011	5,200	1,040	240
2012	5,200	1,080	252
2013	5,200	1,120	265
2014	5,200	1,160	278
2015	5,200	1,200	292

Sources: Fletcher Spaght 2001 market study for IOI for columns 1 and 2.

The probability of achieving base-case sales projections shown in Table 7, column 3, is deemed to be 60 percent, reflecting our conservative assessment of marketplace risks facing a new technology company without current sales but very active in marketing a high performance product. IOI's ability to secure $6.5 million in two consecutive rounds of venture capital funding on the basis of their higher sales projection is additional evidence of the credibility of projected base-case unit sales used in this study.

For a more optimistic step-out scenario, sales levels for each year (over the 2006–2014 period) are increased by 10 percent over base-case levels.

Benefit Estimates

Total cash flow benefits each year are computed by extending U.S. sales of CO_2 sensors by economic benefits from energy savings.

Consider the following base-case calculation for 2007: The projected sale of 48,000 CO_2 sensors (from Table 7) is associated with average economic benefits of $122.60. Multiplying $122.60 by 48,000 unit sales results in total estimated economic benefits of $5,884,800. Assuming a 60 percent probability of realizing sales projections, the expected value of economic benefits is $3,530,880. Reflecting the relative importance and similar size of both ATP and NSF investments, 50 percent of net benefit cash flows are attributed to the NSF for its prior research investment and 50 percent or $1,765,440 is attributed to the ATP (for 2007).

Base-case and step-out scenario cash flows, covering the 2006–2015 period are displayed in Table 8, column 2, and Table 9, column 2, in the Benefit-Cost Analysis section of this chapter, where cash flows for two photonic crystal applications are shown side by side.

BENEFIT-COST ANALYSIS

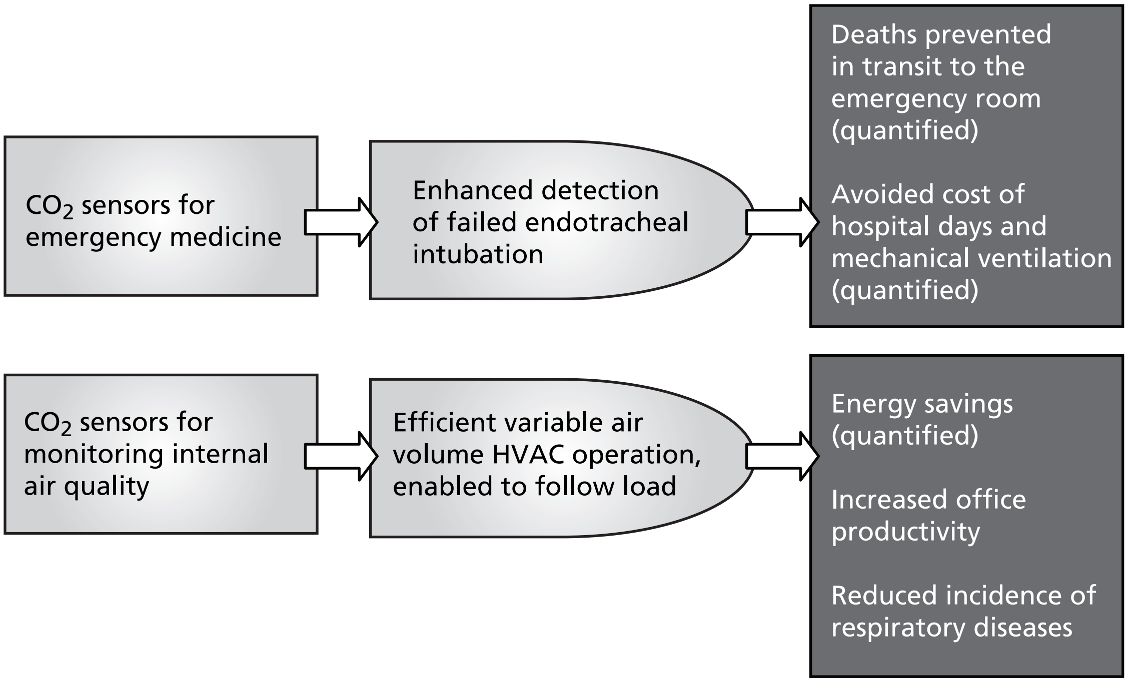
Prevented deaths in transit to the emergency room represent a significant societal and human benefit from the commercial use of the ATP-funded CO_2 sensor technology.

In addition, the technology will also yield significant economic benefits (Figure 19) in the form of:

- Treatment cost savings in emergency medical departments
- Reduced energy costs in commercial office buildings

This section presents performance metrics that capture the economic benefits from avoided hospital days, treatment costs, and energy savings as compared to ATP's investment in the high-risk photonic crystal sensor technology.

Figure 19: Flow of Benefits from ATP-Funded CO_2 Sensor Technology



ATP, NSF, AND INDUSTRIAL PARTNER INVESTMENTS

During the 1999–2001 period, ATP invested $753,000 toward project direct costs and industry partner, IOI, invested $626,000 in the development of photonic crystal CO_2 sensor technology. Several phases of prior and concurrent NSF grants ($850,000) supported prior research and were matched with $500,000 from IOI.

For purposes of cash flow analysis and computation of performance metrics, the ATP investment was normalized to 2005 dollars (as $827,000) and included as one lump sum investment in 2000, the midpoint of the ATP investment period.

PERFORMANCE METRICS

Our quantitative analysis of benefits was limited to public benefits that could be meaningfully quantified and excluded benefits and costs to IOI. Benefits attributable to ATP were determined to be 50 percent of total public benefits identified because NSF and ATP funding were approximately the same magnitude and both were deemed essential to realizing these benefits. We estimated benefit cash flows for a conservative base case and for a more optimistic step-out scenario. We compared these benefits to the cash flow representing ATP investment costs.

This comparison resulted in three sets of economic performance measures: net present value, benefit-to-cost ratio, and internal rate of return.

BASE-CASE ANALYSIS

As indicated in Table 8, the public return on ATP's investment in the CO_2 sensor technology over the 1999–2015 period can be expressed as a net present value of $143 million. Public benefits attributable to ATP are $174 for every dollar invested and the internal rate of return is estimated at 75 percent.

STEP-OUT SCENARIO ANALYSIS

A step-out scenario analysis investigated the sensitivity of base-case performance metrics to a more optimistic assumption about the projected future benefits of each

Table 8: Base-Case Cash Flows and Performance Metrics for ATP-Funded CO_2 Sensors (2004 Dollars, in Millions)

Year	Emergency medicine (1)	Building HVAC controls (2)	Total cash flows (3)
2000			–0.827
2001			
2002			
2003			
2004			
2005			
2006	1.191	0.037	1.228
2007	4.763	1.765	6.529
2008	10.718	3.531	14.249
2009	15.481	5.296	20.778
2010	23.817	7.062	30.879
2011	35.726	8.827	44.553
2012	47.635	9.269	56.903
2013	47.635	9.747	57.381
2014	47.635	10.225	57.860
2015	47.635	10.740	58.374
Net present value			143 million
Benefit-to-cost ratio			174:1
Internal rate of return			75%

Note: A 2000 base year and an OMB-designated 7 percent discount rate were used for analysis. Performance metrics were computed from time series assuming ATP investment in 2000 (project midpoint) and prospective cash flow benefits from 2006 to 2015. Positive cash flows represent public benefits attributable to ATP; negative cash flows represent ATP investment costs (assumed to occur at project midpoint).

CO_2 sensor in emergency medicine and office building air quality applications, in combination with a 10 percent increase in projected sales.

As indicated in Table 9, the public return on ATP's investment in the CO_2 sensor technology is associated with a net present value of $175 million. Public benefits attributable to ATP are $212 for every dollar invested and the internal rate of return is estimated at 79 percent.

Table 9: Step-Out Scenario Cash Flows and Performance Metrics for ATP-Funded CO_2 Sensors (2004 Dollars, in Millions)

Year	Emergency medicine (1)	Building HVAC controls (2)	Total cash flows (3)
2000			–0.827
2001			
2002			
2003			
2004			
2005			
2006	1.440	0.046	1.487
2007	5.762	2.218	7.979
2008	12.964	4.435	17.399
2009	18.726	6.653	25.379
2010	28.809	8.870	37.679
2011	43.213	11.088	54.301
2012	57.618	11.642	69.260
2013	57.618	12.243	69.861
2014	57.618	12.844	70.461
2015	57.618	13.490	71.108
Net present value			175 million
Benefit-to-cost ratio			212:1
Internal rate of return			79%

Note: A 2000 base year and an OMB-designated 7 percent discount rate were used for analysis. Performance metrics were computed from time series assuming ATP investment in 2000 (project midpoint) and prospective cash flow benefits from 2006 to 2015. Positive cash flows represent public benefits attributable to ATP; negative cash flows represent ATP investment costs (assumed to occur at project midpoint).

PRIVATE BENEFITS TO ATP INDUSTRY PARTNERS

ATP's industry partner's continued motivation to refine and commercially market the ATP-funded technology is a necessary pre-condition for commercial- and industrial-scale impact. Only with continued investment will the general public come to enjoy the health care and economic benefits expected to result from ATP's investment in the photonic crystals CO_2 sensor technology.

IOI's commercial progress to date and its continued motivation to actively market and improve CO_2 sensors is indicated by its progress toward commercialization. It has closed three rounds of venture capital financing of $8.2 million subsequent to receiving ATP funding. It has received more than 30 letters of interest, spelling out detailed sensor specifications from OEMs of medical respiration equipment and OEMs of building controls systems.

IOI has shipped customer evaluation units to these and other OEMs, has put in place a MEMS fabrication agreement with a leading MEMS foundry, and plans initial production runs for 2006.

SUMMARY

Performance metrics presented above point to exceptional performance from ATP's investment in the development of photonics crystals for CO_2 detection, as demonstrated by quantified medical benefits, high public rates of return, and important qualitative benefits.

5. Photonics Project Mini-Studies

This section reviews the technical challenges and accomplishments of three additional photonics projects with multi-industry applications. Together with the two case study projects, these three projects comprise the cluster of five ATP-funded photonics projects covered in this study.

The ATP-funded technical tasks for the three projects have been successfully completed and were selected to be part of the cluster study based on their substantial technical accomplishment and commercialization progress. While collectively these projects represent significant potential future benefits, the screening process conducted for this study indicates economic benefits to be somewhat longer term and less quantifiable at this time than for the two case study projects.

INFRARED CAVITY RING-DOWN SPECTROSCOPY

The objective of this project (99-01-2039) was to develop new electro-optical technology (using cavity ring-down spectroscopy (CRDS)) for highly sensitive detection of trace-level contaminants for a variety of industrial applications.

In 1999, Picarro (formerly Blue Leaf, Inc., and Informed Diagnostics, Inc.) of Sunnyvale, CA, submitted a proposal to the ATP for the development of mid-infrared (mid-IR) CRDS to improve detection sensitivity at reduced cost. The ATP agreed to fund the project, but soon it was apparent that owing to a lack of commercially available laser sources, the scope of the project had to be changed from development of mid-IR to development of near-IR CRDS technology.

The ATP-funded project, re-scoped to near-IR CRDS, was successfully completed in 2001 and, along with DOE-funded research (subsequent to ATP funding), led to two orders of magnitude improvement in sensitivity levels relative to prior near-IR CRDS. The ATP-funded project also resulted in a sixfold size reduction of large and cumbersome laboratory instrumentation.

To date, Picarro has realized prototype sales to potential industrial consumers in the semiconductor, petrochemical, and automotive industries. Applications include the detection of:

- Ammonia concentrations, at 1 ppb (parts per billion) sensitivity, in clean rooms
- Acetylene concentrations, at 30 ppb sensitivity, in process streams of 100 percent ethylene
- Hydrogen sulfide concentrations, at 50 ppb sensitivity, for ultra-clean diesel engine development and design

Given that technical advances accomplished with ATP and DOE funding and Picarro's financial resources are sufficient to support proactive marketing and subsequent manufacturing ramp-up, it is expected that customer acceptance will be achieved in the next year or two and that prototype production at fewer than 10 units per year can be ramped up to fully commercial production levels in excess of 100 units per year.

ATP-funded technology development has also led to in-house development of laser sources, which will facilitate potential future development of mid-IR CRDS technologies for homeland security and other applications that require even higher levels of sensitivity. Mid-IR applications are estimated to be four to five years from commercialization.

In 1999, Picarro had approximately 15 employees. The company was then able to raise several rounds of private financing, even during the difficult environments of 2003 and 2004, and is now operating with a staff of 80, underlining investor confidence in the ATP-funded near-IR CRDS technology as well as in Picarro's technical capabilities and management.

Picarro management made it clear that without ATP funding the technology advances and associated market opportunities would not have been realized or would have been realized at a much slower rate.

OPTICAL MAXIMUM ENTROPY VERIFICATION

The objective of this project (97-01-0244) was to develop a low-cost optical authentication technology for counterfeit-resistant labels and identification documents.

In 1996, Physical Optics Corporation of Torrance, CA, submitted a proposal to the ATP to develop a laser-based system to randomly generate patterns to be embedded in phase masks and used as templates for product labels. The authenticity of product labels would then be verified by comparing labels with a reference mask in the optical maximum entropy verification (OMEV) optical reader/correlator, utilizing a joint Fourier transform to verify the randomized optical signature in real time without the need for human interaction or a centralized database.

The project was successfully completed in 2001. In 2004, Physical Optics licensed the OMEV technology to OptiKey LLC, which is currently marketing the technology under the brand name of OptiKey Optical Authenticity Verification System. It is expected that OptiKey will complete commercial proof of concept in 2006.

Physical Optics realized licensing fees from this transaction and, going forward, expects to maintain a relationship with OptiKey as a provider of design and manufacturing services for the OptiKey authentication system. Target markets include:

- Industrial product authentication to reduce global product counterfeiting, currently costing U.S. industry tens of billions of dollars per year
- Secure identification cards (passports, driver's licenses, and military personnel ID) to reduce identity thefts and improve security

According to Physical Optics, the optical maximum entropy verification technology was unlikely to have been developed without ATP funding.

INTEGRATED MICRO-OPTICAL SYSTEMS

The objective of this project (98-02-0034) was to emulate the approach used in the micro-electronics industry in making very small and inexpensive integrated circuits with both optical and electronic components (e.g., lenses, laser diodes, and detectors).

In 1998, Digital Optics Corporation of Charlotte, NC, submitted a proposal to the ATP to develop manufacturing processes for wafer-scale integration of miniaturized micro-optical systems (IMOS).

IMOS would consist of lasers, optics, detectors, and electronics that are aligned and assembled on a wafer into complex, three-dimensional systems. New simulation and design tools as well as new processes for aligning and bonding wafers, mounting fixtures, heat management, packaging, and coating needed to be developed and demonstrated.

The ATP-funded IMOS technology project was successfully completed in 2001. Prototype IMOS were fabricated to demonstrate acceptable front-to-back alignment of laser, detector, and optics components and wafer-scale integration of three-dimensional optical systems on a photonic chip.

As intended, the ATP-funded project resulted in positioning the IMOS technology to move toward becoming an optical counterpart of integrated circuits, shrinking down from expensive macroscopic optical systems to inexpensive and compact photonic chips. Owing to the ATP-funded project, IMOS can potentially evolve toward becoming an infrastructure technology for low-cost photonics manufacturing.

Near-term commercial applications of IMOS chips are expected to be in telecommunications, digital cameras, and optical data storage. Digital Optics is currently in the process of developing IMOS-based products under the OSA or Optical System Assembly brand name. In addition to generalized OSA product applications that will reach cost-effective production levels through mass production, Digital Optics has also concluded some initial sales of customized IMOS or OSA units on a standalone basis.

In 2000, subsequent to the ATP award, Digital Optics received two venture capital equity infusions totaling $45 million, some of which was used to build a 100,000 square foot manufacturing facility. In 2002, Digital Optics was included in Deloitte & Touche's list of 50 fastest-growing technology companies in North Carolina.

6. Benefit-Cost Analysis for the Cluster of Projects

Cluster analysis uses a hybrid approach combining the advantages of detailed case studies and overview studies for a richer assessment of empirical relationships between public-private investments in industry-led science and technology projects and the resulting benefits to industry and end-users.

- Detailed case studies are used to develop insights into market dynamics and technology commercialization pathways and to provide a credible basis for estimating benefit cash flows and associated probabilities.
- Cash flow estimates are used to compute performance metrics to quantify the relationships of investments and resultant benefits.
- Overview studies are used to extend the analysis beyond individual projects and to generate lower-bound performance estimates for the entire cluster.

PHOTONICS PROJECT CLUSTER

Of the five projects in the photonics cluster, one project, Capillary Optics for X-Ray Focusing and Collimating, has reached full commercialization. Another project, MEMS-Based Infrared (Photonic Crystal) Micro-Sensor for Gas Detection, is approaching full commercialization. Near-term, high-probability public benefits are quantifiable.

For the remaining three projects, Infrared Cavity Ring-Down Spectroscopy, Optical Maximum Entropy Verification, and Integrated Micro-Optical Systems, uncertainties exist concerning the nature and size of public benefits, and only project costs, without quantitative benefit estimates, are included in benefit-cost analysis.

Given that this study uses benefit cash flows from only two case study projects in combination with ATP-investments in five projects and that the remaining three projects may yield significant public and private benefits in time, cluster analysis results in this study represent conservative, lower-bound performance estimates as of 2005.

BENEFITS, INVESTMENTS, AND PERFORMANCE METRICS

Once fully commercialized, ATP-funded photonics technologies will generate both public and private benefits. Our emphasis in this study is on measuring public benefits to industry users and to the general public that are attributable to ATP relative to ATP's investment. Public benefits, excluding benefits to the innovating firm will be realized by:

- Health care institutions and industrial and commercial users of new photonics technologies
- Consumers of improved medical services, industrial products, and commercial services
- Society at large, enjoying, among other benefits, reduced environmental emissions

The resulting performance metrics provide a direct indicator of ATP success in addressing its mission to fund high-risk technology development projects with potential for broad economic benefit to the nation.

Figure 20 illustrates the general flow of public benefits in the cluster study process. Public benefits attributable to the ATP are combined with ATP investments to yield economic measures of the return on ATP's investment.

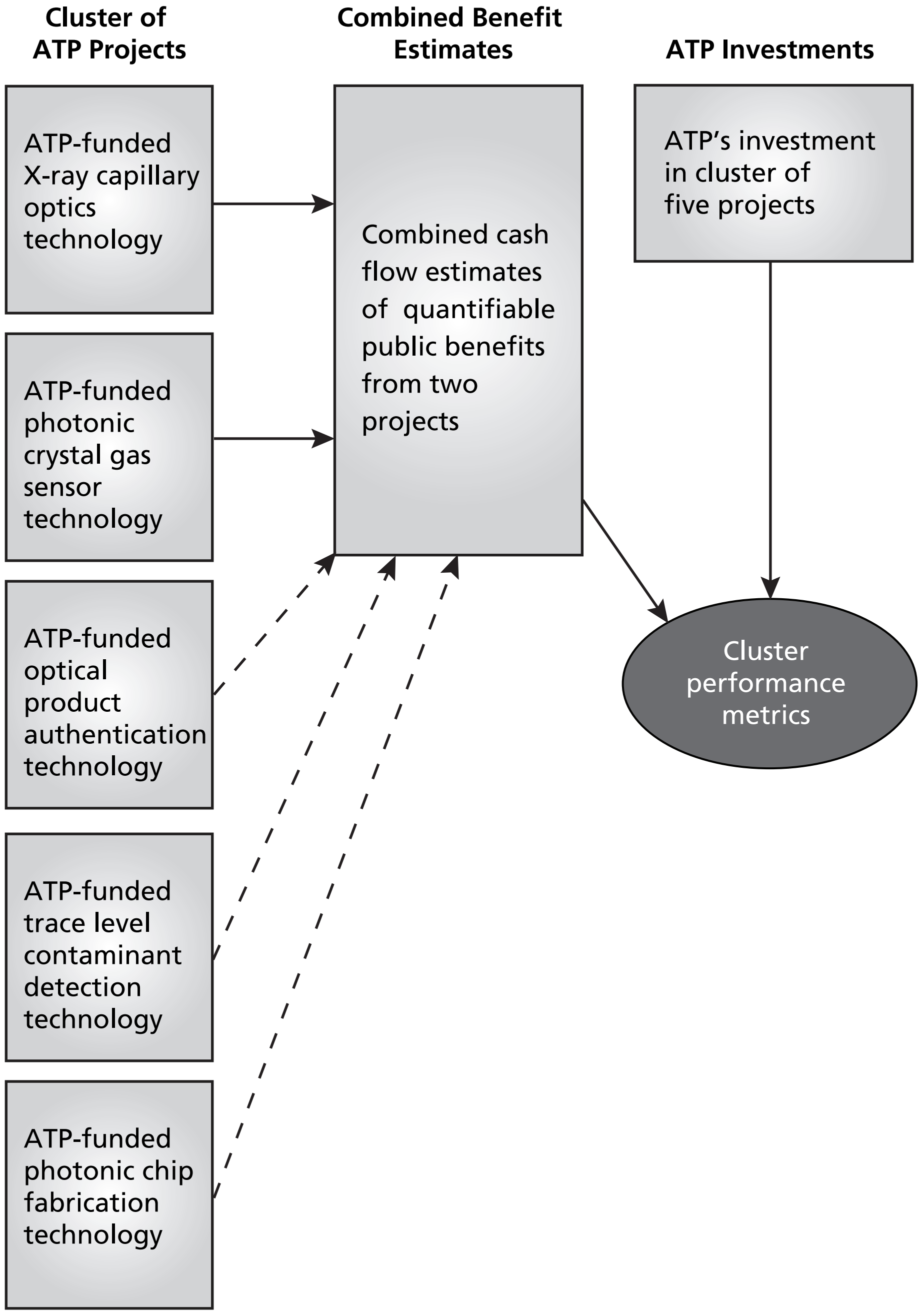
More specifically, Capillary Optics for X-Ray Focusing and Collimating and MEMS-Based Infrared (Photonic Crystal) Micro-Sensor for Gas Detection, two of the five projects in the cluster (in Chapters 3 and 4) associated with quantifiable, high-probability cash flow estimates from medical, petroleum refining and distribution, advanced materials, and commercial real estate applications, are connected with solid line arrows to the Combined Benefit Estimates box in the middle of Figure 20.

Cash flow benefit estimates for the remaining three projects are currently unavailable, as indicated with broken-line arrows to the Combined Benefit Estimates box. Broken line arrows denote possible future cash flows should longer-term benefits from these three projects become more certain through ongoing commercialization efforts. While beyond the scope of the current study, cash flow estimates for these three remaining projects could be developed at a future date.

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

We will also introduce the social rate of return, which is a broader measure of ATP project impact. This measure combines public and private benefits relative to combined public and private investments, including those of the innovating firms.

Figure 20: Public Benefits, Investments, and Performance Metrics for Cluster of Related ATP Projects



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

BASE-CASE CLUSTER ANALYSIS

Conservatively estimated benefit cash flows from the two case study projects, capillary X-ray optics utilization in advanced materials and petroleum refining applications, starting in 1997 and continuing until 2014 (Chapter 3), and photonic crystal gas sensor utilization in emergency medicine and commercial real estate internal air quality control applications, starting in 2006 and continuing until 2015 (Chapter 4), were combined as cluster analysis benefit streams (Table 10, column 2).

ATP's combined investment in the cluster of five projects was $7.47 million. Normalized to 2004 dollars, the combined ATP cluster investment was $8.7 million (Table 10, column 1). Industry partner investment, not included in public return on ATP investment metrics, was $ 6.3 million.

In Table 10, column 4, retrospective cash-flow performance of ATP's investment over the 1997–2003 period is isolated from the combined retrospective and prospective cash-flow performance over the 1994–2000 period.

BASE-CASE CLUSTER PERFORMANCE METRICS

Combined cash flows (retrospective plus prospective) over the 1994–2015 period (Table 10, column 3), representing estimated benefits attributable to ATP from the two case studies netted against ATP investments in the five projects, are used to compute performance metrics for the cluster of projects. These cluster performance metrics (net present value of $276 million, benefit-to-cost ratio of 33:1, and internal rate of return of 48 percent) are indicated in Table 11, column 1.

Cash flow time series over the 1994–2003 period composed of ATP investments in the five projects and realized benefits from one of the two case study projects are used to compute *retrospective* performance metrics for the cluster of projects. As indicated in Table 11, column 2, base-case retrospective performance metrics show a net present value of $2.9 million, benefit-to-cost ratio of 1.9:1, and internal rate of return of 16 percent.

STEP-OUT SCENARIO CLUSTER ANALYSIS

The step-out scenario is based on more optimistic projections of future benefits from ATP-funded technologies. Benefit estimates per unit sold are somewhat higher, in combination with higher unit sales assumptions. ATP investments are the same as for base-case analysis.

Cash flow time series over the 1994–2015 period composed of ATP investments in five projects and both realized and expected benefits from the two case-study projects are used to compute step-out performance metrics for the *cluster* of projects. As indicated in Table 12, column 2, cluster performance metrics show a net present value of $345 million, benefit-to-cost ratio of 41:1, and internal rate of return of 51 percent.

Table 10: Cash Flows Combining ATP Investments in a Cluster of Five Photonics Projects and Combining Benefits from Two Case Study Projects (2004 Dollars, in Millions), Base Case

	ATP investments in five projects (midpoints of investment period) (1)	Combined benefit cash flows from two projects (2)	Net cluster cash flows (retrospective and prospective) (3)	Net retrospective cash flows (4)
1994	–2.496		–2.496	–2.496
1995				
1996				
1997		0.161	0.161	0.161
1998		0.390	0.390	0.390
1999	–3.137	0.734	–2.403	–2.403
2000	–3.021	1.537	–1.484	–2.311
2001		2.937	2.937	2.937
2002		4.887	4.887	4.887
2003		6.906	6.906	6.906
2004		8.840	8.840	
2005		18.191	18.191	
2006		32.261	32.261	
2007		52.313	52.313	
2008		75.384	75.384	
2009		83.565	83.565	
2010		94.905	94.905	
2011		109.281	109.281	
2012		121.941	121.941	
2013		122.667	122.667	
2014		123.248	123.248	
2015		58.374	58.374	

Note: Benefit cash flows in column 2 are computed from Total Cash Flows columns in Tables 3 and 8. The sharp drop in year 2015 "combined benefit cash flows" reflects a period of analysis for X-Ray Optics extending to 2014 while the period of analysis for Ion Optics extends through 2015.

Table 11: Base-Case Performance Metrics Using Benefit Cash Flows from Two Case Studies against ATP Investment in a Cluster of Five Projects (2004 Dollars, in Millions)

	Total performance metrics	Retrospective performance metrics
Net present value	$276 million	$2.9 million
Benefit-to-cost ratio	33:1	1.9:1
Internal rate of return	48%	16%

Note: A 1994 base year and an OMB-designated 7 percent discount rate were used for analysis. Performance metrics were computed from time series representing ATP investments over the 1994–2000 period and retrospective and prospective cash flow benefits from 1997 to 2015.

Table 12: Base-Case and Step-Out Scenario Performance Metrics (2004 Dollars, in Millions)

	Base-case performance metrics	Step-out scenario performance metrics
Net present value	$276 million	$345 million
Benefit-to-cost ratio	33:1	41:1
Internal rate of return	48%	51%

Note: A 1994 base year and an OMB-designated 7 percent discount rate were used for analysis. Performance metrics were computed from time series representing ATP investments over the 1994–2000 period and retrospective and prospective cash flow benefits from 1997 to 2015.

FUTURE EXTENSION OF CASH FLOW BENEFITS

Over time, additional projects in the cluster, and many other ATP-funded photonics projects, will be successfully commercialized. As that occurs, the estimation of cash flow benefits can be expected to lead to an upward adjustment of performance metrics presented in the current study. Given this potential for additional cash flow benefits from future analysis, the levels of performance reported in this study (based on cash flows from only two ATP-funded projects) represent conservative, lower bound estimates of cluster performance.

ADDITIONAL PERFORMANCE METRIC: SOCIAL RATE OF RETURN

ATP-funded projects are cost-shared with innovating companies in the private sector. They benefit the innovating companies, suppliers, customer industries, and end-users—in essence, all taxpayers. Therefore, a measure of the total benefits relative to total costs provides a broader, more complete picture of project performance than public returns on ATP's investment alone. The social rate of return is such a measure and has been used by leading economists as an important indicator for broad social benefits that result from new technologies and innovations (Griliches, 1958; Mansfield, et al., 1977; Jaffe, 1996; Mansfield, 1996).

Economists compare social rates of return to private rates of return (i.e., rate of profit received by innovating companies that use ATP funding to complement their own investment in cost-shared projects). The gap between social and private rates of return is an indication of the project's value to society compared with its value to the innovating company that executed the project in the expectation of a return, or to private investors that might help finance technology investments.

This comparison is a cornerstone of economic justification for government-funded technology development. Broad-based societal benefits, as a point of reference for the widespread benefits that R&D can generate for society, are contrasted to private returns (profits) that innovating firms are typically able to capture and retain, i.e., appropriate for themselves (Mansfield et al., 1977; Yager and Schmidt, 1997).

The "excess of the social rate of return over the private rate of return is the spillover gap" (Jaffe, 1996). A large gap tends to signify the innovating firm's inability to appropriate most technology benefits to itself in the form of additional profits and can lead to private sector under-investment and associated loss of benefits to downstream firms, end-user customers, the economy, and society.

ATP compensates for the spillover gap by partially funding the development of high-risk, innovative technologies that private firms are unable to fund owing to R&D technical risks and appropriability risk.

To estimate social rates of return from ATP's investment in the two case study projects, both public and private benefit cash flows are estimated and combined. Combined benefits are then compared to combined public and private investments using an internal rate of return calculation.

Given the company-sensitive nature of private return information, proxies are used to estimate private returns.

Private rates of return involve sensitive company information and are generally not made available for specific products or lines of business. Hence, an industry-level proxy needs to be used to map sales revenues into expected levels of profit associated with new technologies and products.

As a basis for estimating private rates of return by proxy, two approaches are used depending on the source of investment funds:

- *For corporate industrial sponsors*: Real rate of returns are expected to range from 5 to 25 percent (Mansfield et al., 1977; Mansfield, 1996).
- *For venture capital funds*: Real rates of return over a 10-year investment horizon are reported as 25 percent (Venture Economics, 2004); other sources have reported somewhat lower rates.

Social rates and spillover gaps for the two case study projects are then estimated as follows:

- Private benefits (profits) are computed from projected X-Ray Optical Systems and Ion Optics unit sales and associated revenue projections. Revenue projections are multiplied by 12.3 percent or the reported Q3 2004 average inflation-adjusted profit margin for U.S. technology firms (*Business Week*, 2004) to arrive at estimated profits of ATP industry partners. These profit estimates are a proxy for private benefits from industry partner technology investments.

- Private benefits or profits to be realized by ATP industry partners are combined with projected public benefits to arrive at total benefits.

- Public investments by ATP and other public agencies are combined with industry partner matching funds and with additional private investments that supported the completion of technology and product development, initial marketing, and production ramp-up to arrive at total costs.

- A time series of all investments, public and private, and all benefits, public and private, are used to compute an internal rate of return for each project (the project's estimated social rate of return).

As indicated in Table 13, social rates of return from new X-Ray Optics and from Ion Optics technologies substantially exceed average expected industry returns and can be associated with spillover gaps ranging from 18 to 46 percent. These reported spillover rates are generally consistent with Mansfield's empirical findings, which

Table 13: Constant Dollar Returns for the Two Case Study Projects Comparing Social Returns and Private Returns to Estimate Spillover Gap (Benefits that ATP-Industry Partners Are Generally Unable to Capture)

	Social rate of return	Private rates of return (estimated range)	Spillover gap: Social returns minus private returns
X-Ray Optical Systems, Inc.	43%	5–25%	18–38%
Ion Optics, Inc.	51%	5–25%	26–46%

identified the median spillover gap ranging from 31 to 34 percent (Mansfield et al., 1977; Mansfield, 1991).

Reported spillover rates from the cluster of ATP-funded photonics technologies, in combination with the magnitude of the social rates of return, indicate substantial benefits to the general public beyond that received by ATP grantee companies. Given that these projects would not have been funded at all without an ATP cost-share, the results indicate a fulfillment of the ATP mission to fund high-risk technologies with a potential for large-scale economic benefits to the nation.

7. Conclusions

New photonics technologies have broad implications for U.S. industrial growth and productivity in the manufacturing, medical, entertainment, information technology, telecommunications, and homeland security sectors.

From the early days ATP has funded high-risk photonics projects to enhance U.S. competitiveness through the development of:

- Macrosystem miniaturization and functional integration
- Advanced metrologies for trace-level detection on a near-real-time basis
- Cost-efficient high-quality fabrication methods at scales approaching mass production

A cluster study approach was used to evaluate the retrospective and prospective benefits from several ATP-funded photonics projects, bringing together technical advances from optics and electronics to develop high-performance process, metrology, and product technologies.

The cluster consisted of five projects, spanning applications in industrial materials analysis, petroleum refining and distribution, medicine, and building controls.

These projects were selected for analysis based on the projects' technical success and degree of progress toward commercialization. Within this cluster, two projects were singled out as having achieved full commercialization and/or having highly probable, near-term prospects for commercial deployment and for generating substantial economic benefits:

- Capillary Optics for X-Ray Focusing and Collimating
- MEMS-Based Infrared (Photonic Crystal) Micro-Sensor for Gas Detection

Detailed case studies were conducted for these two projects, and higher level overview studies were conducted for the remaining three projects.

Quantitative analysis points to substantial public returns on ATP's investment, including:

- Estimated 112,000 prevented deaths of trauma victims and critically ill patients on their way to U.S. emergency rooms during the 2006–2015 period.
- Substantial cost savings, based on increasingly efficient industrial materials analysis, energy savings in petroleum refining and distribution, avoided medical treatment costs, and energy savings in commercial real estate. These cost savings are used to compute the following economic performance metrics for the cluster of five projects:
    - ❑ For a base case, $33 of public benefits to U.S. industry, consumers, and the nation for every dollar of ATP's $7.47 million investment
    - ❑ For a step-out scenario with somewhat more optimistic assumptions, $41 of public benefits for every dollar of ATP's investment
    - ❑ Some benefits from ATP technology investments have already been realized, leading to $1.90 of realized public benefits for every dollar of ATP's $7.47 million investment in the cluster of five projects

An alternative, broader performance measure of total public and private (social) rate of return points to significant spillover gaps (the difference between the social rate of return and private rate of return), indicating that the value of the project to the general public is substantially greater than its value to the companies receiving public cost-share funding. Furthermore, these projects would not have been undertaken at all without public funding, so the funding made possible both the public and private benefits.

Levels of social returns ranging from 43 to 51 percent and spillover gaps ranging from 18 to 46 percent provide strong validation for testimonials by ATP industry partners as to the essential nature of ATP cost-shares for the successful completion of high-risk technology development efforts and the eventual commercialization of photonics technologies.

In addition to quantitative performance metrics for public and social returns, the cluster analysis also points to broad-based qualitative benefits including reduced risk of post-emergency room infections, reduced harmful diesel emissions, improved occupant productivity in commercial office space, and accelerated development of advanced materials for new industrial products.

The cluster analysis targeted only two ATP-funded projects with near-term benefits for quantitative analysis. It is likely that the remaining three photonics projects will also progress toward commercialization and lead to additional public and private benefits. Over time, these additional benefit cash flows can be expected to result in upward adjustment of performance metrics presented in this study.

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Appendix: Cluster of ATP-Funded Photonics Projects

Project number	Project title	Industry partner
91-01-0112	Capillary Optics for X-Ray Focusing and Collimating	X-Ray Optical Systems, Inc. http://www.xrayoptics.com
99-01-2051	MEMS-Based Infrared (Photonic Crystal) Micro-Sensor for Gas Detection	Ion Optics, Inc. http://www.ion-optics.com
99-01-2039	Infrared Cavity Ring-Down Spectroscopy	Picarro, Inc. http://www.picarro.com
97-01-0244	Optical Maximum Entropy Verification	Physical Optics Corporation http://www.poc.com
98-02-0034	Integrated Micro-Optical Systems	Digital Optics Corporation http://www.doc.com

Project number	Year funded	Project duration (years)	ATP funding ($ millions)	Industry funding ($ millions)	Total funding ($ millions)
91-01-0112	1991	4	1.95	0.37	2.34
99-01-2051	1999	2	0.75	0.63	1.38
99-01-2039	1999	3	2.00	2.83	4.83
97-01-0244	1997	3	1.11	1.21	2.32
98-02-0034	1998	2	1.66	1.22	2.88
Totals			7.47	6.26	13.75

About the Advanced Technology Program

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

Promising future technologies are the domain of ATP:

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

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

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

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

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

About the Author

Dr. Thomas Pelsoci is the managing director of Delta Research Co., specializing in the economic assessment of new technologies and manufacturing processes, including prospective economic impact studies during early stage proof of concept and later stage demonstration phases.

His industrial experience includes positions as R&D engineer at TRW and management consultant in the high technology practice of BearingPoint (KPMG Peat Marwick Management Consultants). Subsequently, Dr. Pelsoci held senior banking positions at First National Bank of Chicago and at Sanwa Bank, specializing in financing information systems and technology projects. He received a degree in Mechanical Engineering from Case Western Reserve University and a Ph.D. in Public Policy and Administration from the University of Minnesota.