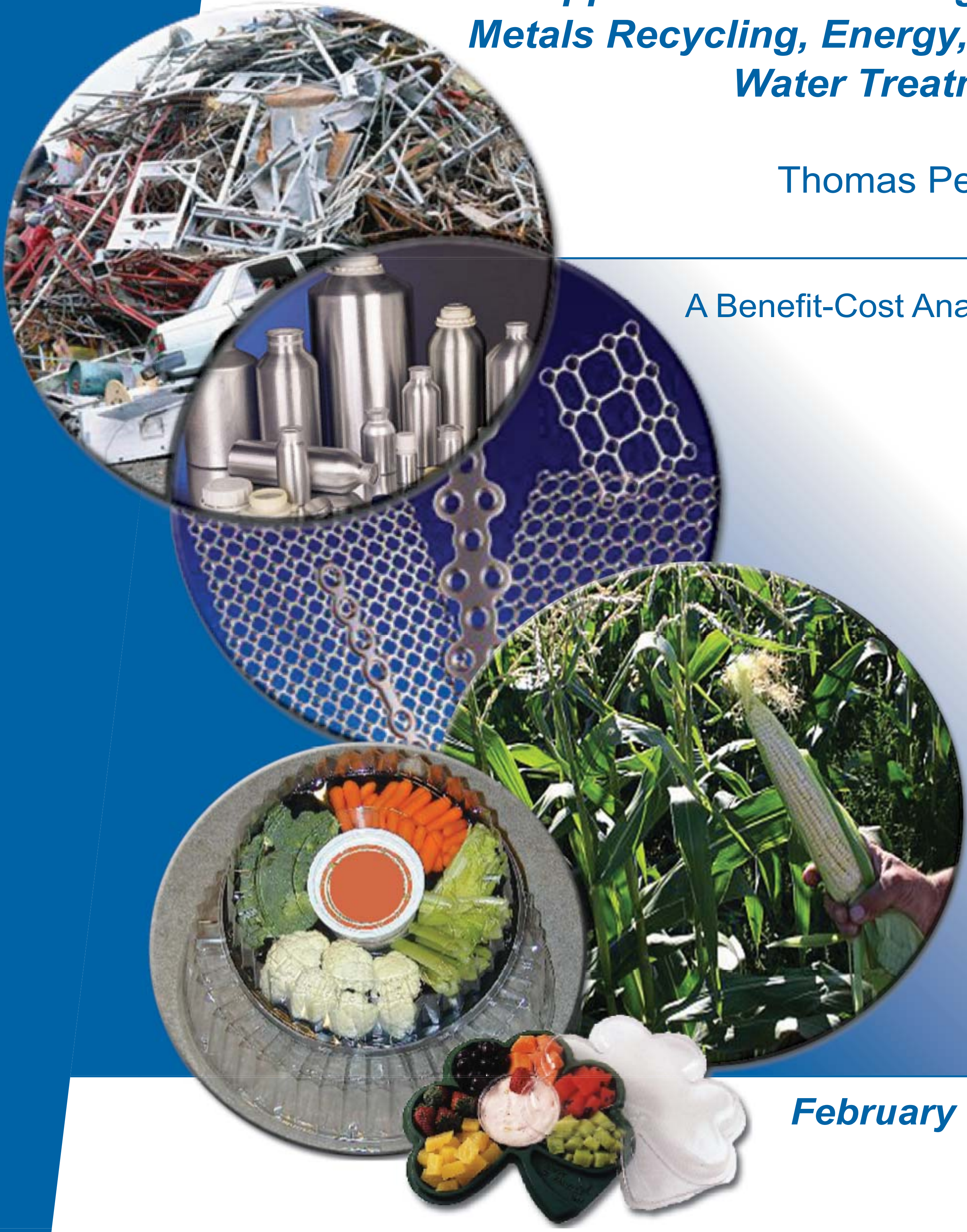
GCR 06-897

ADVANCED TECHNOLOGY PROGRAM

ATP-Funded Green Process Technologies: *Improving U.S. Industrial Competitiveness With Applications in Packaging, Metals Recycling, Energy, and Water Treatment*

Thomas Pelsoci

A Benefit-Cost Analysis



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About ATP's Economic Assessment Office

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.

Since the inception of ATP in 1990, ATP's Economic Assessment Office (EAO) has performed rigorous and multifaceted evaluations to assess the impact of the program and estimate the returns to the taxpayer. To evaluate whether the program is meeting its stated objectives, EAO employs statistical analyses and other methodological approaches to measure program effectiveness in terms of:

- Inputs (program funding and staffing necessary to carry out the ATP mission)
- Outputs (research outputs from ATP supported projects)
- Outcomes (innovation in products, processes, and services from ATP supported projects)
- Impacts (long term impacts on U.S. industry, society, and economy)

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- Nine out of 10 organizations indicate that ATP funding accelerated their R&D cycle.
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Contact ATP's Economic Assessment Office for more information:

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Prepared for
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Abstract

At its outset, the environmental movement targeted the reduction of harmful industrial emissions as an important and self-evident public benefit without assessing the burden of emissions reduction on industrial competitiveness. Over the years, U.S. environmentalism came to recognize the complex nature of linkages to industrial competitiveness. A new approach—a quest for green solutions aimed at reconciling environmental objectives with industrial competitiveness—gradually evolved.

Green initiatives were often fashioned around high-risk new technologies, relying on market price mechanisms to complement regulatory initiatives. These high-risk process technologies could be effective in protecting the environment and, at the same time, reducing manufacturing costs, improving energy security and the security of strategic materials, and enhancing industrial safety and product performance.

From its early days, the Advanced Technology Program (ATP) has funded high-risk, innovative green process technologies. ATP's green technology investments generally followed the principles of Green Chemistry including the reduction of harmful emissions, substituting renewable industrial feedstock for petroleum-based feedstock, reducing industrial waste, promoting industrial recycling, and simultaneously reducing process costs and improving competitiveness.

To assess the economic impact of ATP-funded green process technologies, five technology projects were selected for study, spanning applications in food packaging, textiles, metals, durable goods, coal mining, natural gas production, and wastewater treatment. Two projects that have proceeded beyond initial commercialization were selected for detailed case studies, including quantitative analysis of benefits and costs. Brief mini-studies were conducted for three other ATP-funded green process technology projects.

The two detailed case studies point to substantial public returns on ATP investments over the 2003–17 period.

The ATP-funded Renewable-Resource Based Plastics Manufacturing case study shows:

- Benefit-to-cost ratio on ATP's investment ranging from 11:1 to 24:1
- Net present value of ATP's investment ranging from $21 to $50 million
- U.S. consumption of imported petroleum reduced by 14 to 16 million barrels
- Greenhouse gases reduced by almost two million metric tons

The ATP-funded High-Speed Identification and Sorting of Nonferrous Metal Scrap case study shows:

- Benefit-to-cost ratio on ATP's investment ranging from 11:1 to 14:1
- Net present value of ATP's investment ranging from $20 to $25 million
- Greenhouse gas emissions reduced by over 313,000 metric tons

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

In addition to the benefits quantified in the two detailed case studies, the three mini-studies showed qualitative public benefits including:

- Avoided burying of post-consumer polymer wastes in landfills
- Health benefits from reduced mercury concentrations in post-industrial waste streams
- Health benefits from reduced lead concentrations in paint-removal processes.

Given that ATP's industry partners would not have developed high-risk, low-cost, green process technologies without ATP's cost share, ATP funding enabled these technology advances, associated market opportunities, and resultant public benefits.

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Executive Summary

Green process technologies bring together advances in biology, chemistry, and the other physical sciences to provide practical solutions for a host of environmental, energy dependence, and manufacturing efficiency challenges that have long defied market solutions due to the presence of externalities.

Externalities—that is, market failures to properly reflect damaging environmental emissions and other hidden economic and social costs in price mechanisms—typically have led to regulatory responses that have pitted environmentalists against industry in zero sum contests. Environmental regulation, while effective at protecting health and natural resources, has often been perceived as undercutting U.S. industrial competitiveness.

In contrast to the adversarial relations characterizing the early stages of the environmental movement, the subsequent quest for green solutions is aimed at reconciling environmental objectives with industrial competitiveness. More recent green initiatives often have been fashioned around new, high-risk technologies and have relied on market price mechanisms to effectively complement regulatory initiatives. These high-risk process technologies could protect the environment and, at the same time, reduce manufacturing costs, improve energy security and the security of strategic materials, and enhance industrial safety and product performance.

* * * * *

Since its inception, ATP has been at the forefront of providing financial support for the development of promising green process technologies—with high technical risks—leading to the following environmental and economic benefits:

- Reduced reliance on imported petroleum with renewable domestic feedstock
- Reduced reliance on imported strategic raw materials
- Reduced industrial waste streams and energy use through green design principles

- Cost-effective recycling of post-industrial and post-consumer waste streams
- Reduced harmful environmental emissions, including greenhouse gases

To gauge the effectiveness of ATP green process investments, ATP commissioned a study of five projects to investigate the empirical evidence of the benefits of green technologies. The following projects were selected for analysis:

- Renewable-Resource-Based Plastics Manufacturing
- High-Speed Identification and Sorting of Nonferrous Metal Scrap
- Sorting of High-Value Engineered Plastics (to Facilitate Recycling)
- Molecular Gates Technology for Cost-Effective Purification of Natural Gas
- High-Intensity Ultraviolet Lamp Systems for Water Treatment and Paint Stripping

These projects spanned applications in food packaging, textiles, metals, durable goods, coal mining, natural gas production, and wastewater treatment. To date, four projects have achieved some degree of commercialization and are beginning to generate green benefits, with more significant benefits yet to come. One project, which has not yet achieved commercialization, also has near-term commercial prospects with identifiable green benefits for U.S. industry and society.

Two of the five projects that have proceeded beyond early commercialization were selected for detailed case studies, including the quantitative analysis of benefits and costs:

- Renewable-Resource-Based Plastics Manufacturing, with applications in the food packaging and textiles industries
- High-Speed Identification and Sorting of Nonferrous Metal Scrap—an enabling technology for cost-effective recycling of valuable post-industrial and post-consumer scrap—with applications in the metals, aerospace, and automotive industries

Detailed case studies identified key technical accomplishments and pathways to market and quantified energy savings, efficiency gains, and greenhouse gas benefits.

Benefits from the remaining three projects were assessed on a qualitative basis. Future economic analysis may determine that their benefits can also be captured and quantified.

This report describes the results of the two detailed case studies and the results of three mini-studies that highlight green process technology projects. Data collection and analysis were started in 2005 and completed in early 2006.

Case Study: Renewable-Resource-Based Plastics Manufacturing

Cargill, Inc. of Minnetonka, Minnesota and its wholly owned subsidiary NatureWorks developed an innovative process technology, with ATP funding, that uses U.S.-grown corn as feedstock for the cost-effective manufacturing of polylactic acid (PLA) resins. A fundamental methodology for controlling PLA crystallinity was worked out and used to develop processing technologies to achieve resin properties for a variety of polymer products. PLA resins can replace feedstock derived from imported petroleum and are used to make polymer products for food packaging and textiles applications.

Commercial-scale operations started in 2003. Two-thirds of PLA production is exported to international markets and one-third sold in domestic U.S. markets. Green benefits from commercial operations are projected to include reduced overall energy requirements for plastics manufacturing, substantially reduced utilization of imported petroleum-derived feedstock along with increased feedstock cost stability, avoided landfilling of post-consumer plastic wastes (which can be composted when plastics are made from corn-based feedstock), and reduced greenhouse gas emissions.

Public benefits to industrial customers as well as benefits to society were quantified on the basis of a conservatively estimated production volume of less than 34 million pounds of PLA in 2003 and projected volume of 100 million pounds in 2015. Public returns on ATP's investment over the 1996–2017 study period are summarized through performance metrics that indicate net present values of \$21–\$50 million and benefits of \$11–\$24 for every dollar invested by ATP. Private benefits to Cargill and NatureWorks were excluded.

Economic performance metrics reflect green benefits and cost savings from the use of the ATP-funded PLA process technology in the food packaging and textile industries.

Case Study: High-Speed Identification and Sorting of Nonferrous Metal Scrap

wTe Corporation of Bedford, Massachusetts used ATP funding to develop a proprietary alloy-sorting technology for cost-effective sorting of nonferrous metal scrap including titanium alloys, superalloys, and aluminum alloys, thereby facilitating the increased recycling of these valuable metals.

A wide range of green benefits can be traced to this ATP-funded technology project, including upgrading of mixed nonferrous metal scrap for highest-value use, avoiding outright waste of some metal scrap that cannot currently be recycled on a cost-effective basis, reducing energy use by facilitating less energy–intensive secondary smelting, reducing greenhouse gas emissions associated with primary alloy production, and reducing import dependence for titanium and nickel metal concentrates used in the primary production of titanium alloys and nickel-based superalloys.

Commercial-scale sorting of titanium alloys started in 2005. The sorting of aluminum alloys started in 2006 and superalloy sorting is expected to commence in 2008.

Public benefits to industrial customers from the unambiguous sorting of scrap alloys as well as benefits to the general public were quantified on the basis of conservatively estimated nonferrous scrap sorting volumes of less than 2 million pounds in 2006 and reaching over 70 million pounds per year by 2015. Public returns on ATP's investment over the 2002–15 study period are summarized through performance metrics that indicate net present values of $20–$25 million and benefits of $11–$14 for every dollar invested. Private benefits to wTe Corporation were excluded.

Economic performance metrics reflect green benefits and cost savings from the use of ATP-funded green technologies in the metals, aerospace, and automotive industries.

OVERVIEW OF GREEN BENEFITS

The implicit proposition underlying ATP investments in green process technologies is that innovative new technologies can be used to reduce harmful emissions and dependence on imported petroleum and, at the same time, reduce costs and increase U.S. industrial competitiveness. This proposition was supported by two detailed case studies of ATP investments. Public benefits were conservatively projected, using actual market prices that do not fully internalize the costs of pollution and the growing U.S. reliance on imported petroleum. Should externalities become further internalized into market price structures, even higher levels of benefits may be linked to ATP-funded green technologies.

Beyond the detailed studies, mini-studies of three additional ATP-funded green projects also point to emerging patterns of success, validating ATP's implicit proposition that harmful emission reductions can be achieved along with increased industrial competitiveness. ATP-funded molecular gate technology for natural gas purification (Engelhard Corp.) and ATP-funded plastics sorting technology (MBA Polymers) have achieved commercialization and profitable operations in competitive markets for natural gas recovery and engineered plastics recycling. The ATP investment in high-intensity ultraviolet lamp systems, while at a precommercial stage, potentially will reduce levels of harmful mercury and lead concentrations in post-industrial and post-consumer waste streams.

ATP's early leadership in supporting the development of high-risk, innovative, green process technologies is increasingly being validated through recent investment trends in the agricultural and chemical industries.

Large corporations that are industry leaders in the agricultural and chemical sectors are able to bring about industrial-scale changes from the predominant utilization of petroleum-derived feedstock to the use of plant-based feedstocks for chemicals. Reflecting the growing realization that carbon is carbon—in both petroleum-derived feedstock and in agricultural crops—industry leaders are increasingly placing investment bets on the commercialization of cost-effective green process technologies.

In addition to major industry players betting on new green process technologies, venture capital and institutional investors are exhibiting growing enthusiasm for a broad range of green technology investments.

CONCLUSIONS

Research performed for this study indicates that ATP's industry partners would not have developed or very likely could not have sustained high-risk green process technologies without the ATP cost share. Technical 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 was made for public benefits from other federal sources of science and technology funding.

Performance metrics and qualitative benefits, presented in this Executive Summary and in Table ES-1, illustrate the strong performance of ATP investments in selected green process technologies, including high public rates of return, reduced reliance on imported petroleum, reduced greenhouse gases, and increased U.S. agricultural production and employment. Further benefits from these and other green projects (not part of this study) are expected as ATP cost-shared green process technologies reach the marketplace.

Table ES-1: Public Benefits from ATP-Funded Green Process Technologies

Benefits Identified in Detailed Case Studies

Renewable-Resource-Based Plastics Manufacturing

- For every dollar of ATP investment, U.S. industry, consumers, and the nation will realize \$11–\$24 of cost savings. The net present value of ATP investment is projected to range from \$21 to \$50 million.
- U.S. consumption of imported petroleum is reduced by 14–16 million barrels, greenhouse gases are reduced by almost 2 million metric tons, and new U.S. jobs are created.

High-Speed Identification and Sorting of Nonferrous Metal Scrap

- For every dollar of ATP investment, U.S. industry, consumers, and the nation will realize \$11–\$14 of cost savings. The net present value of ATP investment is projected to range from \$20 to \$25 million.
- Greenhouse gas emissions are reduced by over 313,000 metric tons.

Benefits Identified in Mini-Studies

- Recycling of high-value engineered polymers for highest-value reuse.
- Avoided burying of post-consumer polymer wastes in landfills.
- Cost-effective purification of small-volume flows of coal-bed methane into pipeline-quality natural gas.
- Health benefits from reduced mercury concentrations in post-industrial waste streams and from reduced toxic lead concentrations in paint-removal processes.

Cross-Industry Knowledge Diffusion

The implementation of innovative green process technologies, in combination with licensing and other forms of industrial cooperation, will continue to diffuse new knowledge to other economic agents and expand the benefits to society and the nation.

Contents

Abstract . . . . **iii**

Acknowledgments . . . . **v**

Executive Summary . . . . **vii**

Abbreviations, Acronyms, and Definitions . . . . **xvii**

1. Introduction **1**

OBJECTIVES AND SCOPE 1

PROJECT SELECTION CRITERIA 2

FIVE SELECTED PROJECTS 3

Renewable-Resource-Based Plastics Manufacturing 3

High-Speed Identification and Sorting of Nonferrous Metal Scrap 3

Sorting of High-Value Engineered Plastics 4

Molecular Gates Technology for Cost-Effective Purification of Natural Gas 4

High-Intensity Ultraviolet Lamp Systems for Water Treatment and Paint Stripping 5

2. Analytical Framework and Methodology **7**

SELECTION CRITERIA 7

IDENTIFICATION OF BENEFITS 8

Logic Model of Green Process Technology Benefits 8

Counterfactual Scenario 9

Public and Private Benefits 10

Attribution of Benefits to ATP 10

BENEFIT CASH FLOW ESTIMATES 11

Retrospective and Prospective Benefits 12

Offsets 13

Base Case and Step-Out Scenarios 13

OTHER ANALYSIS 13

PUBLIC BENEFIT PERFORMANCE METRICS 14

METRIC FOR GAUGING THE SPILLOVER GAP 15

3. **Case Study: Renewable-Resource-Based Plastics Manufacturing 17**
PROJECT HISTORY 18
HOW DOES IT WORK? 20
Technical Challenges and Risks of the ATP-Funded Project 20
Technical Accomplishments 22
Patent Estate and Publications 24
COMMERCIAL APPLICATIONS 24
Polymer Industry 24
Pathways to Market 25
PLA Target Applications 26
BENEFIT ASSESSMENT AND MODELING 28
Processed Volumes and Sales Estimates 28
Benefit Assumptions 30
BENEFIT-COST ANALYSIS 36
ATP and Industry Partner Investments 37
Public Returns on ATP Investment—Base Case 37
Public Returns on ATP Investment—Step-Out Scenario 40
Social Rate of Return 41
OTHER BENEFITS 42
Reduced Reliance on Imported Petroleum 42
Benefits to the U.S. Farm Economy 43
CASE STUDY SUMMARY 44

4. **Case Study: High-Speed Identification and Sorting of Nonferrous Metal Scrap 45**
PROJECT HISTORY 46
HOW DOES IT WORK? 47
Technical Accomplishments 51
Patent Estate 52
BENEFIT ASSESSMENT AND MODELING 52
Titanium Alloy Sorting 53
Superalloy Sorting 57
Aluminum Separation and Sorting 61
Total Processed Volumes 67
BENEFIT-COST ANALYSIS 68
Investments and Attribution 68
Public Returns on ATP Investment—Base Case 69
Public Returns on ATP Investment—Step-Out Scenario 71
Social Rate of Return 72
OTHER BENEFITS 73
Reduced Raw Material Import Dependence 73
Increased Availability of Metal Scrap 73
Reduced Energy Usage 73
Reduced Environmental Emissions 74
CASE STUDY SUMMARY 74

5. **Mini-studies of ATP-Funded Green Process Technologies** 75
ENABLING TECHNOLOGY FOR LARGE-SCALE RECOVERY OF HIGH-VALUE PLASTICS FROM DURABLE GOODS: MBA POLYMERS 75
MOLECULAR GATES TECHNOLOGY FOR THE COST-EFFECTIVE PURIFICATION OF NATURAL GAS: BASF CATALYSTS, LLC (FORMERLY ENGELHARD CORPORATION) 77
HIGH-INTENSITY ULTRAVIOLET LAMP SYSTEMS FOR WATER TREATMENT AND PAINT STRIPPING: PHOENIX SCIENCE & TECHNOLOGY INC. 78

6. **Green Technologies that Promote Industrial Competitiveness** 81
PROJECT SPACE FOR GREEN PROCESS TECHNOLOGIES 81
ATP-FUNDED GREEN PROCESS TECHNOLOGIES 82
INDUSTRY AND INVESTOR VALIDATION OF ATP GREEN INVESTMENTS 85

7. **Conclusions** 87

References 91

Figures

Figure 1: Flow of Benefits from ATP-Funded Green Technologies 9
Figure 2: General Representation of Cash Flows for Performance Analysis 11
Figure 3: Manufacturing Lactic Acid and PLA from Corn 21
Figure 4: Current Value Chain for PLA-Based Polymer Production and Use 25
Figure 5: Flow of Public Benefits from PLA Process Technology 37
Figure 6: Proposed Two-Stage Approach Using Alloy Grouper and Alloy Sorter 49
Figure 7: Single-Stage Titanium Alloy Sorter and Superalloy Sorter 49
Figure 8: Single-Stage Aluminum Alloy Sorter with DXRT Front End 50
Figure 9: Major Uses of Titanium Mineral Concentrates 53
Figure 10: Titanium Alloy Manufacturing Process Flows 54
Figure 11: Closed-Loop Recycling for Titanium Alloy Sorting 55
Figure 12: Closed-Loop Recycling for Superalloy Sorting 60
Figure 13: Aluminum Production 63
Figure 14: Estimation of Public Benefits Attributable to ATP Funding 69

Tables

Table ES-1: Public Benefits from ATP-Funded Green Process Technologies xii
Table 1: Projected PLA Resin Sales (Million Pounds per Year) 29
Table 2: Fossil Energy Budgets for PLA and PET (BTU per Pound of Product) 31
Table 3A: EIA Reference Energy Price Scenario (2005 Dollars per Million BTU) 32
Table 3B: EIA High Energy Price Scenario (2005 Dollars per Million BTU) 32
Table 4: Base Case Energy Cost Savings—PLA versus PET (2005 Dollars) 34
Table 5: CO_2 Emission Estimates (Pounds of CO_2 per Pound of Polymer) 34
Table 6: Trading Ranges for Chicago CCX Carbon Credits (Dollars per Metric Ton) 35

Table 7: Base Case—Cash Flows and Performance Metrics for Public Returns on ATP Investments (Millions of 2005 Dollars) 38
Table 8: Step-Out Scenario—Cash Flows and Performance Metrics for Public Returns on ATP Investments (Millions of 2005 Dollars) 40
Table 9: Social Rate of Return and Spillover Gap 41
Table 10: Reduced Petroleum Use—PLA versus PET 43
Table 11: Approximate U.S. Titanium Pricing (per Pound in 2005 Dollars) 57
Table 12: Approximate U.S. Superalloy Price Spread (per Pound in 2005 Dollars) 61
Table 13: Approximate U.S. Aluminum Pricing (2005 Dollars per Pound) .66
Table 14: Avoided CO_2 Generation from Recovery of 3/8 Fraction 67
Table 15: Base Case Processed Volumes (Thousands of Pounds) 67
Table 16: Relevant Public and Private Investments (Thousands of Dollars) 68
Table 17: Base Case Cash Flows and Performance Metrics (Millions of 2005 Dollars) 70
Table 18: Step-Out Scenario Cash Flows and Performance Metrics (Millions of 2005 Dollars) 71
Table 19: Social Rate of Return and Spillover Gap 72
Table 20: Social Rate of Return for Two Case Study Projects 88

Abbreviations, Acronyms, and Definitions

Alloy	Combination of two or more elements, either in solution or as a compound, with at least one element a metal and the resulting material having metallic properties
Aluminum twitch	Mixed aluminum alloys, segregated from "heavier" metallic components of nonferrous concentrates
Amorphous	Randomly oriented polymer chains without crystal-like structures
BTU	British thermal units
CCX	Chicago Climate Exchange
Copolymer	Multiple monomers linked in the same polymer chain
Chirality	Molecular structures that do not line up with their mirror image, not unlike left and right hands. Chiral molecules come in several forms or isomers, sometimes denoted as D-isomer for dextro (right in Latin) and L-isomer for levo (left in Latin). Isomers differ only in the arrangement of atoms.
Crystalline	Polymer chains folding upon themselves in repeating symmetrical patterns. As long polymer chains may become entangled, only partial crystallization is achieved.
Defender technology	Established technology replaced by ATP-funded innovation
D-isomer	Form or isomer of a chiral molecule
Dextrose	Natural form of glucose or sugar
DSC	Differential scanning calorimetry
DXRT	Differential X-ray transmission
Enantiomers	Mirror-image D-isomers and L-isomers of dextrose

Glass transition	Temperatures at which the degree of chain motion is substantially reduced
High Z	High atomic number elements
Ilmenite	Oxide of iron and titanium and a major titanium ore
Isomers	Molecules with the same chemical formula and often with the same kinds of bonds between atoms, but in which the atoms are arranged differently
Lactide	Anhydrous form of lactic acid, cyclic dymer
L-isomer	Form or isomer of a chiral molecule
Low Z	Low atomic number elements
Melting point	Temperature at which crystalline regions of thermoplastic polymer melt
Meso-	Middle or intermediate chemical term that denotes one particular isomer
Monomer	Small molecule that may become chemically bonded to other monomers to form a polymer
NFC	Nonferrous concentrate
NMR	Nuclear magnetic resonance spectroscopy
NRT	National Recovery Technologies
NSF	National Science Foundation
Oligomer	Polymer or polymer intermediate containing relatively few structural units
PET	Polyethylene terephthalate; petroleum-based thermoplastic resin for beverage, food, and liquid containers. Impermeable polymer for bottling carbonated and acidic drinks
PLA	Polylactide; biodegradable, thermoplastic resin derived from lactic acid. Due to chirality of lactic acid, there are several forms or isomers of PLA, including L-, D-, and LD-forms. PLA is usually amorphous but can be crystallized by varying isomer content and nucleating agent.
Polymer	Long molecules or chains consisting of repeating units or monomers strung together through chemical bonds. Many polymers are partially crystalline and partially amorphous in molecular structure, giving them both a melting point and a glass transition temperature.
Polymerization	Chemical reaction of monomer molecules to form linear chains or three-dimensional polymer chains

Post-industrial scrap	Produced during the fabrication of metals and articles
Post-consumer scrap	Retired consumer goods, including automobiles
PP	Polypropylene; petroleum-based thermoplastic polymer with applications including food packaging and textiles
PS	Polystyrene; petroleum-based thermoplastic polymer for "expanded" or foamed PS—a mixture of PS with over 90 percent air—for cups and food containers
Resin	Raw material form of a polymer, usually pellets that melt to viscous liquids, capable of hardening
Ring opening	Polymerization reaction in which the rings of cyclic polymerization monomers are opened, allowing them to be joined together linearly. For PLA, the polymer chain end (in the presence of an appropriate catalyst) "attacks" an ester linkage in the lactide molecule, opening the ring and extending the polymer chain length by two lactic acid residues.
Rulite	Metallic concentrate for primary titanium refining
Singulator	Device for sequencing single pieces of metal on a conveyor
Superalloy	Complex metallic material engineered for very high-temperature applications. Often polycrystalline structure
Thermoplastic	Polymers containing linear polymer chains with covalent bonding within the chains, while chains are joined through weak dispersion forces. Thermoplastic polymers soften when heated and harden when cooled, and are able to go through many melt/freeze cycles without chemical change.
Trommel	Device for screening and sizing metal pieces
UV	Ultraviolet radiation
XRF	X-ray fluorescence

1. Introduction

In the early days of the environmental movement, pollution prevention and remediation often were advocated without incorporating efficiency criteria. This resulted in adversarial relationships when industry was placed under increasingly stringent regulatory mandates to prevent harmful emissions and to remediate past pollution. Industry came to view and often resist pollution prevention measures as unwelcome burdens that would substantially undercut U.S. industrial competitiveness.

In contrast to the early adversarial model, the green movement evolved with a focus on practical solutions for the gradual reduction of harmful emissions and the use of petroleum-based feedstock. Often, new, high-risk, process technologies were the centerpiece of green solutions.

Over the years, ATP investment in green process technologies became aligned with this evolving green movement and its quest for the simultaneous achievement of emission reductions, sustainable use of natural resources, and industrial competitiveness through the application of new and innovative process technologies. In particular, ATP investments appear to have followed the tenets of Green Chemistry, including new process designs that stress the use of renewable industrial feedstock, safer chemicals with fewer toxic components, energy efficiency, and the reduction of industrial wastes and recycling with simultaneous cost savings.

To investigate the evidence of ATP successes in moving toward these interconnected objectives, two detailed microeconomic case studies and several mini-studies were conducted. Data collection and analysis were started in 2005 and completed in early 2006.

OBJECTIVES AND SCOPE

ATP conducts economic analyses to assess the short- and long-run benefits of ATP-funded projects to the nation. These 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 gauge economic benefits from ATP-funded green process technologies and to compare these benefits to ATP investments, the following green technologies were selected for analysis:

- Renewable-Resource-Based Plastics Manufacturing
- High-Speed Identification and Sorting of Nonferrous Metal Scrap
- Sorting of High-Value Engineered Plastics (to Facilitate Recycling)
- Molecular Gates Technology for Cost-Effective Purification of Natural Gas
- High-Intensity Ultraviolet Lamp Systems for Water Treatment and Paint Stripping

These projects spanned applications in food packaging, textiles, metals, durable goods, coal mining, natural gas production, and wastewater treatment and included only projects where ATP-funded technical tasks were completed. To date, four projects have led to realized green benefits with more significant benefits yet to come. One project, yet to reach commercialization, also has near-term commercial prospects with identifiable green benefits for U.S. industry and society.

Two of the five projects with realized benefits and highly probable near-term prospects for substantial future benefits were selected for detailed case studies. They were Renewable-Resource-Based Plastics Manufacturing with application in the food packaging and textiles industries and High-Speed Identification and Sorting of Nonferrous Metal Scrap with applications in the metals, aerospace, and automotive industries, to be used for the cost-efficient recycling of titanium alloys, superalloys, and aluminum alloys.

PROJECT SELECTION CRITERIA

Over 50 ATP-funded green process technology projects were screened to identify two projects for detailed case studies and three projects for mini-studies.

Selection criteria were designed to identify microeconomic case study candidates for which detailed investigation could be expected to yield rich insights into the innovation process and to provide objective quantitative estimates of economic benefits. In particular, the following selection criteria were used:

- Expected green benefits, including the reduction of harmful emissions and petroleum-derived feedstock, increased energy efficiency, and increased recycling of industrial raw materials, along with industrial cost savings
- Successful technical completion of ATP-funded project
- Substantial progress toward commercialization
- Retrospective benefits realized to date, as an indication that commercialization of these innovative technologies is likely to continue and strengthen

FIVE SELECTED PROJECTS

Each of the five projects selected for study involved a single-company awardee. Three companies were in a start-up mode, operating as stand-alone small businesses. One ATP partner had important informal relationships with a regional university. None of the projects included an industrial joint venture or formal collaborative structure.

Quantitative analysis was conducted for two projects.

Renewable-Resource-Based Plastics Manufacturing

With ATP funding, Cargill, Inc. of Minnetonka, Minnesota and its wholly owned subsidiary NatureWorks developed an innovative process technology that uses U.S.-grown corn as feedstock for the cost-effective production of polylactic acid (PLA) resin. PLA resin is used in making polymer products for food packaging and textiles and replaces imported, petroleum-derived feedstock. PLA was commercially introduced in 2003 and its green benefits include the following:

- Reduced overall energy requirements for plastics manufacturing
- Substantially reduced utilization of imported, petroleum-derived feedstock along with increased feedstock cost stability
- Avoided burying of post-consumer plastic wastes in landfills (plastics can be composted when made from corn-based feedstock)
- Reduced greenhouse gas emissions

NatureWorks built a new PLA production facility in Blair, Nebraska. The new plant started operations in 2003. Two-thirds of its production is exported to international markets and one-third is sold into domestic U.S. markets.

High-Speed Identification and Sorting of Nonferrous Metal Scrap

With ATP funding, wTe Corporation of Bedford, Massachusetts developed a proprietary alloy sorting technology for the cost-effective sorting of nonferrous metal scrap including titanium alloys, superalloys, and aluminum alloys. Effective sorting facilitates recycling of these valuable nonferrous alloys and leads to a wide range of green benefits that can be traced to the ATP-funded sorting technology, including the following:

- Upgraded mixed-metal scrap streams for highest-value alloy production
- Reduced energy use by facilitating much more energy-efficient secondary smelting
- Reduced greenhouse gas emissions associated with primary alloy production
- Reduced import dependence for titanium and nickel metal concentrates used in the primary production of titanium alloys and nickel-based superalloys

Commercial-scale sorting of titanium alloys started in 2005. Sorting of aluminum alloys started in 2006 and superalloy sorting is expected to commence in 2008.

In addition to the quantitative case studies, qualitative analysis was conducted for three additional green process technologies.

Sorting of High-Value Engineered Plastics

Engineered thermoplastics are high-value components extensively used in personal computers, appliances, automobiles, and other durable goods. Given the complex variety of these thermoplastics, their recycling and recovery rates are very low, resulting in the loss of valuable petrochemical content and large waste streams that choke landfills and create toxic fumes when incinerated.

With ATP funding, MBA Polymers, Inc. of Richmond, California developed a proprietary plastics sorting technology to cost-effectively segregate engineered plastics by type and by grade. Green benefits from this ATP-funded innovative process technology include the following:

- Increased recycling and reduced landfilling of thermoplastics waste
- Avoided use of petroleum-derived feedstock in virgin plastics production
- Reduced greenhouse gases

After completion of the ATP-funded project, MBA Polymers raised over $30 million in equity investments to fund the construction and operation of two industrial-scale plastic sorting facilities, each with a design capacity of 40,000 metric tons per year.

Molecular Gates Technology for Cost-Effective Purification of Natural Gas

Natural gas from coal mining and some natural gas reserves requires nitrogen removal and upgrading to pipeline-quality gas. With ATP funding, Engelhard Corporation (now BASF Catalysts) of Iselin, New Jersey developed the molecular gates or molecular sieves gas separation technology for cost-effective treatment of small-volume natural gas flows. Green benefits include the following:

- Commercially viable gas separation from smaller coal mines and small-output natural gas wells, reclaiming natural gas that otherwise could not be economically reclaimed
- Removal of hazardous gases from coal-mine formations to reduce the danger of mine explosions and fires

To date, Engelhard Corp. has sold 18 molecular gate gas separation systems for nitrogen rejection, with half of these units installed in coal mines.

High-Intensity Ultraviolet Lamp Systems for Water Treatment and Paint Stripping

With ATP funding, Phoenix Science & Technology, Inc. of Chelmsford, Massachusetts developed a new, high-intensity, ultraviolet (UV) lamp system—without using mercury gas—and demonstrated its technical feasibility. Early commercialization efforts are underway. After commercialization is achieved, the green benefits of using high-intensity UV lamps for water treatment and lead paint–stripping applications are expected to include the following:

- Reduced rates of childhood lead poisoning and reduced levels of chemical and blast media byproducts from paint stripping
- Improved quality of treated water supplies
- Avoided disposal of toxic mercury waste at the end of UV lamp product life

2. Analytical Framework and Methodology

For two ATP-funded green process technologies, detailed microeconomic studies were conducted using a benefit-cost analysis approach.

Benefits were first identified. For benefits that could be quantified with market price mechanisms, estimates of benefit cash flows were developed. Cash flow estimates were then discounted using the discount rate recommended by the Office of Management and Budget (OMB) and compared to ATP investments.

Performance metrics derived from cash flow time series were used to compare benefits to investment costs and to generate quantitative performance measures familiar to the financial and economic communities: net present value, benefit-to-cost ratio, and internal rate of return.

These performance metrics were used to summarize ATP's impact along two dimensions: (1) the scale of public benefits attributable to ATP relative to ATP's investment, and (2) the spillover gaps to validate that private investments were unlikely to have substituted for ATP technology investments.

Beyond quantitative performance measures, which capture only part of the totality of public and private benefits, other important outcomes are discussed without relying on cash flow estimates.

SELECTION CRITERIA

Over 50 ATP-funded green process technology projects were screened to identify two projects for detailed case studies and three projects for mini-studies.

Selection criteria were designed to identify case study candidates for detailed investigations that would yield rich insights into the innovation process and provide quantitative estimates of economic benefits. The following selection criteria were used:

- Technical completion of ATP-funded project
- Progress toward commercialization
- Expected green benefits including reduction of harmful emissions, increased energy efficiency, reduced petroleum use, and increased recycling of industrial raw materials
- Availability of some retrospective benefits (realized to date) to increase confidence in the ongoing commercialization of innovative technologies and the cash flow estimates for future benefits

IDENTIFICATION OF BENEFITS

This section discusses the logic model of green process technology benefits, the counterfactual scenario of likely outcomes without ATP investments, the distinction between public and private benefits, and the attribution of benefits to ATP and other public agencies.

Logic Model of Green Process Technology Benefits

A logic model postulates the flow of benefits from ATP investments to key technical advances or outputs, to green outcomes, and finally to ultimate benefits or impacts for downstream industry, end users, and society (Figure 1).

On the left side of Figure 1, ATP investments are inputs whose impacts are to be determined. Also on the left side of Figure 1 are secondary inputs (other public investments), which need to be identified to make fair attribution of public benefits to ATP and to other sources of public funding.

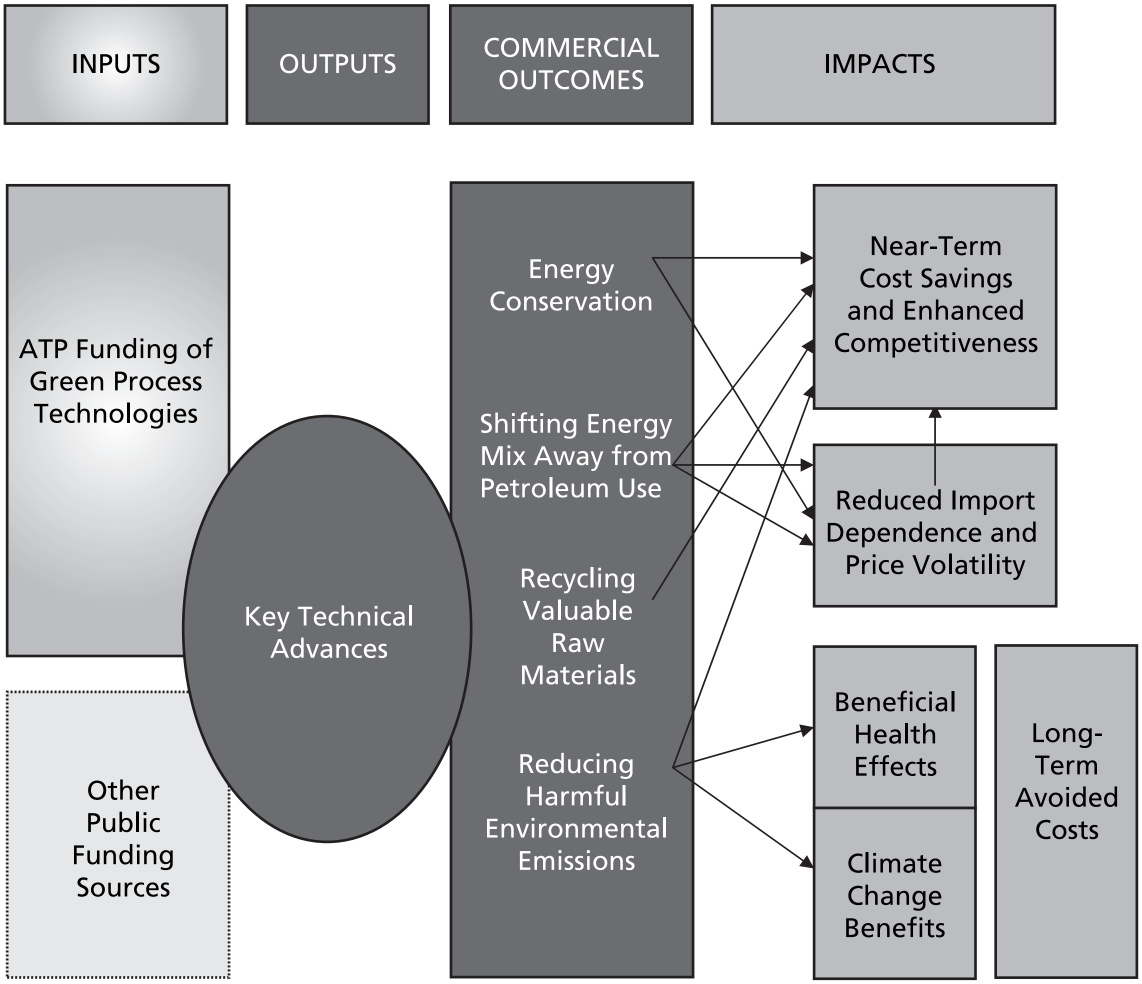
In the center of Figure 1, green outcomes from the commercialization of ATP-funded process technologies are enumerated. Important as these outcomes are, they are not the ultimate benefits. Instead, outcomes represent innovation results that can, in turn, be instrumental toward achieving economic and societal benefits or impacts (the right side of Figure 1). Expected impacts include the following:

- Immediate cost savings to be realized at the same time as increments of energy conservation, reduced petroleum use, additional recycling, and reduced harmful emissions are being realized

- Reduced import reliance and reduced price volatility, which also tends to promote immediate cost savings and industrial competitiveness

- Beneficial health impacts and climate change impacts that have incontrovertible intrinsic value and can be confidently associated with unspecified but highly probable and substantial long-term avoided costs

Figure 1: Flow of Benefits from ATP-Funded Green Technologies



- Long-term avoided costs (from beneficial health impacts and climate change benefits), which need to be distinguished from "immediate cost savings" that can be associated with energy conservation, energy mix changes, and recycling

Counterfactual Scenario

Benefits from technological advances can be examined relative to alternative conditions that would obtain without specific investments. "What if" questions are asked about likely economic and societal outcomes in the absence of technology investments under analysis.

For this study of ATP-funded green process technologies, the basis of comparison against which benefits are identified and quantified is the likely alternative situation that would obtain in the absence of ATP funding.

The likely alternative situation, sometimes referred to as the "counterfactual scenario," is the basis for gauging the additionality of ATP investments and documenting that ATP has been and continues to be a good steward of taxpayer dollars and is effective in generating substantial and measurable economic benefits that contribute to U.S. industrial competitiveness.

Public and Private Benefits

To evaluate the performance of ATP-funded technology projects, innovation benefits are documented for two classes of beneficiaries.

- Economic benefits enjoyed by the innovating firms are considered *private benefits*. The innovating firm's expectation of private benefits or profit contribution from new technologies is a necessary precondition for the firm's continued efforts to complete remaining technical development tasks (after the successful completion of the ATP-funded project phase) and for undertaking subsequent commercialization and marketing efforts. Without commercialization, the economic and social benefits from ATP-funded technology projects could not be realized.

- In contrast to private 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, total benefits from ATP investments can be expected to substantially exceed the magnitude of private benefits (Mansfield et al., 1977).

Public benefits may "trickle down" from industrial customers of the innovating firm to end-use customers. Other public benefits have a public-goods quality that society at large can enjoy directly. Examples of public-goods-type benefits from green process technologies include the following:

- Reduced harmful environmental emissions
- Conservation of scarce energy resources
- Knowledge diffusion about new technologies

Attribution of Benefits to ATP

The central objective of conducting detailed case studies and several mini-studies is to gauge the programmatic impact of rigorously screened and well-timed ATP investments.

At the same time, it is important to identify funding contributions from other public sources and to provide a fair and objective assessment of the portion of public returns that is attributable to ATP and the remaining benefits attributable to other sources of funding.

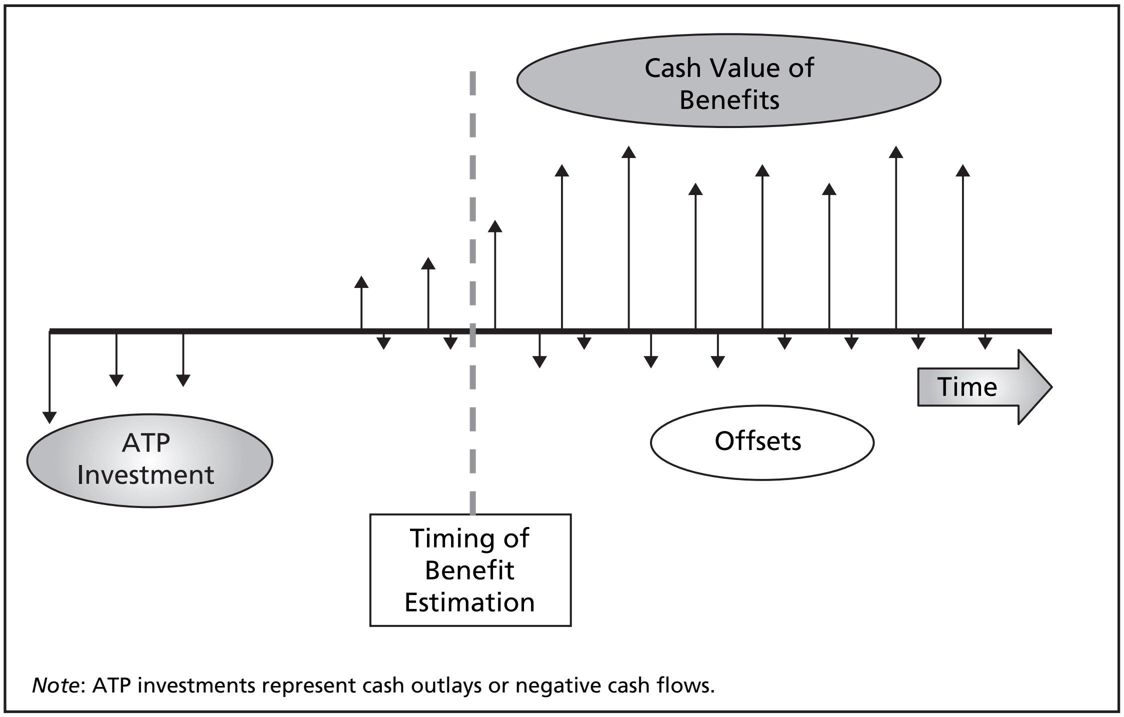
For example, ATP-funded high-risk technology projects may be preceded by basic and applied research funded through the National Science Foundation (NSF) or other U.S. science agencies. Funding from other public agencies can also support technology and product development subsequent to the completion of ATP cost-shared projects. Either way, a series of sequential investments by the ATP and other agencies tend to validate prior investments, relative to the technology's potential to generate economic and social benefits. Such validation requires, however, that a fair attribution of public benefits be made to all sources of public investments.

The appropriate attribution scheme to ATP and other funding agencies will depend on specific circumstances of each case, reflecting the relative importance, timing, and size of respective investments.

BENEFIT CASH FLOW ESTIMATES

For benefits that can be meaningfully quantified, cash flow time series are estimated. Figure 2 illustrates the nature of cash flow time series and their relationship to ATP investments.

Figure 2: **General Representation of Cash Flows for Performance Analysis**



Note: ATP investments represent cash outlays or negative cash flows.

On the left side of Figure 2, ATP and other agency investments are represented as negative arrows indicating cash outlays. After the successful completion of an ATP-funded technology project and the subsequent product development and commercialization, economic benefits begin to be realized. Over time, these benefits may increase, which is represented by upward-pointing (positive) arrows that are scaled to the magnitude of expected annual cash flows.

Both ATP investments (negative cash flows) and resultant benefits (positive cash flows) are normalized to 2005 U.S. dollars. Restating cash flow outlays and benefits in constant-year dollars facilitates a consistent comparison of benefits to investments and the estimation of microeconomic performance metrics.

Retrospective and Prospective Benefits

The temporal placement of benefits is significant for the analysis of innovation benefits. When practical and meaningful, realized benefits (on the basis of retrospective analysis) are distinguished from future prospective benefits as follows:

- Retrospective analysis: Benefits that have been realized prior to the conduct of detailed case studies can be unambiguously documented. Although realized benefits, in the early stages of commercialization, may be of lesser magnitude than subsequent future benefits, the ability to document realized benefits tends to increase confidence in the likelihood of realizing potential future benefits.

- Prospective analysis: Expected future benefits are typically associated with a variety of uncertainties, including market introduction, consumer acceptance, and production ramp-up. These uncertainties may be mitigated through documented expressions of interest from potential customers, prototype sales, rigorous market studies, and reasonable expectations of near-term commercialization. However, 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.

In particular, the expected value EV_i of future benefits for year "*i*" is estimated as the following:

$$EV_i = \text{Probability (Benefit Estimates}_i\text{)} + (1 - \text{Probability})\text{(zero benefits)}$$

Note the conservatism of valuing the benefits from innovation efforts that have not yet come to fruition but have resulted in lessons learned. Often such lessons learned can be correlated to important future advances and commercial successes. However, if it proves difficult to identify, document, and quantify the benefits that may result from such lessons learned, the second term of the expected value expression is conservatively assessed zero benefits.

Offsets

When technological advances are successfully commercialized, resulting in new and better products and manufacturing processes, it is expected that new technologies will, to some extent, displace "defender" technologies in current use. Such displacement occurs only partially, as new technologies will likely create additional sales that may not have been possible with less efficient and less effective "defender" technologies.

Offsets (as indicated in Figure 2) represent negative cash flows subtracted from positive cash flows to arrive at net public benefits. Offsets are not estimated as revenue losses to defender technologies. Rather, offsets are limited to the expected profit component of lost revenues.

In special circumstances, such as when projected benefits are of strategic national interest, offsets are not applied to benefit cash flows. Such special cases may include reduced dependence on imported petroleum and strategic raw materials; reduced environmental pollution in landfills, air, and water; and reduced climate change effects. These benefits are considered to be of strategic national interest because they ameliorate conditions that are detrimental for U.S. society and the world.

Benefits from green process technologies—reduced import dependence for strategic resources, reduced harmful emissions, and reduced climate impacts—meet the above criterion as special benefits. As a result, offsets are not applied in the detailed case studies of ATP-funded green process technologies.

Base Case and Step-Out Scenarios

For 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.

Using base case and step-out scenarios makes it possible to gauge the sensitivity of cash flow estimates to key assumptions and market price fluctuations, and to bracket performance metrics to a range of reasonable assumptions and market price levels.

OTHER ANALYSIS

At this time, benefits in three of the four impact categories (in Figure 1) cannot be meaningfully converted to cash flow time series: (1) the reduction of import reliance for critical energy and industrial raw material supplies, (2) beneficial health impacts from reduced harmful emissions, and (3) reduced climate change impacts.

Realizing benefits in these categories has substantial intrinsic value. The continued availability of critical supplies of energy and raw material—at predictable prices—is a key requirement for continued U.S. industrial competitiveness. Similarly, lives saved and costly medical treatments avoided through reduced levels of harmful environmental emissions also have intrinsic value and unspecified but highly probable and substantial long-term avoided cost benefits.

The simultaneous achievement of immediate cost savings quantified in this study and other long-term benefits that cannot now be meaningfully quantified, but which are nevertheless associated with significant economic and societal benefits, is of great practical consequence. Immediate cost savings will create incentives for the private sector to continue investing in the commercialization of green technologies, and thus facilitate reaching long-term green objectives.

PUBLIC BENEFIT PERFORMANCE METRICS

Once cash flow time series, for both base case and step-out scenarios, are established, they are used to estimate public benefit performance metrics to compare public benefits to public investments. Three performance metrics are used to gauge the effectiveness of ATP investments in high-risk green process technologies:

- Benefit-to-cost ratios
- Net present values
- Internal rates of return

- *Benefit-to-cost ratio* is calculated by dividing the present value of public benefit cash flow estimates, enjoyed by U.S. beneficiaries other than the ATP-funded innovator, by the present value of ATP investment. This measure estimates the benefit to the nation for every dollar of ATP investment.
- *Net present value* is calculated by subtracting the present value of ATP investment from the present value of public benefits from new green process technologies. Cash flows are normalized to 2005 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 2005 dollars.
- *Internal public rate of return* is calculated by iterative solution for a rate at which the discounted value of ATP investment equals the discounted value of public benefits, thus indicating the rate of return to the nation on ATP's investment.

METRIC FOR GAUGING THE SPILLOVER GAP

ATP-funded projects are cost-shared with innovating companies in the private sector and can benefit the innovators as well as suppliers, customer industries, and end users—in essence, taxpayers broadly.

A measure of total benefits relative to total investment costs provides a more complete picture of project performance than public returns on ATP investments. The social rate of return is such a measure and has been used by leading economists as an indicator for broad social benefits that result from new technologies and innovations (Griliches, 1958; Mansfield et al., 1977; Jaffe, 1996).

To estimate social rates of return, public and private benefit cash flows are combined and compared to the sum of all public and private investments, using an internal rate of return calculation.

- *Social rate of return* is a broad-based measure of economic and social impact. It is calculated by iterative solution for an internal rate of return 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 at large.

Social rates of return are then compared to private rates of return that ATP industry partners would expect to realize over the long term. Rates of return are, however, proprietary information that privately held corporations do not publish. Even public corporations that publish average corporate rates of return will not publish or necessarily track returns for specific technology investments or lines of business. To deal with the problem of data availability, a proxy rate of return is used herein. The proxy rate is based on U.S. business press reports that tend to bracket average expectations for corporate investment returns over the term of an investment in the range of 6–13 percent per year.

The comparison of social and private returns is a cornerstone economic justification for government-funded technology development initiatives. 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 for themselves (Mansfield et al., 1977; Yager and Schmitt, 1997). “The excess of the social rate of return over the (proxy) private rate of return is the spillover gap,” which indicates the project’s value to society compared to its value to innovators that execute the project in the expectation of a private return, or to investors that help finance private sector technology investments (Jaffe, 1996).

A large spillover gap indicates the innovating firm's inability to appropriate most technology benefits to itself in the form of additional profits and could lead to private sector underinvestment and associated loss of benefits to downstream firms, end-user customers, the economy, and society at large. ATP compensates for the spillover gap by partially funding the development of high-risk, innovative technologies that private firms are unable to fund due to R&D technical risks and appropriability risk.

* * * * *

Performance metrics for public and social returns are computed on the basis of benefit cash flow estimates from two case study projects. Future economic studies may document and estimate additional benefit cash flows from other ATP-funded green technology projects.

3. Case Study: Renewable-Resource-Based Plastics Manufacturing

Cargill, Inc. of Minnetonka, Minnesota and its wholly owned subsidiary NatureWorks developed an innovative process technology that some have called a trailblazing effort for the industrial-scale production of polylactic acid (PLA) from U.S.-grown corn. In 1994 Cargill received an ATP award to develop the fundamental methodology for controlling PLA crystallinity and utilized that knowledge to develop processing technologies to achieve the resin properties required for a variety of polymer products.

Making PLA from a renewable and plentiful domestic resource like corn opens the possibility of reducing the nation's dependence on imported petroleum feedstock for polymer manufacturing. This leads to public benefits, including the following:

- Significant energy savings in polymer manufacturing
- Reduced reliance on imported petroleum, increased feedstock security and cost stability
- Avoided landfilling of post-consumer polymer wastes
- Reduced greenhouse gas emissions

These benefits from the ATP-funded technology have led to manufacturing cost savings for downstream industries and for society more broadly, as savings are passed on to U.S. consumers of polymer products.

Quantifiable economic benefits (realized and projected) to U.S. industry and end users are estimated to range from $11 to over $23 for every dollar of ATP investment.

PROJECT HISTORY

Polymers are commonly used in making industrial commodity products. Their advantages include durability, strength, low weight, wide application range, ease of processing, and the maturity of underlying manufacturing technologies. However, polymers have the following disadvantages:

- They are traditionally made from petroleum-based feedstocks and thus accelerate the depletion of finite petroleum resources. This also contributes to petroleum price increases and price volatility.

- At the end of product life, post-consumer polymer waste streams lead to significant disposal problems. In landfills, the natural degradation of petroleum-based polymer wastes may require hundreds of years. Polymer recycling, as a way to avoid land filling, has not kept up with consumption. Also, recycling may be associated with new problems, such as the concentration of contaminants (Vink et al., 2002).

With increasingly expensive and scarce petroleum resources and end-of-life waste disposal problems, there has been long-standing commercial interest in developing new biodegradable polymers made from renewable resources.

Polylactic acid—a biodegradable polymer made from renewable resources—is not a new polymer. PLA has been used in soluble surgical sutures and in-vivo medical applications. Manufacturing challenges have, however, limited PLA uses to small-batch production of high-cost specialty products.

In the mid-1980s, Cargill, Inc. launched a technology development effort for a new industrial-scale process to make PLA resins from corn starch and also to improve PLA functional properties. PLA resins were expected to compete on cost and performance terms with petroleum-derived resins such as polyethylene terephthalate (PET).

Based on early development efforts, by the early 1990s Cargill developed a process technology for manufacturing PLA on an industrial scale. Customer evaluations in the food packaging and fiber sectors pointed to performance challenges in a number of areas, including inadequate temperature resistance for storage, shipping, and use with hot foods; long in-mold cycle times; inadequate toughness and barrier properties; and insufficient knowledge about the controlled degradability at end-of-life disposal.

Given the complexity of these technical challenges, in 1994 Cargill submitted a proposal to ATP for cost sharing the “Development of Improved Functional Properties in Renewable-Resource-Based Biodegradable Plastics.” The proposal pointed to a need for enabling research into controlling PLA properties in contrast to trial and error procedures that would be less likely to improve PLA functional properties cost effectively. This level of undertaking required Cargill to go beyond its normal operating paradigm—that of processing and trading grains—into polymer chemistry and manufacturing and was associated with high technical risk.

ATP agreed to cost share the proposed project with Cargill and the project reached successful technical completion in 1998. During the course of the project, Cargill formed a joint development program with Dow Chemical Company, forming Cargill Dow Polymers LLC in 1997 to continue development of the technology. In 2005, Cargill bought Dow's 50-percent share of the partnership and established NatureWorks, a wholly owned subsidiary, to complete product development and to undertake full-scale commercial production and marketing of PLA resins at the new Blair, Nebraska facility.

Cargill was assisted by the following subcontractors in completing the ATP-funded technology development tasks:

- University of Minnesota (nuclear magnetic resonance studies)
- Pennsylvania State University (crystallization rate studies)
- California Institute of Technology (hardening process studies)
- University of Tennessee (PLA fiber formation studies)
- Fiber Science, Inc. (process development for fiber spinning)
- Scott Gessner and Associates (fiber non-woven applications)
- Nangeroni and Associates (thermoforming applications)
- Organic Waste Systems (PLA decomposition testing)
- Technology Management Group (technical reporting)

Recent statements by NatureWorks management have underscored the importance of ATP funding:

> Without ATP-funded enabling research, NatureWorks would not have sufficient knowledge for controlling polymer crystallinity and may only have amorphous (non-crystalline) products—with limited performance capabilities.
>
> Knowledge and credibility from ATP-funded research contributed to NatureWorks' continued viability as a promising new business and led to continued Cargill corporate support beyond short-term financial considerations.

In this sense, the ATP-funded research not only accelerated but made possible important technical advances required for commercially viable PLA commodity products.

HOW DOES IT WORK?

Figure 3 illustrates the process of producing PLA from corn. Production starts with corn growing, harvesting, and the separation of corn starch from other components (gluten and fiber). With the addition of enzymes, the starch is converted into dextrose or sugar. Using proprietary microbial cultures, dextrose is fermented into lactic acid.

Lactic acid is a chiral molecule with L-isomers and D-isomers. The chirality property implies that the individual isomers, while identical in chemical composition, each have a molecular structure that cannot be superimposed on a mirror-image isomer. This is analogous to left and right hands not being superimposable.

Fermentation-derived lactic acid (in contrast to chemically synthesized lactic acid) typically consists of predominantly L-isomers and low levels of D- isomers.

Lactic acid is then converted to a low-molecular-weight "pre-polymer" by dehydration condensation. Continued heating leads to the formation of lactide, a cyclic oligomer of lactic acid. Lactide is vacuum distilled to remove impurities and to control the D-isomer content of product streams.

Ring opening polymerization of lactide streams completes the manufacturing process, yielding different families of high-molecular-weight (longer-chain polymer) PLA resins with varying L- and D-isomer content that influences crystallization and functional properties.

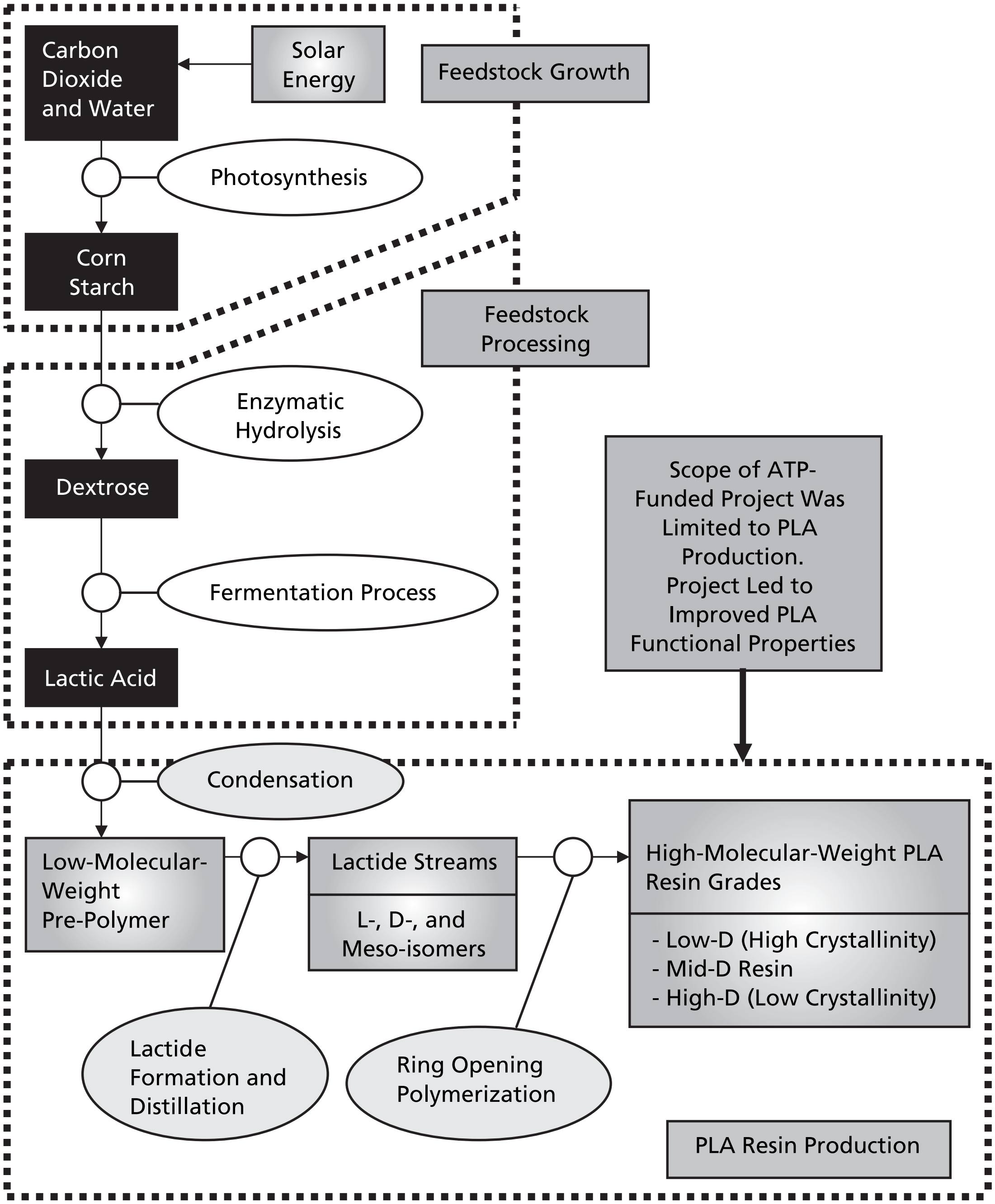
The process yields resins in the form of small pellets. These are sold to "converters" to be melted and shaped into thermoform and film products, injection molded products, and woven and nonwoven textile goods. PLA resins are produced as part of three families:

- High-crystallinity resin: Low D-isomer content for high-temperature fiber and film applications
- Moderate-crystallinity resin: Medium D-isomer content, for thermoforms (semirigid containers), bottles, and some fibers
- Amorphous-grade resin: High D-isomer content for room-temperature film and foam applications

Technical Challenges and Risks of the ATP-Funded Project

The first objective of the ATP-funded project was to research the key physical and chemical properties of PLA. Research would lead to fundamental knowledge that could be used to improve heat resistance, stiffness, barrier properties, color stability, and compostability. Alternative research strategies included:

Figure 3: Manufacturing Lactic Acid and PLA from Corn



- Controlled development of crystallinity
- Use of copolymers and copolymerization catalysts
- Blending PLA with other polymers

The second objective was to generate application-specific technical knowledge to understand how PLA resin properties could be controlled for different product applications—thermoformed, injection molded, film, and fiber products. Application-specific technical knowledge was developed in the following areas:

- Increasing thermal resistance and stiffness of thermoformed products
- Accelerating crystallization of injection-molded products to reduce in-mold cycle times
- Increasing film flexibility and strength
- Reducing fiber shrinkage and heat performance
- Biodegradation mechanisms for end-of-life product disposal

Technical Accomplishments

In 1998, the ATP-funded project was successfully completed, leading to advances in scientific and engineering knowledge and application-specific technical solutions.

Advanced analytical tools were used for characterizing the PLA polymer system, including microscopy and X-ray studies, leading to more detailed understanding of fundamental microstructures. In particular, the following techniques were used:

- Microscopic techniques were used to examine the morphology, crystal structure, and crystal growth habits of PLA.
- DSC (differential scanning calorimetry) was used to study the relationship of PLA crystallinity and thermal performance.
- Nuclear magnetic resonance (NMR) spectroscopy was used for gaining improved understanding of the role of L- and D-isomers for crystallinity control.
- X-ray and spectroscopy techniques (including Raman) were used to determine solid and melt compositions and the extent of crystallization and polymer-chain orientation.

ADVANCES IN FUNDAMENTAL KNOWLEDGE

Early in the project, crystallinity control was identified as the most promising approach for improving thermal properties and structural rigidity. The alternative copolymer approach would, in all likelihood, have taken much longer and the polymer-blending approach (using petroleum-based polymers) could have compromised end-of-life biodegradability.

Subsequent research efforts were directed at gaining a good understanding of the nature and requirements of PLA crystallinity. NatureWorks learned how to control crystallization rates by varying the percentage of D-isomers and processing conditions in the presence of various nucleating agents or fillers.

The project also improved understanding of degradation mechanisms for end-of-life disposal. One mechanism consists of hydrolytic PLA degradation, followed by microbial attack and subsequent mineralization.

MANUFACTURING ADVANCES

Enhanced understanding of crystallinity control was used to develop multiple grades of PLA resin, distinguished by D-isomer content. Resin with high crystallinity (low D content) is used for high-temperature applications. Resin with moderate crystallinity (intermediate D content) is used for thermoforming and injection-molding applications. Resin with low crystallinity (amorphous high D content) is used for applications where low-temperature sealing is advantageous. Achievements include the following:

- Increasing PLA melting point by decreasing D-isomer content: This is useful for thermoformed packaging and cup applications. At lower D levels, semicrystalline PLA has improved heat resistance (Bosiers, 2003). Additional research is needed to maintain heat-resistance gains without compromising clarity.
- Developing a process technology for manufacturing film oriented in two directions (biaxial oriented film) with desirable functional properties.
- Reducing the shrinkage of nonwoven fabrics using crystallinity control.
- Understanding the relationship of melt shear rates and in-mold crystallization rates: This resulted in a 90 percent increase in crystallization rates and facilitated commercially viable cycle times for injection-molded bottles.

REMAINING TECHNICAL CHALLENGES

While technical advances have been made in all application areas, additional heat resistance is needed for bottles involving the hot filling of juices and for robust transport of thermoformed products, at all times of the year. Thermoforms constitute a significant part of U.S. sales and improved heat resistance will further increase market acceptance.

The identification of appropriate nucleating agents to reach desired levels of crystallinity and heat resistance without loss of clarity remains a high priority for NatureWorks. As a result of structured assessments of over 100 nucleating agents, completed during the ATP-funded project, NatureWorks is showing clear progress toward identifying nucleating agents that yield heat-resistant thermoformed products.

Patent Estate and Publications

U.S. Patent 6,506,873—“Degradable Polymer Fibers: Preparation, Product, and Methods of Use”—was filed in 1998 and issued on January 14, 2003 (Chris M. Ryan et al.). Eleven technical publications were accepted by refereed journals and fifteen presentations were made at technical conferences.

COMMERCIAL APPLICATIONS

NatureWorks’ ATP-funded PLA process technology uses renewable feedstock for producing resins, which in turn are used for making polymer products.

Polymer Industry

Approximately 20,000 manufacturing establishments operate in the United States, generating over $310 billion in shipments. Additional shipments worth $83 billion are generated by upstream industrial producers for total annual industry levels of nearly $400 billion (SPI, 2004).

According to the American Plastics Council, over the last two years U.S. polymer industry shipments increased at 6–8 percent per year (PlasticsTechnology, 2005). Future projections point to continued growth of 4–5 percent per year (BASF AG, 2003). Segments of the polymer industry reported the following:

- Thermoplastic segment: The thermoplastic polymer industry segment reported 2004 shipments of 92.3 billion pounds (American Plastics Council, 2005). Annual sales of polyethylene terephthalate (PET) —an important thermoplastic polymer and the key defender technology to be replaced by PLA—were reported at 9.8 billion pounds and growing at 5.5 percent per year (The Innovation Group, 2004).

- Renewable and biodegradable segment: According to Freedonia Market Research, the renewable and biodegradable subsegment currently represents less than one percent of the polymer industry. This subsegment is expected to grow at 14 percent annually through 2008 and beyond (Freedonia, 2004a).

“As prices and functional properties become more competitive with conventional petroleum-derived polymers (such as PET) … renewable and biodegradable resins will lead market gains, especially polylactic acid (PLA). Biodegradable packaging and film will grow the fastest” (Freedonia, 2004a).

Continued petroleum price increases and considerable price volatility, growing interest in reducing greenhouse gas emissions, increased public awareness of end-of-product-life waste management issues, and some customer willingness to pay a premium for sustainable green products are expected to support continued rapid growth of the renewable and biodegradable segment (Freedonia, 2004a).

Pathways to Market

As indicated in Figure 4, the value chain for PLA-based polymer products consists of the following:

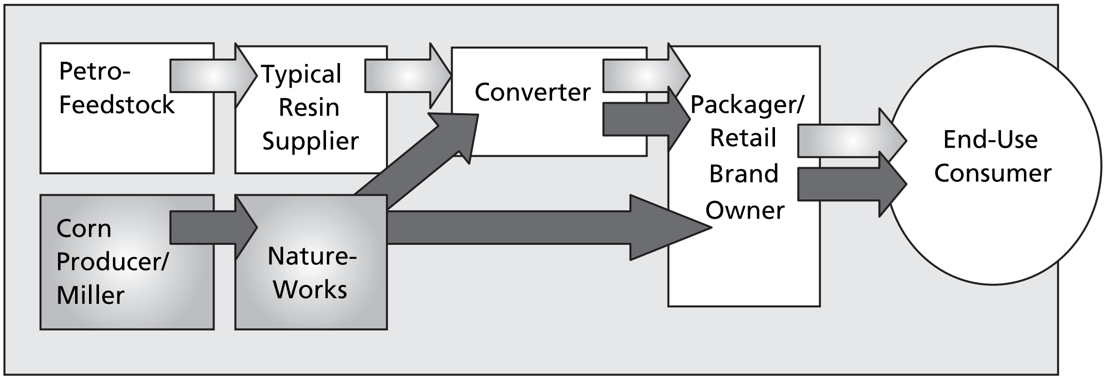
- Corn growers and resin suppliers producing PLA resin from corn starch
- Converters processing PLA resins into manufactured products—semirigid thermoforms, cups, and films
- Retail brand owners purchasing semirigid thermoform, cup, and film products and then branding and selling these products to supermarkets and fast food restaurants, soft drink companies, and other food service providers

Resins sales are traditionally completed under long-term agreements between resin suppliers and converters. In the context of long-term business relationships, resin suppliers typically refrain from bypassing converters and selling directly to brand owners (see Figure 4). These long-term relationships also facilitate converters' incremental investments in manufacturing process improvements for established resins.

In the context of established long-term business relationships, the introduction of new resins (such as PLA) may encounter resistance for the following reasons:

- Converters must make substantial investments in production equipment, new configurations of equipment, and new molds. These changes can represent substantial business risks and may lead to a converter preference for established resins.
- Suppliers of established resins (such as PET) also resist the introduction of competing renewable and biodegradable resins.

Figure 4: **Current Value Chain for PLA-Based Polymer Production and Use**



To overcome resistance and to broaden its customer base, NatureWorks used an unconventional, two-pronged marketing approach (see Figure 4) focused on two kinds of customers:

- Converters willing to accept the risks of switching to bio-based resins
- Early adopters among brand owners willing to challenge more traditional converters to use NatureWorks PLA resins

Based on this dual marketing approach, NatureWorks has succeeded in broadening its customer base. Fifty percent of NatureWorks' top 10 customers in 2005 were new customers in 2004.

PLA Target Applications

NatureWorks targets PLA resin sales in three application areas: rigid and semirigid polymer thermoforms for retail food packaging and cups, polymer film products for food packaging and for consumer products, and polymer fiberfills for pillows and comforters.

RIGID AND SEMIRIGID THERMOFORMS

The 2003 North American market for semirigid food packaging represents 25 billion units of shipment and $7.2 billion in sales (Freedonia, 2004b). It included clear food containers or clamshells for retailing salads, fruits, and other fresh food items; clear soft drink cups; opaque plates and bowls for hot food service; and shallow-draw microwavable trays.

Semirigid containers are made by thermoforming, a polymer conversion process similar to metal pressing and stamping. Resin is heated and formed into flat sheets and shaped into semirigid objects by heated dies. In 2003, North American thermoformed products were manufactured by over 150 companies or converters (PCRS, 2004).

Approximately one-third of NatureWorks' PLA sales for thermoform applications are in the United States. The remaining two-thirds of PLA sales are overseas, particularly in the Far East. This ratio of domestic to overseas sales is expected to continue over the period of analysis.

U.S. customers include Brenmar Co., Wilkinson, and other converter companies and Coca Cola (soft drink cups), McDonald's (fast food salad containers) and other brand-owners. Commercial relationships with U.S. brand-owners include Whole Foods, Del Monte, Newman's Own Organic Salads, and Wal-Mart.

"Wal-Mart is going green. The retail giant, which is also the nation's largest grocery seller, is beginning to switch from petroleum based plastics to NatureWorks corn-based PLA polymer packaging. The first substitution, starting in November 2005, involves 114 million clear polymer clamshell containers used annually by the retailer for fresh fruit, herbs, and vegetables" (Brubaker, 2005).

PLA-based polymer will be used by Wal-Mart for "clear clamshells as well as bread bags and donut boxes. Just those four products translate into the equivalent of avoiding the use of 800,000 gallons of gasoline" (Zimmerman, 2005).

POLYMER FILMS

In 2000, U.S. film sales for packaging applications were $13.4 billion (Freedonia, 2000).

PLA resin is converted into film product by an extrusion process. Resin pellets are loaded into a hopper and fed into a long heating chamber. At the end of the heating chamber, the molten polymer is forced out through a small opening or die and extruded in the form of a tube, which is split as it comes from the die and stretched and thinned to desired dimensions.

PLA-based films are used for making compost bags with high impact and tear resistance; for shrink-wrapping consumer goods; for twist-wrapping candy and flower wraps; and for windows in envelopes, bags, and cartons. Approximately one-third of NatureWorks' PLA sales for film applications are in the United States. The remaining sales are overseas, particularly in Europe and the Far East.

FIBERFILL FOR PILLOWS AND COMFORTERS

Nonwoven fabrics are manufactured by putting small fibers together in the form of a sheet and then binding them. Spunbond fabrics, a type of nonwoven fabric, are made in a two-step process. Fibers are spun and directly dispersed in a web and then bonded either through thermal bonding (calendering through heated rollers) or via hydro-entanglement (the mechanical intertwining of fibers by water jets). Nonwoven fabrics made from PLA are used to manufacture wipes, personal hygiene products, and geotextiles.

PLA-based fiberfill for nonwoven products offers attractive health and safety features, including low flammability and low levels of bacterial growth.

Some PLA-based, nonwoven products are available in U.S. markets, from Faribault Mills (under Ingeo Blankets brand) and Bed, Bath & Beyond (under Natural Balance brand). However, direct PLA resin sales for fiber applications appear to be limited to overseas converters. Offshore textile products made from PLA resins are imported to the United States and make it possible for U.S. retail customers to enjoy the health and safety benefits of bio-based textiles.

POSSIBLE FUTURE APPLICATION

Bottles and beverage containers are a potential future application of corn-based PLA resins. Bottles are made by injection stretch-blow molding. In this process, thermoplastic resins are injection molded into a pre-form. With the use of compressed air and heat the pre-form is inflated to conform to the interior of a chilled mold. PLA bottles must have good impact resistance and clarity, remain unaffected by bottle contents, and have strong barrier properties to prevent change in contents during extended storage.

By 2007, U.S. demand for beverage containers is projected to increase to $17.5 billion. Metal cans and paperboard containers continue to lose market share and polymer-based containers are expected to grow at 2 percent per year (Freedonia, 2003a).

BENEFIT ASSESSMENT AND MODELING

PLA resins for food packaging and fiberfill applications will lead to benefits for customers, end users, and society, including the following:

- Avoided use of imported petroleum
- Substantial net gains in energy efficiency and associated cost savings
- Reduced greenhouse gas emissions
- Reduced landfill requirements for end-of-life disposal

Without the ATP-funded PLA technology, these benefits would not have been realized over the timeframe of this study. Instead, polymer products, if not displaced by ATP-funded PLA technology, would continue to be made from petroleum-derived resins, associated with higher costs, higher greenhouse gas emissions, and end-of-life land filling.

Processed Volumes and Sales Estimates

The following data points and assumptions for PLA processed volumes were estimated on the basis of available information from NatureWorks and from industry experts.

- Production start-up was achieved in late 2002. Given negligible 2002 production volumes, Table 1 indicates production levels starting in 2003.

Table 1: Projected PLA Resin Sales (Million Pounds per Year)

	Base Case		Step-Out Scenario	
Year	PLA Production at Blair NE (1)	PLA U.S. Sales (2)	PLA Production at Blair NE (3)	PLA U.S. Sales (4)
2003	10	3.33	10	3.33
2004	30	10.00	30	10.00
2005	60	20.00	60	20.00
2006	100	33.33	120	40.00
2007	115	38.24	144	48.04
2008	132	43.87	173	57.71
2009	151	50.33	208	69.31
2010	173	57.73	250	83.25
2011	199	66.23	300	100.0
2012	228	76.00	300	100.0
2013	262	87.17	300	100.0
2014	300	100.00	300	100.0
2015	300	100.00	300	100.0
2016	300	100.00	300	100.0
2017	300	100.00	300	100.0
Compound Annual Growth Rate	14.72% (2007–2014)		20.11% (2007–2011)	

Notes:
1. Production start-up was achieved in 2003. As indicated by the shaded area in Table 1, full-capacity production levels are achieved in 2014 under a base case scenario and in 2011 under a step-out scenario.
2. Analysis covers a period of 15 years from the time of the Blair production start-up. As indicated by the shaded area in Table 1, there is an expectation that full production can be achieved on an accelerated basis compared with conventional industry expectations of 20 years to achieve full production.

- Production design capacity is 300 million pounds per year.
- In 2003, 2004, and 2005, production levels were estimated at 10 million, 30 million, and 60 million pounds, respectively. The 2006 production level for a base case scenario was estimated at 100 million pounds.
- New polymers generally "make their mark" and gain industry acceptance within 20 years from start-up. In contrast, the Blair facility is projected to reach full capacity in just 12 years (base case scenario), with production levels growing at annual compound rates of almost 15 percent. Accelerated ramp-up is based on the following:
  - NatureWorks' production and sales performance to date, including the recently implemented Wal-Mart relationship
  - Considerable marketing strength of the parent company (Cargill)
  - Faster growth rates expected for renewable polymers than for PET

- For a more optimistic step-out scenario, 2006 production was projected at 120 million pounds and thereafter growing at 20 percent per year until 2011, at which time the Blair facility is assumed to reach full production capacity.

- Currently, U.S. sales of PLA resins are estimated at one-third of Blair production levels. Based on expert input, this relationship—U.S. sales to total production—is maintained over the 2006 to 2017 period of analysis. Estimated PLA production levels and U.S. resin sales are presented in Table 1.

Benefit Assumptions

Quantifiable benefits of PLA-based polymers—as a replacement for petroleum-based PET—include energy costs savings, reduced CO_2 emissions, and reduced landfilling of polymer wastes.

Energy cost savings, reduced CO_2 emissions, and landfilling benefits are common to all PLA resin applications, including semirigid packaging, film, or fiberfill products.

ENERGY COST SAVINGS

Energy costs for PLA polymers and petroleum-derived PET (the defender technology) are estimated on the following bases:

- Required energy resources: BTU of petroleum, natural gas, coal, and electricity for the production of one pound of PLA-based polymer product compared to one pound of PET-based polymer product
- Projected cost of energy resources over the period of analysis, ending in 2017

The total energy content of PLA-based polymer product at 23,312 BTU per pound is 36 percent lower than the energy content of petroleum-based PET product at 36,166 BTU per pound (see Table 2). Each pound of PLA-based product contains about 1,200 BTU of petroleum-derived content, while each pound of PET-based product contains over 31,000 BTU, or 26 times the petroleum content of PLA.

For PLA-based polymers, the energy content in corn starch is derived from solar energy, except for limited fossil energy required to fuel farm equipment, provide fertilizer feedstock, and facilitate the transportation of pellets to the converter's facility (Vink et al., 2003). Energy requirements for the manufacturing process—corn to pellet conversion, packing, and converter operations—are estimated as one-third from natural gas, one-third from coal, and one-third from electricity.

Table 2: Fossil Energy Budgets for PLA and PET (BTU per Pound of Product)

	Fossil Energy Content by Type of Energy Resource				Total Fossil
	Oil	**Natural Gas**	**Coal**	**Electricity**	**Energy Content**
PLA					
Corn Production	914				914
Corn Feedstock—Solar Energy					
Feed to Pellet		5,806	5,806	5,806	17,419
Packing		150	150	150	450
Transport	276				276
End-Product Operations		1,418	1,418	1,418	4,253
Energy Budget	1,190	7,374	7,374	7,374	23,312
PET					
Petroleum Production	1,015				1,015
Petroleum Feedstock	16,132				16,132
Feed to Pellet	13,811				13,811
Packing					
Transport	276				276
End-Product Operations		1,644	1,644	1,644	4,932
Energy Budget	31,234	1,644	1,644	1,644	36,166

Source: Vink et al., 2003, supplemented by additional information from NatureWorks.

For PET-based product, 86 percent of energy content comes from petroleum-derived feedstock and from petroleum derivatives used for the cogeneration of process steam and electricity (Vink et al., 2003).

To estimate energy cost savings associated with PLA utilization, information about respective energy resources and energy content is supplemented with energy cost projections for each resource—petroleum, natural gas, coal, and electricity.

In early 2006, the Energy Information Administration (EIA) of the U.S. Department of Energy published its final *2006 Annual Energy Outlook* with cost projections for a reference energy price scenario and for a high energy price scenario. The base case analysis of PLA energy savings uses energy costs from the EIA reference scenario (see Table 3A).

Base case energy cost savings to be realized from PLA replacement of PET are estimated by combining PLA sales volumes, energy content by type of resource, and energy prices for each resource (see Table 4) in the following manner: U.S. resin sales in millions of pounds (from Table 1) are multiplied by fossil energy savings that result from replacing PET with PLA expressed in BTU per pound of product (from Table 2) and finally multiplied by "reference energy prices" expressed in dollars per million BTU (from Table 3A).

Table 3A: EIA Reference Energy Price Scenario (2005 Dollars per Million BTU)

Year	Petroleum	Natural Gas	Coal	Electricity
2003	5.49	5.09	0.92	23.04
2004	7.00	5.51	1.01	22.94
2005	9.67	7.64	1.07	25.27
2006	10.22	6.88	1.09	24.89
2007	9.62	6.16	1.10	23.69
2008	9.04	5.80	1.11	22.89
2009	8.67	5.36	1.11	22.50
2010	8.18	5.05	1.12	22.16
2011	8.19	4.80	1.09	21.77
2012	8.24	4.74	1.08	21.63
2013	8.19	4.82	1.06	21.86
2014	8.11	4.72	1.05	21.78
2015	8.26	4.54	1.04	21.58
2016	8.33	4.48	1.04	21.59
2017	8.35	4.55	1.04	21.64

Source: Energy Information Administration, January 2006.

Table 3B: EIA High Energy Price Scenario (2005 Dollars per Million BTU)

Year	Petroleum	Natural Gas	Coal	Electricity
2003	5.49	5.09	0.92	23.04
2004	7.00	5.51	1.01	22.94
2005	9.67	7.64	1.07	25.27
2006	10.21	6.92	1.09	24.87
2007	10.25	6.58	1.12	24.10
2008	10.35	6.43	1.12	23.56
2009	10.57	6.12	1.15	23.24
2010	10.84	5.98	1.14	23.08
2011	11.24	5.82	1.13	22.95
2012	11.69	5.89	1.11	22.91
2013	12.22	5.96	1.10	23.19
2014	12.68	6.02	1.09	23.40
2015	13.19	5.68	1.08	22.95
2016	13.53	5.45	1.09	20.70
2017	13.73	5.52	1.09	22.74

Source: Energy Information Administration, January 2006.

For an optimistic step-out scenario, estimated energy cost savings reflect higher PLA production levels, higher U.S. resin sales (as the Blair facility reaches full-production levels in 2011 instead of 2014), and higher projected petroleum costs per EIA's high-price scenario (Table 3B). By 2017 the high-price scenario for petroleum indicates price levels at $13.73 per million BTU or 64 percent higher than the reference scenario at $8.35 per million BTU.

To illustrate the estimation of energy cost savings, consider the 2006 base case for PLA and PET energy costs.

PLA ENERGY COSTS:

Using the information from Table 2, the energy budget of PLA in BTU per one million pounds is indicated as

1,190 million BTU of petroleum
7,374 million BTU of natural gas
7,374 million BTU of coal
7,374 million BTU of electricity

The above components of the PLA energy budget are next multiplied by 2006 energy price levels from Table 3A to yield the cost components for each type of energy:

1,190 million BTU of petroleum × \$10.22/million BTU = \$12,162
7,374 million BTU of natural gas × \$6.88/million BTU = \$50,733
7,374 million BTU of coal × \$1.09/million BTU = \$8,038
7,374 million BTU of electricity × \$24.89/million BTU = \$183,539
PLA energy costs per million pounds of PLA = **\$254,472**

PET ENERGY COSTS:

Using the information from Table 2, the energy budget of PET in BTU per one million pounds is indicated as

31,234 million BTU of petroleum
1,644 million BTU of natural gas
1,644 million BTU of coal
1,644 million BTU of electricity

The above components of the PET energy budget are next multiplied by 2006 energy price levels from Table 3A to yield the cost components for each type of energy:

31,234 million BTU of petroleum × \$10.22/million BTU = \$319,211
1,644 million BTU of natural gas × \$6.88/million BTU = \$11,311
1,644 million BTU of coal × \$1.09/million BTU = \$1,792
1,644 million BTU of electricity × \$24.89/million BTU = \$40,919

PET energy costs per million pounds of PET = **\$373,233**

Table 4: **Base Case Energy Cost Savings—PLA versus PET (2005 Dollars)**

	PLA U.S. Sales (Million Pounds)	PLA Energy Costs per Million Pounds	PET Energy Costs per Million Pounds	Energy Savings per Million Pounds	Total Annual Energy Savings (Million $)
2003	3.333	0.221	0.219	–0.001	–0.005
2004	10.000	0.226	0.267	0.041	0.413
2005	20.000	0.262	0.358	0.096	1.915
2006	33.333	0.254	0.373	0.119	3.959
2007	38.240	0.240	0.351	0.112	4.265
2008	43.869	0.230	0.331	0.101	4.428
2009	50.326	0.224	0.318	0.094	4.755
2010	57.734	0.219	0.302	0.083	4.809
2011	66.233	0.214	0.301	0.087	5.790
2012	76.000	0.212	0.302	0.090	6.854
2013	87.167	0.214	0.301	0.087	7.596
2014	100.00	0.213	0.299	0.086	8.577
2015	100.00	0.210	0.303	0.093	9.260
2016	100.00	0.210	0.305	0.095	9.501
2017	100.00	0.211	0.306	0.095	9.498

To complete illustrative calculations using the assumptions in Tables 2 and 3A, energy savings per million pounds are $373,233 minus $254,472, or **$118,761.** Multiplied by PLA domestic sales of 33.333 million pounds, 2006 total energy savings are $3,958,665, rounded to **$3.959 million** in Table 4.

Value Creation from Avoided CO_2 Emissions

As indicated in Table 5, for each pound of PLA, carbon dioxide emissions are 1.633 pounds lower than emissions from using a pound of PET (Vink et al., 2003). Over the 2003 to 2017 study period, total PLA production at Blair is estimated at 2.66 billion pounds (from Table 1). When PLA production is multiplied by 1.663 pounds

Table 5: **CO_2 Emission Estimates (Pounds of CO_2 per Pound of Polymer)**

	PET	PLA	Avoided CO_2 Emissions Going from PET to PLA
Feedstock	0.017	–1.606 (see note)	
Feed to Pellet Operations	2.879	2.993	
Packing	0.000	–0.024	
Transport	0.051	0.051	
End-Product Operations	0.774	0.673	
Total CO_2 Emissions	3.721	2.088	1.633

Note: Negative CO_2 emissions are due to photosynthesis acting as carbon sink.
Source: Vink et al., 2003, and supplemental data supporting the analysis.

of avoided CO_2 emissions per pound of PLA, CO_2 savings over the study period are projected at 4.34 billion pounds, or 1.99 million metric tons.

Avoided CO_2 emissions will reduce adverse climate change impacts, which can be associated with a multitude of health, economic, and other risks.

To conservatively estimate the value of avoided climate change impacts, PLA carbon emission reductions are valued as U.S. carbon credits traded on the Chicago Climate Exchange (CCX), denominated in dollars per metric ton. As a basis for projecting the value of CCX carbon futures, recent price levels are provided in Table 6.

- For a base case, carbon credits are conservatively valued at $2.16 per metric ton for the entire period of analysis through 2017.

- For the step-out scenario, carbon credits are valued at $5.00 per metric ton beyond 2006. With recent trends toward an increasing valuation of CO_2 (see Table 6), expected societal emphasis on climate change mitigation, and the likelihood of additional future regulatory requirements, the $5.00 estimate can also be considered conservative, particularly in light of the following:

    - Traded European Union carbon credits are ranging from $24 to $37 per metric ton (Morrison, 2006), which is 5–7 times the $5 valuation for the step-out scenario.
    - New York, California, and eight other states are suing the U.S. EPA for refusing to proactively regulate CO_2 emissions of power plants (Hakim, 2006).

Value Creation from Avoided Landfilling (through Composting)

In 2001, the United States generated 229 million tons of municipal solid waste. Polymers accounted for approximately 11 percent of this waste stream, with food service packaging a significant subsegment of the polymer waste stream (EPA, 2001).

Table 6: **Trading Ranges for Chicago CCX Carbon Credits (Dollars per Metric Ton)**

December 2003	0.92–1.00	**Over 100 percent increase in two years**
October 2004	0.98–1.53	
January 2005	1.74–2.02	
October 2005	2.16–2.50	

Source: Chicago Climate Exchange.

Unrecovered (and not recycled) polymer wastes—about 80 percent of total polymer wastes—are disposed of in landfills. In 2004, U.S. landfill tipping fees averaged $34.29 per ton, varying from $24 in the Southwest to over $70 in the Northeast (Repa, 2005). In addition to incurring tipping fees, landfill disposal results in long-term waste management problems.

Unlike petroleum-based products, PLA-based products enable an alternative disposal method of composting in industrial-scale composting facilities. An informal survey of U.S. composing facilities identified tipping fees at composting facilities in the range of $25–$30 per ton (BioCycle, 1999) or over $4 per ton lower than average tipping fees for landfill disposal.

While composting will be a practical method of disposal, input from various industry experts suggest that only a small segment of the PLA waste stream is likely to be composted. Based on this input, it was assumed that five percent of PLA sales will be composted and avoid over $4 per ton in tipping fees.

To estimate *expected values* for benefit cash flows, the combined probability of achieving future production and sales levels and of realizing energy savings, reducing CO_2 emissions, and increasing end-of-life composting (beyond 2005) is deemed to be 85 percent for both base case and step-out scenarios.

BENEFIT-COST ANALYSIS

While benefit-cost analysis—in general—compares the stream of projected benefits to the investment, the focus of this study is limited to comparing public benefits that are attributable to ATP to the ATP investment.

For benefits that can be meaningfully quantified, cash flows are estimated for a conservative base case scenario. Cash flows are also estimated for an optimistic step-out scenario based on higher unit sales projections and higher benefit levels per unit.

Using alternative base case and step-out scenarios makes it possible to investigate cash flow sensitivity to key assumptions and to bracket performance metrics for a range of assumptions from conservative to more optimistic.

ATP and Industry Partner Investments

The ATP investment was \$1.910 million, or \$2.377 million in 2005 dollars. The NatureWorks cost share was \$1.784 million, or \$2.222 million in 2005 dollars. Furthermore, it is estimated that NatureWorks made an additional direct investment of \$7 million to refine the PLA process technology after the ATP-funded project was completed. NatureWorks' investments are utilized for the estimation of social return metrics but not for metrics that gauge public returns on ATP's investment.

Cargill also made significant investments in feedstock processing prior to the ATP-funded project. These investments are not included in the benefit-cost analysis of the ATP-funded project because they were outside of the scope of the ATP-funded project and its direct benefits.

Public Returns on ATP Investment—Base Case

The flow of public benefits from ATP's investment are composed of energy savings, avoided CO_2 emissions, and avoided landfill tipping fees, as illustrated in Figure 5.

Base case cash flow estimates and performance metrics, gauging the scale of public benefits resulting form ATP investment, are presented in Table 7.

Figure 5: Flow of Public Benefits from PLA Process Technology

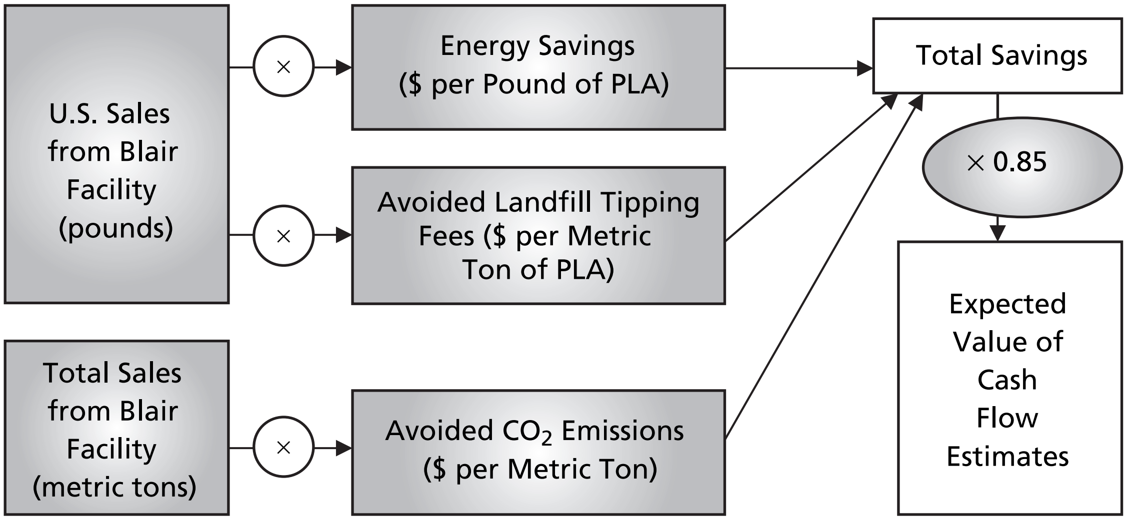


Table 7: Base Case—Cash Flows and Performance Metrics for Public Returns on ATP Investments (Millions of 2005 Dollars)

	Energy Savings	CO_2 Emission Credits	Avoided Landfill Tipping Fees	Sum of Benefits	Expected Value of Benefits (85%)
1996				–2.377	–2.377
1997					
1998					
1999					
2000					
2001					
2002					
2003	–0.005	0.016	0.000	0.011	0.011
2004	0.413	0.048	0.001	0.462	0.462
2005	1.915	0.096	0.002	2.013	2.013
2006	3.959	0.160	0.003	4.122	3.504
2007	4.265	0.184	0.004	4.452	3.784
2008	4.428	0.211	0.004	4.642	3.946
2009	4.755	0.242	0.005	5.002	4.251
2010	4.809	0.277	0.005	5.092	4.328
2011	5.790	0.318	0.006	6.114	5.197
2012	6.854	0.365	0.007	7.226	6.142
2013	7.596	0.418	0.008	8.023	6.819
2014	8.577	0.480	0.010	9.066	7.706
2015	9.260	0.480	0.010	9.749	8.287
2016	9.501	0.480	0.010	9.990	8.492
2017	9.498	0.480	0.010	9.987	8.489
Net Present Value (Millions of 2005 Dollars)					21.2
Internal Rate of Return (%)					26
Benefit-to-Cost Ratio					10.6:1

Note: A 1996 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 1996 (project midpoint) and prospective cash flow benefits through 2017. Positive cash flows represent public benefits attributable to the ATP; negative cash flows represent ATP investment costs (assumed to occur at project midpoint).

The net present value of the ATP investment is estimated at $21.2 million in 2005 dollars. The internal rate of return is projected at 26 percent and the benefit-to-cost ratio is almost 11 dollars of benefits for every dollar of ATP investment.

It is assumed that, at a minimum, the ATP-funded PLA production process will be economically viable for 15 years. Corresponding to the assumed economic life of the ATP-funded process, a 15 year study period is used for cash flow analysis.

To illustrate cash flow benefit calculations, consider base case calculations for 2006.

Energy savings are **$3.959 million**, from Table 4.

Cash flow benefits from CO_2 emission savings are estimated by the following:

- Converting 100 million pounds of global PLA sales (from Table 1) to 45,351 metric tons
- Multiplying this amount by 1.633 metric tons of CO_2 saved per ton of PLA (from Table 5) and arriving at total CO_2 savings of 74,059 metric tons
- Multiplying 74,059 tons by $2.16 per ton to arrive at a saving of **$159,967**

Cash flow benefits from reduced tipping fees are estimated by the following:

- Converting domestic PLA sales of 33.333 million pounds into metric tons and multiplying this amount by 5 percent—the estimated amount to be composted over and above current polymer waste recycling rates—to arrive at 755.9 tons of avoided landfilling
- Multiplying 755.9 tons by $4.2 of savings per ton to yield 2006 savings of **$3,175**

As indicated in Table 7, total 2006 cash flow benefits are **$4.122 million** or the sum of $3.959 million, $159,967, and $3,175.

The expected value of total cash flow benefits is computed by multiplying $4.122 million by an 85 percent probability.

As a result, the expected value of 2006 benefits is estimated at **$3.504 million** (see Table 7).

Public Returns on ATP Investment—Step-Out Scenario

Step-out scenario assumptions (relative to the base case) are as follows:

- Higher processed volumes. Blair facility reaches full capacity in 2011 (see Table 1).
- Using EIA high price scenario to value energy savings. By 2017 this scenario is associated with a 64 percent higher petroleum price than EIA's reference scenario.
- Using $5 per metric ton to value avoided CO_2 emissions.

Step-out scenario benefit cash flow estimates and performance metrics are presented in Table 8.

Table 8: Step-Out Scenario—Cash Flows and Performance Metrics for Public Returns on ATP Investments (Millions of 2005 Dollars)

	Energy Savings	CO_2 Emission Credits	Avoided Landfill Tipping Fees	Sum of Benefits	Expected Value of Benefits (85%)
1996				–2.377	–2.377
1997					
1998					
1999					
2000					
2001					
2002					
2003	–0.005	0.016	0.001	0.012	0.012
2004	0.413	0.048	0.002	0.463	0.463
2005	1.915	0.096	0.004	2.015	2.015
2006	4.743	0.192	0.008	4.943	4.202
2007	6.037	0.534	0.010	6.581	5.594
2008	7.656	0.641	0.012	8.309	7.063
2009	9.886	0.770	0.014	10.670	9.070
2010	12.699	0.925	0.017	13.641	11.595
2011	16.630	1.111	0.021	17.762	15.098
2012	17.991	1.111	0.021	19.123	16.254
2013	19.385	1.111	0.021	20.517	17.440
2014	20.604	1.111	0.021	21.736	18.475
2015	22.613	1.111	0.021	23.745	20.183
2016	25.054	1.111	0.021	26.185	22.258
2017	24.435	1.111	0.021	25.567	21.732
Net Present Value (Millions of 2005 Dollars)					50.2
Internal Rate of Return (%)					32
Benefit-to-Cost Ratio					23.6:1

Note: A 1996 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 1996 (project midpoint) and prospective cash flow benefits through 2017. Positive cash flows represent public benefits attributable to the ATP; negative cash flows represent ATP investment costs (assumed to occur at project midpoint).

The net present value of the ATP investment is estimated at $50.2 million in 2005 dollars. The internal rate of return is projected at 32 percent and the benefit-to-cost ratio is almost 24 dollars of benefits for every dollar of ATP investment.

Social Rate of Return

The PLA technology project was cost shared by ATP and Cargill and will lead to benefits for suppliers, customer industries, and end users—in essence, taxpayers broadly—as well as benefits for Cargill and NatureWorks.

A measure of the total benefits relative to total costs provides a broader, more complete picture of project performance than just public returns on ATP's investment. The social rate of return is such a measure and has been used by leading economists as an important indicator of broad social benefits that result from new technologies and innovations.

To estimate social rates of return, public and private benefit cash flows are combined and compared to the sum of all public and private investments, using an internal rate of return calculation. Next, social rates of return are compared to approximate private rates of return that ATP's industry partners would expect to realize over the long term. The excess of the social rate of return over the private rate of return is the spillover gap. 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 could lead to private sector underinvestment and associated loss of benefits to downstream firms, end-user customers, the economy, and society at large.

Estimates of the social rate of return, proxy private rate of return, and the spillover gap for the NatureWorks PLA process technology are provided in Table 9.

For the PLA process technology, the spillover gap ranges from 4 to 11 percent and points to significant benefits to the general public beyond benefits to the industry partner.

Given the high likelihood that the PLA process technology project would not have been funded to technical completion without an ATP cost share, the results indicate a fulfillment of ATP's mission to fund high-risk technologies with significant economic benefits to the nation.

Table 9: Social Rate of Return and Spillover Gap

Social Rate of Return	Proxy Private Rates of Return	Spillover Gap: Social Return Minus Private Returns
17%	6% to 13%	4% to 11%

OTHER BENEFITS

Many important benefits expected to result from the use of renewable PLA feedstock for polymer products are effectively captured through cash flow estimates and performance metrics. At the same time, other important benefits cannot at this time be quantified as cash flow estimates; rather, they are discussed in a qualitative manner, including the benefits of reduced reliance on imported petroleum and benefits to the U.S. farm economy.

Reduced Reliance on Imported Petroleum

Using PLA to replace petroleum-based PET results in lower energy content in polymer products and provides the first source of cost savings. Since petroleum is the most expensive energy resource for polymer production, replacing petroleum with domestically grown corn feedstock leads to a second source of cost savings. Beyond cost savings captured in performance metrics, given that most U.S. consumption of petroleum is supported with imports, reduced petroleum consumption also provides an increment of reduced import reliance. Although reduced import reliance for this strategic energy resource is clearly an important benefit, it is not captured in performance metrics. Instead, the following analysis provides an indication of the scale of these benefits.

For every pound of petroleum-based PET polymer being replaced by PLA, U.S. petroleum consumption will be reduced by over 30,000 BTU. Extended by the annual production at the Blair facility for both U.S. and offshore consumption, the estimated 2006 annual reduction in petroleum use will be 518,000 barrels of oil, over 70 percent of which is now imported. By 2014 (in the base case) and by 2011 (in the step-out scenario), the Blair facility is expected to reach full production, at which time the estimated annual reduction in petroleum use will be over 1.5 million barrels.

For the base case, over the 2003–2017 period, 13.8 million barrels of petroleum use will be avoided as a result of the ATP-funded PLA process technology. Under the step-out scenario, total avoided petroleum use is estimated at over 16 million barrels (Table 10). What is the “full value” of PLA’s utility in reducing U.S. dependence on imported and finite petroleum resources?

A 1998 study by the International Center for Technology Assessment (ICTA) estimates the real price of gasoline at almost $24 per gallon (in 2005 dollars). At this level, the real price of gasoline would be 8 times higher than recent (2006) gasoline prices at the pump and the real price of petroleum from which gasoline is refined would also be 8 times higher. To arrive at these estimates, the ICTA study examined many cost factors, only some of which are fully internalized in current market prices (ICTA, 1998). Costs that remain externalities and, therefore, are not effectively captured by market mechanisms, include U.S. government subsidies to the petroleum industry; cost of protecting oil supplies, including military expenditures for protecting

Table 10: Reduced Petroleum Use—PLA versus PET

	Base Case		Step-Out Scenario	
Year	Blair Production (Million pounds)	Avoided Use of Petroleum Feedstock (Millions of Barrels)	Blair Production (Million pounds)	Avoided Use of Petroleum Feedstock (Millions of Barrels)
2003	10	0.052	10	0.052
2004	30	0.155	30	0.155
2005	60	0.311	60	0.311
2006	100	0.518	120	0.622
2007	115	0.594	144	0.747
2008	132	0.682	173	0.897
2009	151	0.782	208	1.077
2010	173	0.897	250	1.294
2011	199	1.029	300	1.554
2012	228	1.181	300	1.554
2013	262	1.355	300	1.554
2014	300	1.554	300	1.554
2015	300	1.554	300	1.554
2016	300	1.554	300	1.554
2017	300	1.554	300	1.554
Total	2,660	13.772	3,095	16.031

the Middle East and other oil-rich regions; and environmental, health, and social costs, including those of global warming (ICTA, 1998).

Another recent study (Leiby and Greene, 2005) estimates oil security benefits from reduced oil imports at up to $16 per barrel, depending on cartel behavior among oil producers, potential future embargoes, and future wars in the Middle East.

In addition to macro benefits from reduced dependence on imported oil, significant microeconomic benefits can be anticipated, including reduced vulnerability to petroleum shortages, reduced volatility in costs, and improved brand image from using renewable resources (Suarez, 2004).

Benefits to the U.S. Farm Economy

U.S. produced corn feedstock for PLA resin will result in the following benefits:

- Agricultural and nonagricultural employment in the region and exports will increase.
- Two-thirds of the Blair production capacity or 200 million pounds (at full capacity) are slated for overseas export. At an estimated price of 90 cents per pound, there will be $180 million of additional U.S. exports.

Based on an analysis conducted at the Center for Economic and Business Development of Oklahoma State University, the economic impact of a PLA production facility (manufacturing approximately 300 million pounds of PLA resin annually) would result in increased regional employment of 1,335 jobs over the 2008–2010 period, including 206 new farm-sector jobs and 1,129 nonfarm jobs (Chiappe, 2003).

CASE STUDY SUMMARY

Performance metrics indicate strong performance of the ATP-funded PLA process technology, including a high public rate of return (26–32 percent), a significant social rate of return (17 percent), and a spillover gap of 4–11 percent.

In addition to performance metrics, the case study points to important additional benefits, including reduced petroleum imports and a stronger U.S. farm economy.

4. Case Study: High-Speed Identification and Sorting of Nonferrous Metal Scrap

wTe Corporation of Bedford, Massachusetts used ATP funding to develop a proprietary alloy-sorting technology for cost-effective sorting of nonferrous metal scrap including titanium alloys, superalloys, and aluminum alloys, thereby facilitating the increased recycling of these valuable metals.

The U.S. economy generates large volumes of metal scrap, often as complex mixtures of ferrous and nonferrous alloys and contaminants. The ferrous components can be segregated with magnetic separation technologies and subsequently recycled. It is, however, often impractical to cost-effectively segregate nonferrous scrap into its components and this tends to result in the downgrading of mixed nonferrous scrap streams to lower-value uses.

The ATP-funded High-Speed Identification and Sorting of Nonferrous Metal Scrap project made it possible for wTe Corporation to unambiguously sort valuable nonferrous metal scrap (titanium, superalloys, and aluminum), increase recycling rates, and reduce production costs relative to virgin metal alloys. A wide range of public benefits can be traced to this ATP investment, including the following:

- Avoiding the outright waste of high-value nonferrous metal scrap and making it available for cost-effective secondary alloy production
- Reducing energy requirements for alloy production
- Reducing greenhouse gas emissions
- Reducing import dependence for titanium- and nickel-based metal concentrates for the primary production of titanium alloys and nickel-based superalloys

Benefits from this ATP-funded technology will lead to manufacturing cost savings in the U.S. metals industry. Some of these savings will be passed on to end users of metal products made from titanium, superalloys, and aluminum.

Commercialization is underway. Economic benefits (realized and projected) to U.S. industry and end users are estimated at over $10 for every dollar of ATP investment.

PROJECT HISTORY

In 1999, wTe Corporation of Bedford, Massachusetts submitted a proposal to ATP for developing an advanced optical technology for sorting nonferrous metal scrap.

The proposal referenced significant technical risks associated with developing the following aspects of the technology:

- High-speed material handling systems for mixed and contaminated scrap
- Novel X-ray detector configurations to unambiguously sort metals with high atomic numbers as well as metals with low atomic numbers
- Achieving high levels of throughput and reliability

Given the scale of potential public benefits, the presence of high technical risks, and wTe's limited financial resources, in 2000 the ATP agreed to fund the proposed project.

Subsequent to the completion of the ATP-funded project, wTe, together with its joint venture partner National Recovery Technologies (NRT), established Spectramet LLC as a joint-venture company to commercialize the high-speed optical sorting technology. Spectramet ownership is shared at 50 percent by joint-venture partners wTe and NRT.

wTe was formed in 1981 as a consultancy to the waste-to-energy industry. By the early 1990s the company evolved into operating large-scale waste-to-energy and waste-recycling plants. Currently, wTe owns and operates a plastics-recycling facility located in Albany, New York, and an auto-shredder facility in Greenfield, Massachusetts that has significant market share in the New England region.

Spectramet (the joint-venture company) is co-located with wTe's Greenfield auto-shredder facility. NRT was a spinoff from Vanderbilt University and specializes in equipment design and manufacturing for plastics processing and recycling, including X-ray vision systems for high-speed, high-accuracy plastics sorting.

The ATP-funded project was successfully completed in 2003. wTe's technical contribution included the development of customized material-handling subsystems and pneumatic ejection systems as well as overall systems integration, testing, and subsequent commercialization. NRT made significant technical contributions in the areas of opto-electronic sensors and the development of specialized algorithms to match secondary X-ray fluorescence (XRF) emissions to a database of characteristic emission spectra for hundreds of alloys.

In addition, an active advisory board of leaders from academia and industry provided substantial technical input regarding the physics and metallurgy of nonferrous alloy sorting; access to university research laboratories and test facilities; business guidance; and introductions to major industry users of recycled titanium, superalloys, and aluminum alloys. Academic advisors in the areas of physics and opto-electronics came from Vanderbilt University and from the Massachusetts Institute of Technology in the areas of materials science and metallurgy.

Over the 1993–2003 period, wTe also received funding from the National Science Foundation (NSF). Two modestly funded projects preceded the ATP investment and were used to develop fundamental knowledge, which later facilitated the ATP proposal and investment process. A third NSF-funded project (funded after the completion of the ATP project) supported the development of the DXRT (differential X-ray transmission) system, complementing the ATP-funded technology by making it possible to separate out copper (Cu), zinc (Zn), stainless steel, and other "heavy" components of nonferrous concentrates and enabling aluminum alloy sorting.

To date, titanium alloy sorting has been launched as a viable commercial operation. With the installation and testing of a DXRT unit also completed, aluminum twitch and aluminum alloy sorting are now moving toward commercialization. Superalloy sorting will be developed in the near future as a third nonferrous metal sorting service.

Without ATP, the above technology development projects would not have been completed and the resultant technical advances would not have been achieved.

HOW DOES IT WORK?

Prior to the development of ATP-funded metal scrap sorting technology, available methods for separating nonferrous scrap metals into constituent alloys included the following:

- Manual sorting: This method works by color and "feel" and is typically used in low-wage labor markets.
- Spark sorting: This method uses grinding wheels, is slow, and requires experienced operators.
- Chemical sorting: This method uses a litmus paper approach, which is also slow and requires experienced operators.
- Heavy media separation: This method uses various liquid mediums, in which heavy nonferrous components sink to the bottom and lower specific density components float near the surface. While able to separate aluminum alloys from heavier metals, this method is unsuitable for the identification and sorting of specific alloys.
- Benchtop and hand-held X-ray analyzers: These methods are accurate, slow, and expensive and therefore not suitable for supporting industrial-scale operations (Spencer, 2005).

To overcome the speed and cost limitations of traditional methods for nonferrous metal sorting, wTe proposed to ATP a new, lower-cost technology using opto-electronic instrumentation for unambiguously sorting nonferrous metal scrap into constituent alloys at high speeds.

The Spectramet approach uses commercially available X-ray instruments to irradiate small pieces of metal scrap with high-energy X-rays on a fast moving conveyor belt. Incident X-rays excite atoms within the pieces of scrap, which in turn emit secondary radiation with wavelengths characteristic of the alloy's elemental components. In this manner:

- Emitted secondary wavelength intensities are detected by X-ray fluorescence sensors and accumulated for constituent elements of each piece of scrap to be identified and sorted (Thermo Fisher Scientific).
- Intensity levels of secondary emissions are fed into computers with specialized algorithms to match emissions to a database of characteristic emission spectra for hundreds of alloys.
- Since fluorescent emissions are characteristic of particular elements and virtually independent of their state of chemical combinations, measuring the intensity of emitted secondary X-rays can provide a reliable means of quantitative analysis for elemental composition (XRF analysis).

The proposed Spectramet technology concept was a two-stage configuration (Figure 6). The first-stage *alloy grouper* would sort mixed metal scrap into groups or related alloys (titanium alloys, superalloys, and aluminum alloys) and the second-stage *alloy sorter* unambiguously would separate individual alloys within each group.

The alloy grouper and alloy sorter utilize XRF sensors to identify emission spectra. Emission spectra, fed to computer processors, are used to identify scrap by elemental composition and also to activate high-pressure pneumatic air jets to eject objects moving along the conveyor belt into specific bins. The alloy sorter operates at high power levels for the accurate characterization of individual alloys.

For initial commercialization, the above two-stage approach was modified to a single-stage configuration, when XRF proved ineffective in separating low-Z (low atomic number) alloys. A decision was made to focus initially on commercializing sorting of titanium alloys.

A single-stage alloy sorter is now in commercial operation at Spectramet's Greenfield, Massachusetts facility for the sorting of titanium alloys. The sorter uses XRF detectors, in combination with a material-handling system and a pneumatic ejection system (see Figure 7).

Figure 6: Proposed Two-Stage Approach Using Alloy Grouper and Alloy Sorter

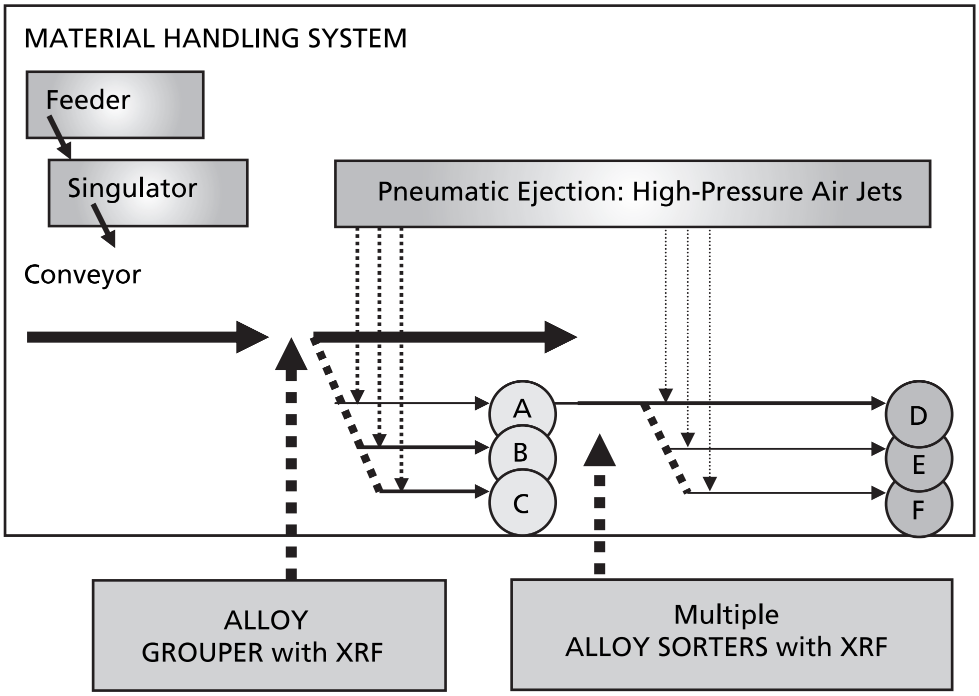
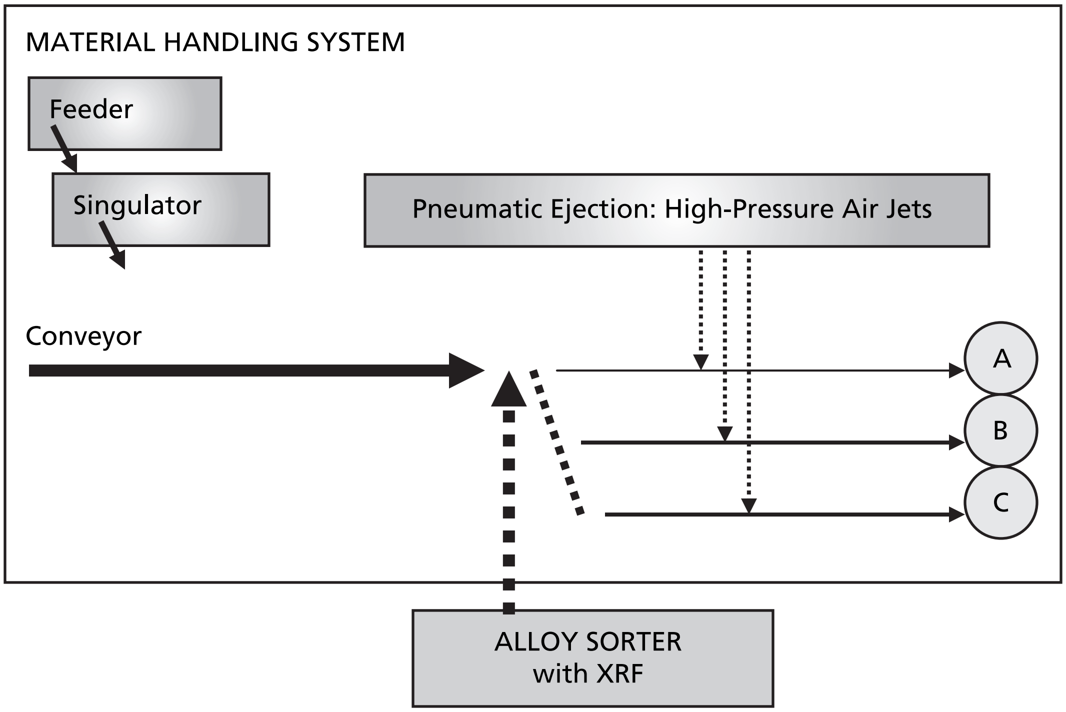


Figure 7: Single-Stage Titanium Alloy Sorter and Superalloy Sorter

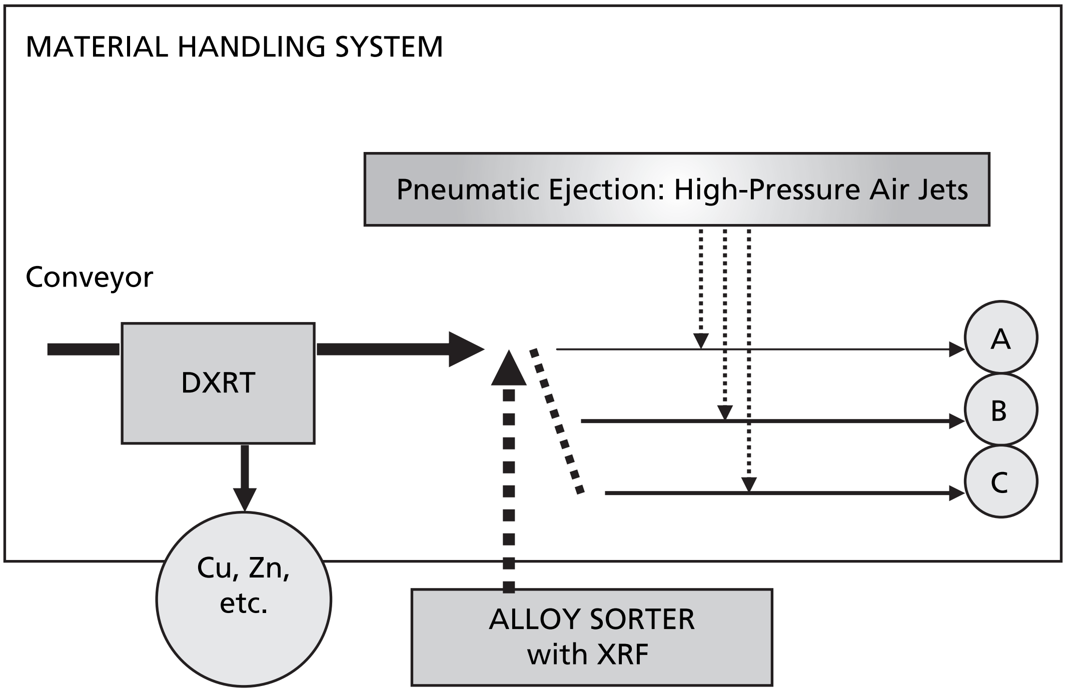


A second modification of the initial two-stage approach resulted from the recognition that XRF analytical methods are ineffective at identifying and unambiguously sorting high-Z (high atomic number) nonferrous metals from low atomic number aluminum alloys.

Additional new technology (differential X-ray transmission or DXRT) was developed with NSF funding to unambiguously separate nonferrous concentrates (NFC) into "heavy" components—copper (Cu), zinc (Zn), magnesium (Mg), and other nonferrous metals—and lighter aluminum alloys. The DXRT technology is placed in front of the single-stage alloy sorter, which subsequently separates mixed aluminum alloys into specific aluminum alloys, represented by A, B, and C in Figure 8.

While single-stage alloy sorters for titanium and aluminum alloys are currently in commercial and precommercial stages, a two-stage alloy grouper/alloy sorter combination remains an option for future development and for identifying and segregating mixed nonferrous metal scrap.

Figure 8: Single-Stage Aluminum Alloy Sorter with DXRT Front End



Technical Accomplishments

In 2003, the ATP-funded, high-risk technology project was successfully completed, leading to the following technical accomplishments.

MATERIAL HANDLING

- Completed design and engineering tasks for vibrating feeder, conveyor belt trommel, conveyor-fed singulator, and other materials handling subsystem components.

X-RAY FLUORESCENCE SENSOR

- Optimized X-ray source-to-detector geometries (situated under conveyor belts), distances, and angles.

ALLOY GROUPER

- Completed design, detailed engineering, prototype construction, and installation of pneumatic ejection system and ejection stations. Achieved near-real-time spectra acquisition and pneumatic sorting (based on computer-driven comparison of XRF detector data with spectra pattern look-up tables) for Cu, Zn, Fe, and brass alloys.
- Completed testing on a 20,000 pound lot of aluminum twitch, which was sorted into 14,000 pounds of high-zinc aluminum and 6,000 pounds of low-zinc aluminum.

ALLOY SORTER

- Completed design and installation of a prototype alloy sorter with improved and simplified man-machine interface. Entered compositions for more than 200 alloys into a computer database. Tested alloy sorter with titanium alloys, Ni/Co superalloys, and stainless steel. Achieved 100 percent identification of all common titanium alloys. Achieved 100 percent identification of nickel- and cobalt-based superalloy samples.

SYSTEM INTEGRATION

- Completed integrated design and operating specifications for processing titanium and superalloy scrap, at up to five objects per second, sized from 3/4 inches to 6 inches.

Patent Estate

Spectramet's current intellectual property strategy is to employ a combination of patents and trade secrets. Such a strategy may be explained by the fact that "technologies are patented at an early experimental stage after conception and proof of concept, at bench scale, but before technology development efforts yield much technical know how about proprietary new industrial processes" (David Spencer, interview, July 2005).

Accordingly, the results of the NSF-funded invention, at the proof-of-concept stage, were patented in U.S. Patent Number 6,266,290, issued on July 24, 2001. In contrast, the results of the subsequent ATP-funded high-risk technology projects are treated as trade secrets and are not made public through patent application and issuance.

Over time, this strategy may change and Spectramet could decide to license its scrap sorting technology to expand geographically and to include additional nonferrous metal scrap. A decision to license technology will contribute to the diffusion of the ATP-funded innovative process technology.

BENEFIT ASSESSMENT AND MODELING

Metal scrap has greatest value when segregated into individual alloys in a clean and dry state. In contrast, when scrap is not properly segregated into constituent alloys and cleaned from contaminants, it is generally downgraded to lower-value uses or is wasted.

> The Spectramet sorting technology makes it possible to cost-effectively sort valuable metal scrap into constituent alloys, leading to manufacturing cost savings in the metals industry. Some of these cost savings will be passed on to end users of metal products made from titanium, superalloys, and aluminum.
>
> Savings can be estimated by comparing prices of high-value alloys with unsorted metal scrap that is downgraded for lower-value uses.

This section introduces assumptions for modeling benefits that can be expected to result from the ATP-funded technology for sorting:

- Titanium scrap into individual alloys
- Nickel-based superalloy scrap into individual alloys
- Contaminated aluminum scrap into clean aluminum twitch and individual alloys

Titanium Alloy Sorting

Titanium scrap is post-industrial waste from the melting, forging, casting, and fabrication processes. Less than 50 percent of titanium scrap—typically larger pieces that can be visually inspected and sorted into alloy groups—is recycled into high-grade titanium alloys (USGS Minerals Yearbook, 2003b). Intermediate-size and small pieces that cannot be effectively segregated by alloy are downgraded and used as lower-value ferrotitanium for steel making.

Downgrading for lower-value use represents the *counterfactual scenario* against which the benefits of titanium alloy sorting using the ATP-funded technology are gauged.

* * * * *

Titanium is a metallic element, the ninth most common in the Earth's crust. Ilmenite and rulite concentrates are common raw materials for titanium production (see Figure 9). Approximately 95 percent of mineral concentrates are used in the production of titanium dioxide (TiO_2), a pigment with good covering power for paints and plastics. Only 5 percent is processed into virgin titanium "sponge" using the Kroll primary smelting process (see Figure 10). Titanium sponge, alone or blended with high-purity titanium scrap, is then used for casting titanium ingots alloyed to meet exacting military, aerospace, and medical specifications.

Figure 9: Major Uses of Titanium Mineral Concentrates

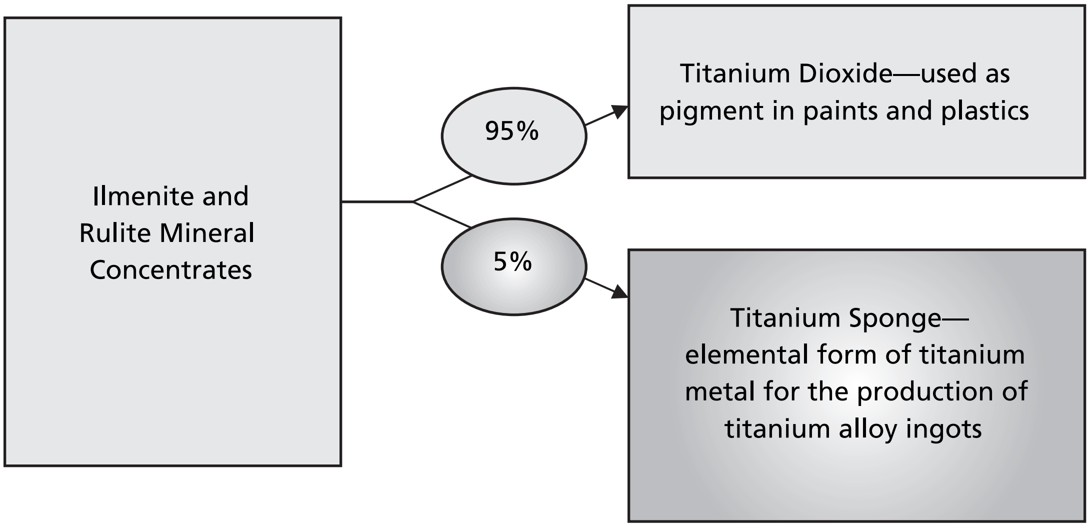
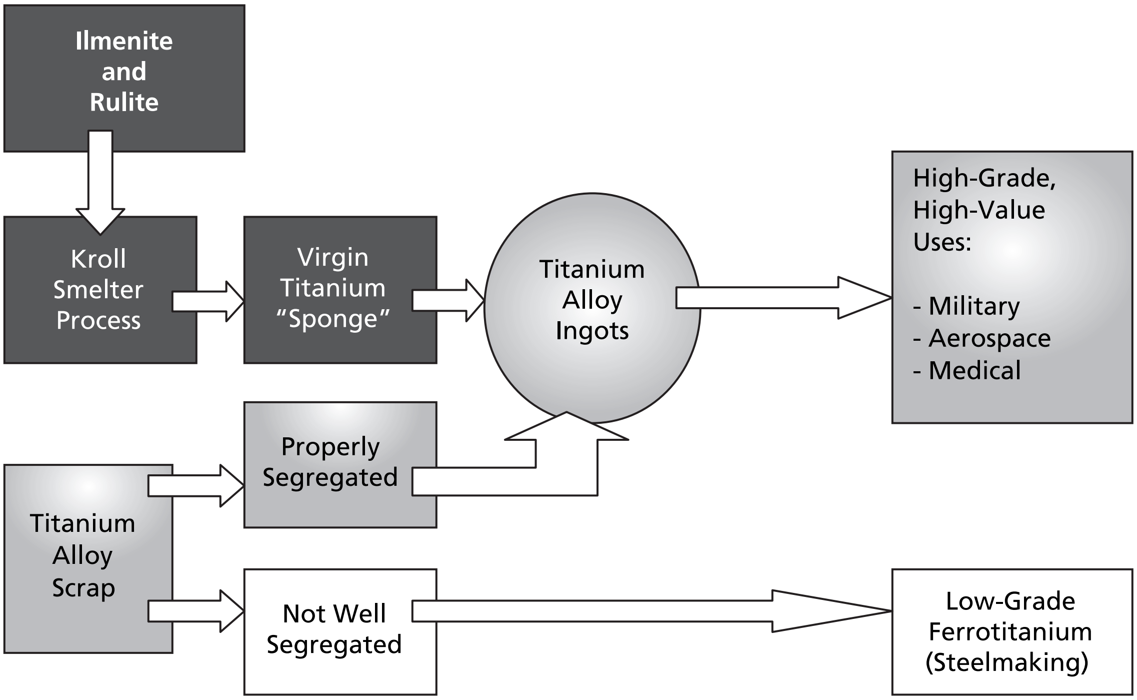


Figure 10: Titanium Alloy Manufacturing Process Flows



MARKET DEMAND

Titanium alloys have excellent corrosion resistance to acids, chlorine gas, and common salt solutions and are known for their high strength-to-weight ratios. They are resistant to metal fatigue and as strong as steel but 43 percent lighter than steel.

There is market demand for titanium ingots and milled products (bars, plates, and pipes forged and rolled from ingots) in the following industry sectors (TIMET, 2004):

- Commercial aerospace—engine components and airframes
- Military—aerospace and armor
- Oil and gas—saltwater cooling systems and corrosion resistant applications
- Automotive—exhaust systems, suspension springs, and engine valves
- Corrosion resistant parts—chemical plants, power plants, and desalination plants
- Medical and dental—bone and joint replacements, dental implants, and pacemaker cases

CONSUMPTION

Worldwide annual titanium consumption is approximately 60,000 metric tons (132 million pounds). In addition, approximately 32,000 metric tons (over 70 million pounds) are consumed as ferrotitanium in steel making (Roskill, n.d.).

U.S. annual consumption in 2005 was over 40,000 metric tons (88 million pounds), two-thirds of which was converted to milled products and the remainder shipped as titanium alloy ingots and billets for re-melting and casting (USGS, December 2005). U.S. consumption is supported by the processing of over 22,000 metric tons (48 million pounds) of virgin sponge and by the recycling of over 21,000 metric tons (46 million pounds) of titanium scrap.

Over 55 percent of virgin sponge is directly imported from Kazakhstan, Japan, and Russia. The remaining 45 percent is processed from 1.4 million metric tons of mineral concentrates, 63 percent of which is imported.

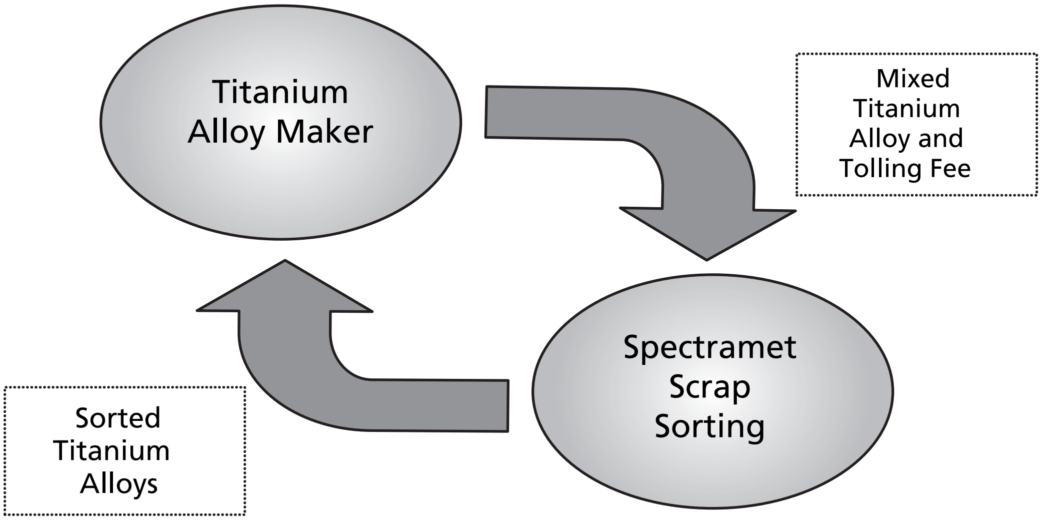
Of the estimated 30,000 metric tons (66 million pounds) of U.S. titanium scrap, approximately 10,000 metric tons (22 million pounds) are downgraded to ferrotitanium for steel making.

BUSINESS MODEL: TITANIUM SCRAP TOLLING

Spectramet's business approach for commercial sorting of titanium alloys is to use a tolling arrangement in partnership with major alloy makers who provide mixed titanium alloys (pieces that are larger than an ounce but under 5 pounds) and receive sorted alloys in exchange for a tolling fee (see Figure 11).

In the near future, Spectramet expects to develop business partnerships for sorting mixed titanium alloy fasteners and chips (small pieces less than 3/8 inch mesh). It is yet to be determined whether this arrangement will be one of tolling or one of purchasing from machine shops and fabricators and reselling to alloy makers.

Figure 11: **Closed-Loop Recycling for Titanium Alloy Sorting**



MODELING ASSUMPTIONS FOR TITANIUM SORTING

Benefit cash flows expected to result from the ATP-funded alloy sorting technology over the 2005–2015 period are estimated from processed titanium scrap volumes and from price spreads between high-value primary titanium and low-value ferrotitanium.

Processed Volumes

Annual processed volumes of titanium scrap are estimated to grow from 560,000 pounds in 2006 to almost 1.7 million pounds in 2015 (see Table 15, column c).

These estimates are in the current industry context of almost 90 million pounds of annual titanium consumption in the United States (USGS, December 2005), supported by almost 50 million pounds of high-grade titanium scrap. At the same time, over 20 million pounds of mixed scrap are downgraded to ferrotitanium (USGS, 2003a).

Relative to these market trends, it is estimated that when Spectramet reaches its highest level of production in 2015, it will have upgraded 9 percent of the 20 million pounds of titanium scrap that is currently downgraded.

Price Spreads

Titanium alloy prices have increased substantially since 2003 and generally higher prices are likely to be sustained. This is because titanium is a key military and industrial commodity with limited sources of supply and expected long-term demand growth in the aerospace, automotive, and chemical industry sectors.

Based on published data over the last three years, as well as input from industry participants, the approximate price spread—from ferrotitanium to primary titanium alloy—will range from $3.50 to $4.00 per pound for intermediate-size titanium scrap (see Table 11).

Spectramet's $1.75 per pound tolling fee is a private benefit. The remaining benefit of $1.75 to $2.25 per pound (base case versus step-out scenario) is enjoyed by downstream industry and the U.S. economy. These private and public benefits result from diverting high-value scrap from ferrotitanium utilization.

Other Assumptions

When titanium scrap is recycled into titanium alloys, some metal content is lost in the re-melt process. Based on discussions with industry sources, melt losses are estimated at 10 percent for intermediate-size titanium scrap and at 25 percent for recycling smaller titanium fastener scrap.

Table 11: Approximate U.S. Titanium Pricing (per Pound in 2005 Dollars)

	Base Case	Step-Out Scenario
Primary Titanium Alloy	13.00	13.50
Titanium Alloy Scrap	12.50	13.00
Titanium Sponge	12.00	12.00
Ferrotitanium	9.50	9.50
Price Spreads		
Ferrotitanium to Ti alloy	3.50	4.00
Minus Tolling Fee	–1.75	–1.75
Public Benefits	1.75	2.25

Sources: Industry sources and www.metalprices.com.

Based on a review of remaining uncertainties (technical and commercial), the probabilities of realizing estimated alloy-sorting volumes, price spreads, and staying within projected melt loss levels over the 2005–2015 period, are deemed to be the following:

- 90 percent for titanium alloys (less than 5 inch but larger than 3/8 inch mesh)
- 60 percent for titanium fasteners and chips (less than 3/8 mesh).

Superalloy Sorting

Due to stringent customer specifications, superalloy scrap in mixed form is not suitable for recycling and is sold as lower-value feedstock for stainless steel production and to cast iron foundries (USGS, 2003a). This represents the counterfactual scenario for the superalloy application.

The ATP-funded alloy sorter technology makes it possible to sort mixed, nickel-based superalloy scrap into high-value alloys that can be cost-effectively recycled. This generates economic benefits to industry users of superalloys based on price spreads between nickel-based superalloys and superalloy scrap downgraded to stainless steel and iron foundry feedstock.

* * * * *

Superalloys are complex metallic materials developed for very high–temperature applications. They provide superior mechanical strength, good surface stability, corrosion resistance, and an ability to withstand high temperatures without oxidizing or losing mechanical properties.

Many superalloys have a polycrystalline structure. Advanced superalloys can also be grown as single crystals to avoid grain boundaries. Turbine blades in advanced gas turbines are made from superalloys cast from single crystals (Langston, 2006).

Crystallization is a solid-liquid separation process from a liquid solution. Metallic crystals are grown or precipitated as ordered super-lattice microstructures from a molten amorphous matrix of component elements, under tightly controlled conditions. To control composition and minimize impurities (such as oxygen), vacuum induction melting has become the norm for close alloy control (Cobalt Development Institute, 2003). Other methods also are used for re-melting superalloy scrap, including vacuum arc re-melting and electro-slag re-melting.

After precipitates are formed, they are “age hardened” in a controlled process of slow cooling, lasting from 12 to 200 hours. Hardening is further induced through sequenced heat treatment or thermal cycling to produce microstructures with appropriate grain sizes. As the last step in the superalloy production process, age-hardened superalloys are hot formed and cold worked into billets (for re-melting and casting), and into bars, rods, plate, and sheet forms.

By chemical composition, surperalloys are grouped into nickel-based (greater than 50 percent nickel by weight), cobalt-based, or iron-based alloys (Cobalt Development Institute, 2003). Nickel-based alloys represent the bulk of commercially available superalloys, with Inconel 625, Inconel 706, and Inconel 718 accounting for the majority of nickel-based production (Carneiro and Tither, 2000).

Spectramet sorting of superalloys will be limited to nickel-based alloys engineered with alloying elements, including Chromium (Cr), Boron (B), Hafnium (Hf), Tungsten (W), Molybdenum (Mo), Tantalum (Ta), Niobium (Nb), Titanium (Ti), Rhenium (Re), Zirconium (Zr), Carbon (C), and Aluminum (Al). Boron and Zirconium tend to be grain boundary–strengthening elements in polycrystalline alloys and C, Cr, Mo, W, Nb, Ta, Ti, and Hf are carbide formers. Carbides tend to precipitate at grain boundaries and reduce the tendency for grain boundary sliding (Tancret et al., 2003).

MARKET DEMAND

The driving force behind the development of superalloys has been the development of jet engines with ever-increasing operating temperatures. Beyond jet engines, the use of superalloys now extends into other fields including other types of turbines, space vehicles, nuclear reactors, power plants, and chemical process equipment.

The primary application, however, remains the “hot section” of aircraft gas turbine engines (Frank, 2005). Gas turbines are axial-flow machines converting the heat of combusted fuel into thrust power (in jet engines) or shaft power (in electric generators) by means of momentum changes of gas flow through passages formed by stationary and rotating airfoils. The thermal efficiency of gas turbines increases with greater temperatures of gas flow exiting the combustor and entering the turbine. Operating temperatures for modern high-performance jet engines can exceed 3,000 degrees Fahrenheit, while nonaviation gas turbines operate at 2,700 degrees Fahrenheit. “Even nickel-based superalloys, when conventionally vacuum cast, will soften and melt between 2,200 and 2,500 degrees Fahrenheit and turbine blades and vanes must be cooled to reach acceptable service levels” (Langston, 2006).

Based on discussion with industry experts, 60–70 percent of U.S. superalloy utilization is in the aerospace industry.

CONSUMPTION

Annual U.S. consumption of nickel-based superalloys is conservatively estimated at 27,613 metric tons (61 million pounds).

- USGS data indicate 12,600 metric tons (28 million pounds) of annual U.S. nickel consumption for the production of nickel-based superalloys (USGS, 2003b).
- Assuming 47 percent by weight average nickel content, U.S. consumption of nickel-based superalloys in 2003 is estimated at 26,808 metric tons (59 million pounds). Over the 2003–2005 period, nickel-based superalloy consumption is estimated to have increased to 27,613 metric tons or 61 million pounds (USGS, 2006).

BUSINESS MODEL: SUPERALLOY SCRAP TOLLING

Spectramet’s approach for the commercial sorting of superalloy scrap will use a similar tolling arrangement as for titanium scrap. Alloy makers will deliver mixed superalloy pieces and receive sorted alloys in exchange for a tolling fee (see Figure 12). Tolling fees for both base case and step-out scenarios are projected at $2 per pound.

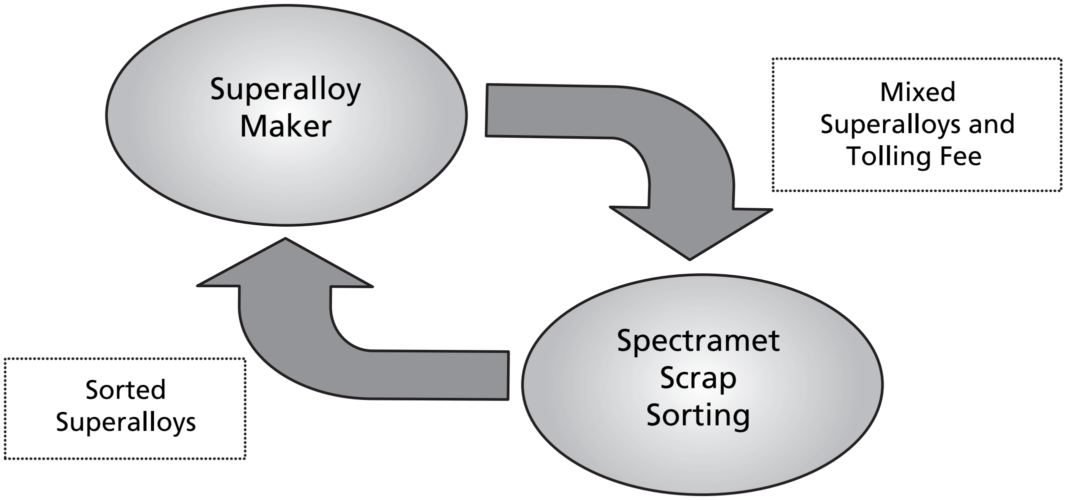
MODELING ASSUMPTIONS FOR SUPERALLOY SORTING

Benefit cash flows expected to result from the ATP-funded alloy sorting technology over the period 2005–2015 are estimated based on processed superalloy scrap volumes and price spreads between primary superalloys and scrap.

Processed Volumes

Reflecting input from industry experts, annual processed volumes are estimated to grow from 100,000 pounds of nickel-based superalloy in 2006 to 483,000 pounds in 2015 (see Table 15, column d).

Figure 12: **Closed-Loop Recycling for Superalloy Sorting**



These estimates are in the context of 61 million pounds of annual superalloy consumption in the United States in 2005. Half of U.S. consumption or 30.5 million pounds was used in the aerospace industry, where up to 80 percent (24.2 million pounds) of superalloy raw materials becomes postindustrial scrap (Spencer, 2005). Of this scrap stream, one can conservatively posit that one-fifth or 4.8 million pounds is currently downgraded to stainless steel and iron foundry feedstock.

Relative to these market trends, it is estimated that at 2015 production levels, Spectramet will upgrade up to 10 percent of the 4.8 million pounds of superalloy scrap that is currently downgraded to lower-value uses.

Price Spreads

Superalloy prices are estimated on the basis of nickel prices and the costs of alloying elements. Further, it is assumed that the Spectramet's business approach will focus on the processing of high-value superalloys. Price spreads in Table 12 reflect the following additional assumptions:

- Nickel prices at $7.00 per pound (USGS, 2005) and alloying element costs at $30.80 per pound (Allegheny Ludlum, 2006; Richard, 2005)
- With 47 percent nickel content, superalloy prices at $19.60 per pound
- Unsorted superalloy scrap, downgraded for stainless steel mills and iron foundries, at $4.20 per pound (Metal World, 2006)

Using the above price levels, the base case estimated economic value of unambiguous sorting—the spread between primary alloy and scrap prices—is $15.40 per pound. Of this amount, Spectramet is expected to retain a tolling fee of $2.00 and downstream industry is expected to realize benefits of $13.40 per

Table 12: Approximate U.S. Superalloy Price Spread (per Pound in 2005 Dollars)

	Base Case	Step-Out Scenario
Price of Nickel Component	7.00	7.00
Price of Alloying Component	30.80	38.10
Estimated Average Superalloy Price	19.60	23.50
Price of Low-Value Superalloy Scrap	4.20	4.20
Price Spreads		
Superalloy to Low-Value Scrap	15.40	19.30
Minus Tolling Fee	–2.00	–2.00
Public Benefits	13.40	17.30

Sources: Industry sources and www.metalprices.com.

pound. For a step-out scenario, the price of nickel and of low-value scrap remain unchanged, reflecting greater price stability. Alloying costs are assumed at $38.10 per pound and average superalloy price levels are estimated at $23.50 per pound. The spread between alloy and scrap prices is $19.30. Of this amount, Spectramet is expected to retain a tolling fee of $2.00 per pound and downstream industry to realize benefits of $17.30 per pound.

Other Assumptions

When superalloy scrap is recycled, some metal content is lost in the re-melt process and melt loses are estimated at 10 percent. Based on a review of remaining technical and commercial uncertainties, the probability of realizing superalloy-sorting volumes, price spreads, and staying within melt loss levels over the 2005–2015 period is estimated to be 60 percent.

Aluminum Separation and Sorting

After ferrous and nonmetallic components are extracted from auto-shredder scrap, the remaining nonferrous concentrate (NFC), composed of aluminum alloys, copper, zinc, and other metals, can be processed using a heavy media separation method. Heavier metals sink to the bottom and lighter aluminum twitch—mixed aluminum alloys along with small pieces of attached Cu, Zn, and stainless steel—float to the surface to be harvested for recycling.

However, heavy media separation is ineffective in capturing the so-called 3/8 fraction or small pieces that fall through a 3/8 inch mesh, which represents about 25 percent of NFC. Currently, the aluminum content of the 3/8 fraction is lost to the aluminum industry and must be replaced with energy-intensive and environmentally polluting primary production.

Intermediate-size and contaminated aluminum twitch that floats to the surface in heavy media separation is sold to secondary smelters for re-melting and recycling into aluminum ingots. Scrap is added to melts in many small steps, with significant melt analysis and alloying with virgin raw materials at each step. This can be an inefficient process as “melt analysis and alloying requirements are time-consuming and costly and are also associated with an increased use of raw materials and environmental emissions from primary refining” (Spencer, 2005).

The loss of the 3/8 fraction and an inefficient secondary smelter recycling process for intermediate-size aluminum scrap represent the *counterfactual scenario*.

The ATP-funded alloy sorter, in combination with the DXRT technology, will make it possible to avoid the loss of the 3/8 fraction and unambiguously sort aluminum twitch into aluminum 380 alloy (Al 380) and other alloys.

* * * * *

Aluminum is a metallic element, the third most abundant in the Earth’s crust. Bauxite ore is the principal raw material and aluminum is made by refining bauxite in primary smelters. Secondary smelters use a mix of primary aluminum and aluminum scrap.

Primary production starts with the extraction of bauxite ore, typically using an open-pit method involving crushing, washing, and drying operations. The next stage is the commercial production of alumina using the Karl Bayer process. Alumina is refined into primary aluminum metal by electrolysis using the Hall-Heroult process (see Figure 13). The elemental metal, in either molten or cast form, is transferred to specialized processing plants for making aluminum plate, sheet, bar, forgings, and cast parts before being sent to fabricators to make finished products (EERE, 2005).

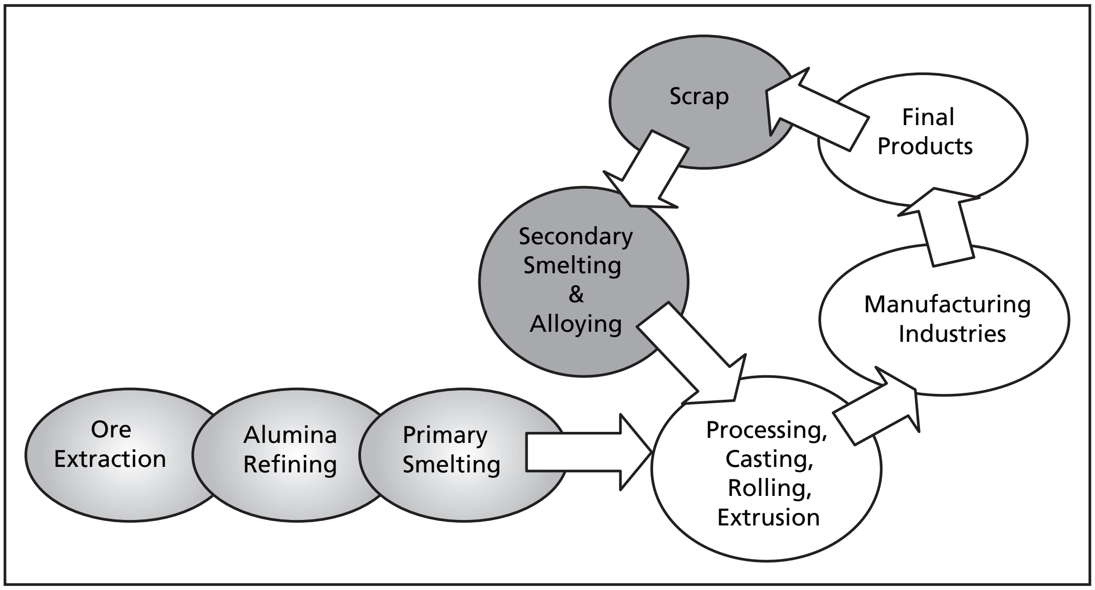
In contrast to multistage, complex, and expensive primary production, secondary production is a relatively simple process of melting, purifying, and alloying of aluminum scrap. See Figure 13 for primary and secondary smelting linkages.

In 1998, the aluminum industry used an estimated 1 quadrillion or 10^{15} BTU of energy, representing over 30 percent of primary aluminum production costs. Electricity provides over three-fourths of the energy requirements, mostly for electrolysis of alumina. Natural gas accounts for the remaining energy use (EIA, 1998). The energy intensity of secondary refineries is 94 percent lower and capital costs are approximately one-tenth those of primary refining facilities (The Aluminum Association, 2005).

DEMAND

Elemental aluminum is a soft, lightweight metal that is highly malleable and ductile. It has limited tensile strength. Once alloyed, its tensile strength can increase nearly

Figure 13: **Aluminum Production**



Source: IAI, 2002.

15-fold. It is easily machined and cast and has excellent corrosion resistance. It is one-third as dense as steel.

There are over 100 grades of aluminum alloys, of which some “work-horse” alloys are extensively used in the automotive industry and other industries. Major alloy families are die-cast alloys (360 and 380), cast alloys, and wrought alloys.

In 2002, net U.S. shipments of wrought products were 7.2 million metric tons and of cast products were 2.4 million metric tons (Plunkert, 2004). Indicative of the importance of workhorse alloys, the online resources *American Metals Market* (http://amm.com/) and *Platts Metals Week* (http://www.platts.com/) periodically publish prices for Al 360, Al 380, and Al 319 cast alloys.

CONSUMPTION

U.S. aluminum consumption in 2004 was 6.6 million metric tons. This was supported by the following inputs:

- 2.5 million metric tons of primary production (USGS, December 2005)
- 1.87 million metric tons of post-industrial “new” scrap—over 20 percent of feedstock used in the aluminum fabrication process becomes “new” scrap (Plunkert, 2005)
- 1.16 million metric tons of post-consumer or “old” scrap (USGS, December 2005)
- 3.2 million metric tons of net imports (USGS, December 2005)

> The growth of secondary production from recycling aluminum scrap represents the greatest change in the structure of the U.S. aluminum industry. Secondary metal, which accounted for only 18 percent of U.S. aluminum metal production in 1960, accounted for 52 percent in 2002. However, further growth in secondary production is limited by the effectively limited supply of scrap in the United States. Intense global competition from countries that recognize the economic (and environmental) benefits of producing secondary metal has contributed to a tight international scrap market (EERE, 2005).

Reflecting growing global competition for aluminum scrap, U.S. secondary production using "old" scrap has declined from 1.37 million metric tons in 2000 (Plunkert, 2005) to 1.16 million metric tons in 2004 (USGS, 2006).

U.S. supplies of "old" aluminum scrap substantially exceed current usage in secondary production. Available U.S. "old" scrap is estimated at over 4 million metric tons in 2000, while only 1.37 million metric tons are used in secondary production (Plunkert, 2005).

Aluminum scrap, sorted by alloy, has greater value to secondary refiners than aluminum twitch (mixed aluminum alloys, otherwise uncontaminated) and higher value still than nonferrous concentrates with up to 75 percent aluminum content.

A 2005 USGS study indicates that while "new" scrap is 100 percent consumed in secondary production, only 42 percent of "old" scrap is recycled, leaving 2.66 million metric tons of valuable aluminum alloys unrecovered each year (Plunkert, 2005). Aluminum parts that cannot be segregated from other metallic scrap components are often landfilled.

The estimated annual value of unrecovered "old" (mostly automotive) aluminum scrap, at 50 cents per pound, represents a loss of $2.93 billion to the U.S. economy (computed as 2.66 million metric tons, extended by 2,205 pounds in each ton, and by $0.50 per pound to yield $2.93 billion in losses). At $1 per pound, these losses would reach $6 billion per year.

BUSINESS MODEL: ALUMINUM SCRAP

Spectramet's commercial approach for recovering aluminum scrap from nonferrous concentrates will consist of two process streams, differentiated by scrap size:

- Small pieces that fall through a 3/8 inch mesh: Aluminum content in the 3/8 fraction cannot now be cost-effectively recovered and represents a material loss to the U.S. aluminum industry. With the Spectramet alloy sorting technology, the 3/8 fraction will be recovered and the full cost of refining a corresponding volume of primary ingot will be avoided.

- Intermediate-size pieces of less than 5 inches: These pieces are sourced from auto-shredders, refuse-derived fuel (RFD), and municipal mass-burn facilities. During the sorting of intermediate-size scrap into aluminum twitch (mixed aluminum alloys that have been mostly separated from other components such as Zn, Cu, and stainless steel), twitch is cleaned of remaining contaminants and sorted to individual alloys.

Aluminum content from the recovered 3/8 fraction, from cleaned twitch, and from sorted aluminum alloys will be sold to smelters at prevailing market prices instead of prearranged tolling fees. Exploratory discussions are currently underway with large corporations in the aluminum industry, which are potential customers for Spectramet sorting services.

MODELING ASSUMPTIONS

Benefit cash flows expected to result from the ATP-funded alloy sorting technology over the 2005–2015 period are estimated on the basis of processed aluminum scrap volumes and price spreads between primary aluminum ingot and aluminum twitch.

Aluminum Processed Volumes

Spectramet processed volumes are estimated to grow from less than 2 million pounds in 2006 to 71 million pounds in 2015 (see Table 15, column g).

These estimates are in the context of almost 7 billion pounds of unrecovered, post-consumer, “old scrap” in the United States. A recent USGS study indicates that while 100 percent of post-industrial “new” scrap is consumed in secondary aluminum production, only 42 percent or 6 billion pounds of post-consumer “old” scrap is recycled (Plunkert, 2005).

Price Spreads

Aluminum content in the 3/8 fraction that now represents a material loss to the U.S. aluminum industry will be recovered through the application of the Spectramet alloy sorting technology. The higher cost of refining a corresponding volume of primary ingot will be avoided.

Out of the total benefit of reclaiming the aluminum content in the 3/8 fraction, Spectramet can be expected to claim the spread between the price of aluminum twitch and the price of nonferrous concentrates—approximately 8 cents per pound. Downstream industry and the U.S. economy can be expected to realize benefits equal to the spread between the price of primary ingot and aluminum twitch—40 cents per pound (see Table 13).

A second benefit stream from the Spectramet technology is related to sorting aluminum twitch into Al 380 alloy and the residual share of mixed twitch. For the Al 380 fraction, sorting is estimated to result in approximately 28 cents of additional value per pound. Of this, Spectramet is expected to retain 10 cents and downstream industry will save 18 cents.

While step-out scenario price levels for primary aluminum are 12 percent higher than the base case, the price spread from twitch to Al 380 remains at 28 cents.

Other Modeling Assumptions

The 3/8 fraction that would have been lost to the U.S. aluminum industry, but would be recovered and recycled with the Spectramet technology, replaces virgin aluminum. Based on industry expert input, up to 25 percent of the 3/8 fraction will still be lost during the melting and recycling process. Hence the level of avoided higher-cost primary production will correspond to 75 percent of the recovered 3/8 fraction.

Primary aluminum is associated with CO_2 greenhouse gas emissions at each stage of production—from mining and processing of bauxite, to the electrolytic refining of alumina, to the casting of aluminum. Reclaiming the 3/8 fraction will result in reduced primary aluminum production and associated emission of 13 tons of CO_2 for every ton of recycled aluminum (Aleris, n.d.).

Based on the 13 to 1 ratio between CO_2 generation and avoided primary production, over the 2005–2015 period, almost 314,000 metric tons of CO_2 emissions will be avoided by reclaiming the 3/8 fraction (see Table 14).

Table 13: Approximate U.S. Aluminum Pricing (2005 Dollars per Pound)

	Base Case	Step-Out Scenario
Primary Aluminum Ingot	1.00	1.12
Average Aluminum Alloy	0.95	1.06
Al 380 (NASAAC)	0.88	0.98
Mixed Aluminum Twitch	0.60	0.70
Nonferrous Concentrate	0.52	0.62
Price Spread for First Benefit Stream: Twitch to Primary Ingot	0.40	0.42
Price Spread for Second Benefit Stream: Twitch to Al 380	0.28	0.28

NASAAC = North American Special Aluminium Alloy.

Sources: London Metal Exchange, industry sources, and www.metalprices.com.

Table 14: Avoided CO_2 Generation from Recovery of 3/8 Fraction

Year	Metric Tons of Avoided CO_2
2005	
2006	1,515
2007	4,544
2008	9,088
2009	18,177
2010	36,354
2011	39,989
2012	43,988
2013	48,387
2014	53,225
2015	58,548
Total	313,814

Avoided emissions, valued at $5 per metric ton of CO_2 (from CCX), are extended by processed sorting volumes (from Table 15) to estimate cash flow benefits displayed in column f of Tables 17 and 18.

Based on a review of remaining technical and commercial uncertainties, the probability of realizing over the 2005–2015 study period estimated alloy-sorting volumes, price spreads, melt losses, and avoided CO_2 emissions is estimated to be 75 percent for both intermediate-size aluminum scrap (Al 380 fraction) and the 3/8 fraction.

Total Processed Volumes

Processed volumes are estimated on the basis of discussions with Spectramet management; industry sources; and market analysis for titanium, superalloy, and aluminum scrap. The results are summarized in Table 15.

Table 15: Base Case Processed Volumes (Thousands of Pounds)

	Processed Volumes of Titanium Scrap				Processed Volumes of Aluminum Scrap		
	New Titanium Scrap	Titanium Fasteners	Total Processed Volume	Super-alloy Volume	Recovered "Lost" 3/8 Fraction	Intermediate-Size Twitch to Al 380	Total Processed Volume
	a	b	c	d	e	f	g
2005	230		230				
2006	460	100	560		457	1,370	1,827
2007	506	200	706		1,370	4,111	5,481
2008	557	300	857	100	2,741	8,222	10,962
2009	612	330	942	200	5,481	16,443	21,924
2010	673	363	1,036	300	10,962	32,886	43,848
2011	741	399	1,140	330	12,058	36,175	48,233
2012	815	439	1,254	363	13,264	39,792	53,056
2013	896	483	1,380	399	14,590	43,771	58,362
2014	986	531	1,518	439	16,049	48,148	64,198
2015	1,085	585	1,669	483	17,654	52,963	70,618

Source: Spectramet and industry sources.

BENEFIT-COST ANALYSIS

While benefit-cost analysis—in general—compares the stream of estimated benefits to the investment, the focus of this study is on comparing public benefits that are attributable to ATP to the ATP investment.

For those benefits that can be meaningfully quantified, cash flow estimates are generated for a conservative base case and for a more optimistic "step-out" scenario that incorporates higher unit sales projections and higher per-unit benefit estimates.

Using alternative base case and step-out scenarios makes it possible to investigate the sensitivity of cash flow analysis results to various key assumptions and to bracket performance metrics associated with these assumptions.

Investments and Attribution

The ATP investment in the Spectramet alloy sorting technology was $2,168,000 in 2005 dollars and the industry cost share was $613,000 in 2005 dollars. The NSF also made prior investments as well as investments after the completion of the ATP-funded project (see Table 16).

Table 16: Relevant Public and Private Investments (Thousands of Dollars)

Approximate Midpoint of Investment	Source of Public Investment	Public Investment		Industry Cost Share	
		Midpoint Year ($)	2005 ($)	Midpoint Year ($)	2005 ($)
1996	NSF	75	94		
1997					
1998	NSF	100	120		
1999					
2000					
2001					
2002	**ATP**	**1,997**	**2,168**	565	613
	NSF	350	380		
2003					
2004	NSF	1,100	1,137	1,000	1,034
Total		3,622	3,899	1,565	1,647
	ATP		**2,168**		
	NSF		1,731		

Sources: ATP and Spectramet.

To properly attribute well-timed and substantial ATP investments and NSF investments, public benefits derived from the Spectramet technology are allocated in the following manner:

- Two modestly funded NSF projects preceded the ATP grant and resulted in important knowledge gains that enabled the ATP investment process and the resultant public benefits. Accordingly, the value added by NSF and ATP is deemed to be greater than a strictly prorated allocation of respective investments. As a result, 30 percent of public benefits is attributed to NSF funding for pre-DXRT technology development and 70 percent is attributed to ATP funding.

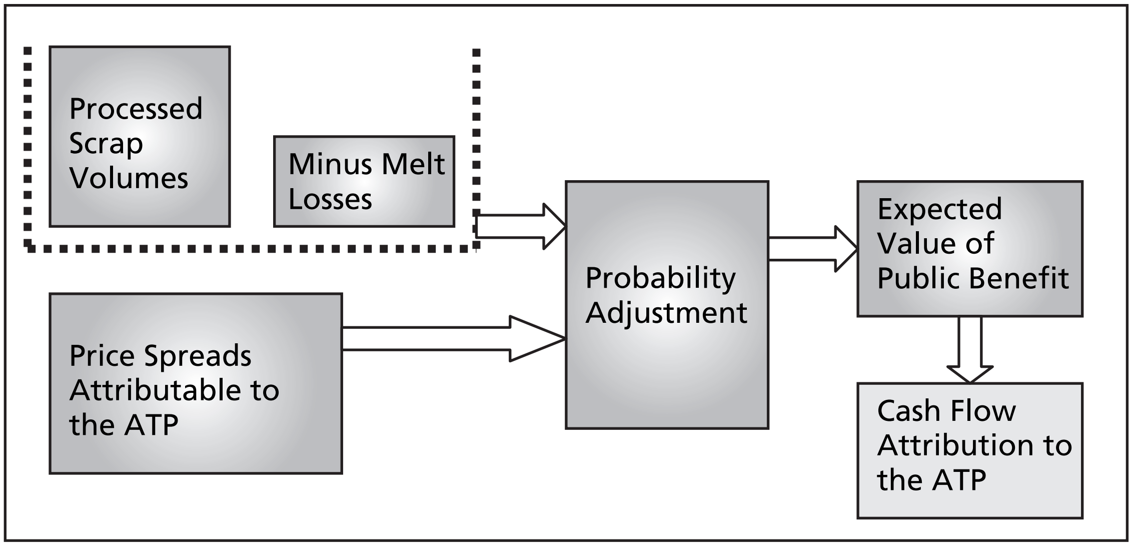
- After the technical completion of the ATP-funded project, the NSF invested an additional $1,137,000 in the development of the DXRT system. It was reported that DXRT development benefited substantially from prior ATP-funded knowledge gains. Therefore, 60 percent of DXRT-related benefits were attributed to NSF funding and 40 percent to ATP funding.

Public Returns on ATP Investment—Base Case

As indicated in Figure 14, public benefits from ATP investment are estimated using the following:

- Scrap volumes, adjusted by melt losses
- Price spreads attributable to ATP, after netting out amounts that Spectramet will claim as tolling fees and revenues

Figure 14: **Estimation of Public Benefits Attributable to ATP Funding**



- Probability estimates for realizing expected processed volumes and price spreads
- Attribution of benefits to the ATP and NSF

Investments by wTe are not included in the analysis.

Base case cash flow estimates for benefits attributable to ATP funding and performance metrics gauging the impact of ATP investment are presented in Table 17. The net present value of the ATP investment is estimated at $19.6 million in 2005 dollars. The internal rate of return is projected at 40 percent and the benefit-to-cost ratio is almost 11 dollars of benefits for every dollar of ATP investment.

To illustrate how benefit estimates are calculated in Table 17, consider base case calculations for fiscal year 2005. During 2005, Spectramet processed 230,000 pounds of titanium scrap (from Table 15). After melt losses of 10 percent or 23,000 pounds, the remaining 207,000 pounds of properly segregated titanium alloys were recycled. Each pound of recycled alloy was associated with $1.75 of public benefits (from Table 11). Of these benefits, 70 percent or $253,575 was attributed to ATP funding.

Table 17: Base Case Cash Flows and Performance Metrics (Millions of 2005 Dollars)

Year	Titanium Alloy Scrap	Titanium Fastener	Ni-Based Superalloy	3/8 Aluminum Fraction	Al 380	CO_2 Avoided	Combined Cash Flow
	a	b	c	d	e	f	g
2002							–2.168
2003							
2004							
2005	0.254	0.000	0.000	0.000	0.000	0.000	0.254
2006	0.456	0.039	0.000	0.041	0.067	0.001	0.604
2007	0.502	0.077	0.000	0.123	0.200	0.009	0.911
2008	0.552	0.116	0.507	0.247	0.400	0.018	1.839
2009	0.608	0.127	1.013	0.493	0.799	0.036	3.077
2010	0.668	0.140	1.520	0.987	1.598	0.073	4.985
2011	0.735	0.154	1.672	1.085	1.758	0.080	5.484
2012	0.809	0.169	1.839	1.194	1.934	0.088	6.032
2013	0.889	0.186	2.023	1.313	2.127	0.097	6.636
2014	0.978	0.205	2.225	1.444	2.340	0.106	7.299
2015	1.076	0.226	2.447	1.589	2.574	0.117	8.029
	Net Present Value (Millions of 2005 Dollars)					19.6	
	Internal Rate of Return (%)					40	
	Benefit-to-Cost Ratio					10.7:1	

Given that 2005 cash flows represented actual, not projected, benefits, the probability adjustment is 1.0.

Public Returns on ATP Investment—Step-Out Scenario

Relative to the base case, the step-out scenario includes the following assumptions:

- Ten percent higher processed volumes for titanium, superalloy, and aluminum scrap
- Public benefits of 50 cents per pound or 29 percent higher than base case—for titanium
- Public benefits of 42 cents per pound (34 percent higher)—for titanium fasteners
- Public benefits of $3.90 per pound (29 percent higher)—for superalloys
- Public benefits of 2 cents per pound (5 percent higher)—for 3/8 fraction aluminum
- Price spreads unchanged for sorting aluminum twitch into Al 380

Step-out scenario estimates of benefit cash flows attributable to ATP funding and performance metrics that gauge the impact of the ATP investment are presented in Table 18. The net present value of the ATP investment is estimated at $25.4 million in 2005 dollars. The internal rate of return is projected at 45 percent and the benefit-to-cost ratio is almost 14 dollars of benefits for every dollar of ATP investment.

Table 18: Step-Out Scenario Cash Flows and Performance Metrics (Millions of 2005 Dollars)

Year	Titanium Alloy Scrap	Titanium Fastener	Ni-Based Superalloy	3/8 Aluminum Fraction	Al 380	CO_2 Avoided	Combined Cash Flow
	a	b	c	d	e	f	g
2002							–2.168
2003							
2004							
2005	0.323	0.000	0.000	0.000	0.000	0.000	0.323
2006	0.646	0.057	0.000	0.047	0.073	0.003	0.826
2007	0.710	0.114	0.000	0.142	0.220	0.009	1.196
2008	0.781	0.172	0.719	0.285	0.440	0.018	2.415
2009	0.859	0.189	1.439	0.570	0.879	0.036	3.972
2010	0.945	0.208	2.158	1.140	1.758	0.073	6.281
2011	1.040	0.228	2.374	1.253	1.934	0.080	6.909
2012	1.144	0.251	2.611	1.379	2.127	0.088	7.600
2013	1.258	0.276	2.872	1.517	2.340	0.097	8.360
2014	1.384	0.304	3.160	1.668	2.574	0.106	9.196
2015	1.522	0.334	3.475	1.835	2.831	0.117	10.116

Net Present Value (Millions of 2005 Dollars)	25.4
Internal Rate of Return (%)	45
Benefit-to-Cost Ratio	13.5:1

Social Rate of Return

The alloy sorting technology project was cost shared by the ATP and wTe and will lead to benefits for suppliers, customer industries, and end users—in essence, taxpayers broadly—as well as benefits for wTe and NRT.

A measure of total benefits relative to total costs provides a broader, more complete picture of project performance than just public returns on ATP's investment. The social rate of return is such a measure and has been used by leading economists as an important indicator of broad social benefits that result from new technologies and innovations.

To estimate social rates of return, public and private benefit cash flows are combined and compared to the sum of all public and private investments, using an internal rate of return calculation. Next, social rates of return are compared to approximate private rates of return that ATP's industry partners would expect to realize over the long term. The excess of the social rate of return over the private rate of return is the spillover gap. 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 could lead to private sector underinvestment and associated loss of benefits to downstream firms, end-user customers, the economy, and society at large.

The estimated social rates of return, proxy private rates of return, and the spillover gap for the Spectramet alloy sorting process technology are provided in Table 19.

For the Spectramet process technology, the spillover gap ranges from 23 to 30 percent and points to significant benefits to the general public beyond benefits to the industry partners.

Given that the alloy sorting project would not have been funded at all without an ATP cost share, the above results suggest a fulfillment of the ATP mission to fund high-risk technologies with significant economic benefits to the nation.

Table 19: Social Rate of Return and Spillover Gap

Social Rate of Return	Proxy Private Rates of Return	Spillover Gap: Social Return Minus Private Returns
36%	6% to 13%	23% to 30%

OTHER BENEFITS

The ATP-funded alloy sorting technology reduces the volume of metal scrap that would otherwise be downgraded to lower-value uses or wasted in landfills and leads to cash flow benefits estimated on the basis of market prices, as indicated above.

In addition to cash flow benefits, the avoidance of downgraded or wasted metal scrap leads to important benefits that are not fully reflected at this time in market prices. These additional benefits include the following:

- Reduced raw material import dependence
- Increased availability of useful metal scrap
- Reduced energy usage
- Health benefits from reduced environmental emissions

Reduced Raw Material Import Dependence

Titanium sponge imports comprise over 55 percent of U.S. titanium consumption. Half of these imports are from Kazakhstan, over 40 percent from Japan, and 10 percent from Russia. In addition, 63 percent of mineral concentrate used in U.S. titanium sponge production is imported (USGS, 2006). Over the period 2005–2015, titanium sorting using the ATP-funded technology can be expected to reduce imported titanium sponge by 9 million pounds.

For nickel-based superalloys, U.S. import dependence is 54 percent for nickel, with the bulk of imports from Russia, Australia, and Canada (USGS, 2006). Over the period 2005–2015, superalloy scrap sorting using the ATP-funded technology can be expected to reduce imported nickel by 900,000 pounds.

Increased Availability of Metal Scrap

According to a recent USGS study (Plunkert, 2005), only 42 percent of U.S. post-consumer aluminum scrap is recycled and the remainder is lost to the U.S. aluminum industry. Over the 2005–2015 period, aluminum twitch sorting using the ATP-funded technology can be expected to divert almost 380 million pounds of aluminum scrap that would otherwise have been downgraded to lower-value uses or landfilled.

Reduced Energy Usage

Increased titanium, superalloy, and aluminum scrap utilization is associated with reduced energy consumption for mining and primary processing.

Energy savings from increased scrap utilization have the greatest impact in the aluminum industry. In 2002, the aluminum industry consumed almost one quadrillion or 10^{15} BTU of energy. Electricity was 85 percent of energy consumption, primarily used in the electrolysis of alumina (Choate and Green, 2002). The energy intensity of secondary refineries is 94 percent lower than for the production of primary aluminum, and capital costs are approximately one-tenth those of primary refining facilities.

These energy savings are reflected to some extent in the respective price levels of primary aluminum and aluminum scrap for secondary production. However, market prices do not adequately reflect all externalities associated with primary production, including scarcity of certain forms of energy and harmful environmental emissions.

Reduced Environmental Emissions

Cash flow benefit estimates for avoided CO_2 emissions—as they relate to primary aluminum refining—are included in quantitative benefit analysis (see Tables 17 and 18, column f). However, cash flow estimates understate the full value of avoided emissions because externalities, including climate change effects and increased levels of particulates. Furthermore, associated health risks are not adequately reflected in current CCX market prices.

Increased scrap utilization can also lead to the avoidance of other harmful emissions. While more complicated to track, the mining and refining of titanium concentrates, nickel, and other alloying elements are associated with a variety of harmful air, water, and soil emissions and discharges. These emissions can be effectively avoided when increased scrap utilization replaces primary refining.

CASE STUDY SUMMARY

Performance metrics point to the strong performance of ATP's investment in the Spectramet alloy sorting technology, including high (40–45 percent) public rates of return, a high (36 percent) social rate of return, and a substantial (23–30 percent) spillover gap.

In addition to performance metrics, the case study also points to important qualitative benefits associated with reduced energy consumption, reduced environmental pollution, reduced industrial feedstock import dependence, and increased availability of metal scrap for U.S. metal industries.

5. Mini-studies of ATP-Funded Green Process Technologies

ATP has funded the development of many high-risk green process technologies. This section highlights the technical challenges and accomplishments of three additional ATP-funded green technologies that have made significant progress toward commercialization and are generating or are expected to generate substantial near-term public benefits.

Mini-studies discuss three ATP-funded green technologies: (1) sorting of high-value engineered polymers to facilitate industrial-scale recycling, (2) cost-effective purification of coal-bed methane into pipeline-quality natural gas, and (3) water purification and paint removal using high-intensity ultraviolet lamp systems. Green benefits from these innovative technologies are identified and their progress toward full-scale commercialization is noted. Mini-studies do not quantify the benefits; they tell the story qualitatively.

ENABLING TECHNOLOGY FOR LARGE-SCALE RECOVERY OF HIGH-VALUE PLASTICS FROM DURABLE GOODS: MBA POLYMERS

Engineered thermoplastics are high-value components that are extensively used in personal computers, appliances, automobiles, and other durable goods. However, due to the complexity of these thermoplastics, a variety of additives and coatings, and intermixture with metal components, the recycling and recovery rates for engineered thermoplastics are very low, estimated to range from less than 1 percent to 4 percent (Hook, 2006). Low recycling rates result in the loss of valuable petrochemical content and lead to large waste streams that choke landfills and create toxic fumes when incinerated.

MBA Polymers of Richmond, California was founded in 1994 to develop and commercialize new technologies for the efficient sorting of engineered thermoplastics and thereby facilitate their recovery and reuse in industrial processes.

In 1997 the ATP provided an award of $687,000 and MBA Polymers provided a $645,000 cost share to develop the recovery technology. ATP funding was awarded based on the technical complexity and challenges of effectively sorting complex engineered plastics on an industrial scale. The award also took into account MBA Polymer's status as a recent start-up company without sufficient financial resources to undertake multiyear, high-risk technical development.

The project was successfully completed in 1999 and resulted in the development of proprietary mechanical recycling technologies that can be customized to unambiguously identify and segregate a variety of high-value engineered plastics—by types and grades—without the use of chemicals.

The sorting process starts with a feedstock of plastics-rich shredded waste material from durable goods. After a size-reduction step, plastic pieces are "liberated" from metallic contaminants and segregated by type of plastics and grade, using the ATP-funded proprietary process technology. Segregated plastics are reduced to small pellets, cleaned, and sold to plastics recyclers for extrusion molding into new products and components.

Subsequent to project completion, MBA Polymers raised over $30 million in equity investments to fund the construction and operation of two industrial-scale plastic-sorting plants (in China and in Austria), each with design capacity of 40,000 metric tons per year, and a smaller plant in Richmond, California, with design capacity of up to 10,000 metric tons per year. With recent substantial price increases of petrochemical feedstocks—used in the manufacturing of primary plastics—it is expected that U.S. demand for recycled engineering plastics will increase sufficiently and provide commercial incentives for expanding MBA Polymers' scale of operations in the United States.

Green benefits from this ATP-funded innovative process technology include the following:

- Increased recycling and reduced landfilling of engineered thermoplastics waste
- Avoidance of corresponding amounts of petrochemical feedstock that would be used in the manufacture of virgin plastics
- Reduced greenhouse gases at the rate of 2–3 tons of CO_2 for every ton of recycled plastic replacing virgin plastics production
- Significant reductions in industrial process water use

MOLECULAR GATES TECHNOLOGY FOR THE COST-EFFECTIVE PURIFICATION OF NATURAL GAS: BASF CATALYSTS LLC (FORMERLY ENGELHARD CORPORATION)

Natural gas from coal mining and degassing operations (coal-bed methane), as well as over 10 percent of U.S. natural gas reserves, require nitrogen removal and upgrading to pipeline-quality gas. Historically, due to scale requirements of existing separation technologies, large-volume gas flows were required for nitrogen rejection. For smaller gas flows, nitrogen, CO_2, and other contaminants could not be efficiently removed and a substantial portion of domestic energy resources could not be developed and utilized.

Engelhard Corporation—now BASF Catalysts LLC of Iselin, New Jersey—developed the Molecular Gates (molecular sieves) separation technology using their proprietary crystalline microporous materials to leapfrog traditional separation technologies in the cost-effective treatment of small-volume gas flows. The full commercial utilization of Molecular Gates was, however, precluded by the lack of fundamental knowledge about the operation of specific mechanisms that could be used to precisely control pore sizes of molecular sieves, particularly for achieving the separation of similar sized molecules.

Natural gas and its major contaminants (nitrogen and CO_2) have nearly identical molecular diameters. To develop a cost-effective and commercially viable version of the Molecular Gates separation technology for the purification of contaminated natural gas, Engelhard Corporation submitted a proposal to the ATP to develop a new nitrogen-rejection process with titanium silicate lattice molecular sieves that would contract to yield controllable, uniform pore sizes. The process would also demonstrate simultaneous removal of nitrogen, CO_2, and other contaminants.

In 1999 the ATP agreed to support the proposed project with a $1.789 million award, and Engelhard Corporation provided a $2.301 million cost share. The three-year project was completed in early 2003, with technical assistance from University of Massachusetts at Amherst and Cleveland State University. In 2006, Engelhard Corporation was acquired by BASF and is now part of the BASF Group.

The ATP-funded project developed fundamental understanding of control mechanisms for the pore contraction behavior of titanium silicate lattices and their gas adsorption characteristics at different temperatures and pressures. This resulted in the resolution of technical issues and accelerated commercial introduction. In the absence of ATP support, much slower technical progress may have resulted in slower commercial implementation, leading to a loss of corporate support and, possibly, to project termination.

A prime commercial application of this leapfrog separation technology has been the purification and upgrading of coal-mine and coal-bed methane to pipeline-quality natural gas. In addition, the technology is used to treat contaminated natural gas that would otherwise remain unrecovered in shut-in wells. Finally, the ATP-funded separation technology is also expected to be used for the treatment and upgrading of landfill methane.

To date, BASF reports the sale of 18 Molecular Gates gas separation systems for nitrogen rejection, with about half of the units installed in coal mines. Green benefits of a societal and economic nature are being realized in several areas:

- Commercially viable gas separation in coal mines and natural gas wells. Pre-ATP separation technologies reached acceptable economies of scale by treating flows greater than 10 million standard cubic feet (MM SCF) of contaminated gas per day, which limited production to larger wells. In contrast, the ATP-funded technology can operate on an economic basis when treating much smaller flows of contaminated gases, as little as 0.5 MM SCF per day.

- The technology reclaims an estimated 40 MM SCF of U.S. pipeline-quality natural gas per day that otherwise could not be reclaimed on an economic basis and thereby facilitates the recovery and use of otherwise undeveloped domestic energy resources.

- The technology removes hazardous gases from coalmine formations, making explosions and fires less likely.

HIGH-INTENSITY ULTRAVIOLET LAMP SYSTEMS FOR WATER TREATMENT AND PAINT STRIPPING: PHOENIX SCIENCE & TECHNOLOGY, INC.

New methods are needed for disinfecting drinking water to address health and safety concerns with current technologies, which generate carcinogenic and/or toxic byproducts, and to reduce water disinfection costs to the public.

Safer and lower-cost methods are needed for stripping paint to reduce the generation of toxic debris, and to provide an effective tool for lead abatement, in pursuit of the national goal of eliminating childhood lead poisoning.

Ultraviolet (UV) lamp systems for disinfection and lead abatement work on the same principle as fluorescent lamps. The lamp bulb is filled with low-pressure gases, including mercury vapor. When electric current is applied to the cathode, electrons are emitted and ionize the mercury vapor, causing it to emit light in the UV region of the spectrum. The shortwave UV light ionizes oxygen and produces ozone, which can kill many biological pathogens including bacteria, viruses, and protozoans.

Both water disinfection and lead abatement markets are increasing the use of UV technologies, despite concerns about mercury gases in commercial UV systems that are associated with a product end-of-life disposal problem. This disposal problem appears to stem from federal and state regulatory initiatives, which target mercury disposal problems by providing guidelines for landfilling and imposing noncompliance penalties, especially for systems intended for commercial use.

Phoenix Science & Technology, Inc. of Chelmsford, Massachusetts submitted a proposal to the ATP for developing a new UV technology without using mercury gas. The proposed surface discharge high-intensity ultraviolet lamp systems would achieve the following:

- Eliminate the mercury disposal problem
- Increase operating efficiency levels and lower the system's lifecycle costs
- Improve the quality of treated drinking water supplies
- Enable a new, photolytic paint-removal process

In 2001, the ATP agreed to support this innovative technology project with a $2 million award and Phoenix Science & Technology, Inc. agreed to provide a cost share contribution of $393,000. The project was successfully completed at the end of 2004, demonstrating the technical feasibility of high-intensity surface discharge UV lamps.

To improve on the efficiency of traditional mercury UV lamps, a pulsed electric discharge from the surface of the tube generates light-emitting plasma, increasing efficiency levels, relative to medium-pressure mercury lamps, from 12 to 17 percent respectively. The system is designed for retrofit into existing water treatment systems and produces higher water treatment rates than medium- and low-pressure mercury lamp systems.

Early commercialization efforts are underway for the following applications:

- Ultraviolet water treatment: Work to commercialize this technique is currently supported by the Environmental Protection Agency (EPA) and the National Science Foundation.
- Lead paint stripping: Work to commercialize this technique is currently supported by the Department of Housing and Urban Development (HUD) and EPA.

While impressive technical progress has been achieved, full commercialization is still some steps away. Ongoing development is focused on achieving thousands of hours of lamp life so as to demonstrate the commercial viability of high-intensity UV systems.

The green benefits of high-intensity UV lamps, after commercialization is achieved for water treatment and lead paint stripping applications, will include the following:

- Reduced rates of childhood lead poisoning
- Reduced generation of chemical and blast media byproducts from paint stripping
- Improved quality of treated water supplies
- Avoidance of hazardous mercury disposal problems as well as avoidance of chemicals in the water treatment process
- Expected cost savings from increased efficiency levels of high-intensity UV systems

Beyond the two detailed case studies, mini-case studies for three additional ATP-funded green process technologies point to strong technical and commercial progress toward simultaneously achieving environmental and economic objectives. Industrial innovators, downstream industrial firms, customers, and society at large will be better off from well-targeted ATP investments in these promising green technologies.

6. Green Technologies that Promote Industrial Competitiveness

To place detailed case study results and mini-study results into a wider, more meaningful context, this section discusses the project space for green process technologies, reviews specific green process technologies funded by ATP, and points to an accelerating pace of industry green investments.

PROJECT SPACE FOR GREEN PROCESS TECHNOLOGIES

At the outset of the environmental movement, pollution prevention and remediation were advocated often without incorporating efficiency criteria. Industry was placed under increasingly stringent regulatory mandates to prevent harmful emissions and to remediate past pollution. An adversarial relationship developed between industry and environmentalists, and industry came to view and often resist pollution prevention measures as unwelcome burdens that would substantially undercut U.S. industrial competitiveness.

During the early 1980s, the related concept of sustainable development emerged from the findings of the United Nations' World Commission on Environment and Development. Proponents of sustainability argued that boosting the economy, protecting natural resources, and ensuring social justice were not conflicting but rather interwoven and complementary goals.

> Yet even as sustainable development was becoming conventional wisdom, something went wrong. Because the concept stresses the interconnection of everything, it has become a magnet for special interest groups. Human rights watchdogs, large chemical companies, small island nations, green architects, and nuclear power plant operators have attached themselves to this fashionable notion only to (adopt) it for their own ends. Instead of bringing together nature, the economy, and social justice, sustainable

> development has spawned overspecialized and (often) meaningless checklists and targets. Particularly harmful has been a series of consensus-driven UN summits that have yielded broad and incoherent documents and policies. Sustainable development, the compass that was designed to show the way to just and viable economics, now swings in all directions (Victor, 2006).

In contrast to the early adversarial model and to diffuse and often utopian notions of sustainability, an informal “green movement” also evolved with a focus on practical, cost-effective solutions to bring about the gradual reduction of harmful emissions and to reduce the use of petroleum-based feedstock. Often, new, high-risk, process technologies were at the centerpiece of these green solutions.

Over the years, ATP’s investment in green process technologies was aligned with this evolving green movement and its quest for the simultaneous achievement of emission reductions, sustainable use of natural resources, and industrial competitiveness through the application of new and innovative process technologies. In particular, ATP investments appear to have followed the tenets of Green Chemistry, including new process designs that stress the use of renewable industrial feedstock, safer chemicals with fewer toxic components, energy efficiency, and the reduction of industrial wastes, the promotion of recycling, and simultaneous cost savings.

Green Technologies and Renewable Energy

The ATP has also made substantial investments in renewable energy technologies for energy generation, transportation, and commercial and residential uses. While benefits from renewable energy investments may appear as overlapping with the benefits from green process technologies, these two investment categories were deemed to be sufficiently distinct to limit the current cluster study to ATP investments in industrial green process technologies.

ATP-FUNDED GREEN PROCESS TECHNOLOGIES

Since its inception, ATP has been at the forefront of providing financial support for the development of green process technologies to provide cost-effective solutions for the reduction of harmful industrial emissions and the replacement of petroleum-based industrial feedstock.

The implicit proposition underlying ATP investments in green process technologies is that innovative new technologies can be used to reduce harmful emissions and waste and, at the same time, reduce costs and increase U.S. industrial competitiveness. This proposition was borne out in the two detailed case studies of ATP investments: Renewable-Resource-Based Plastics Manufacturing (NatureWorks) and High-Speed Identification and Sorting of Nonferrous Metal Scrap (wTe Corp.).

The two detailed case studies lend support to the proposition that green process technologies, relying on market price mechanisms rather than government subsidies, can reduce harmful emissions and at the same time contribute to increased industrial competitiveness.

Mini-studies of three additional ATP investments lend further support to the above proposition. ATP-funded Molecular Gate technology for natural gas purification (Engelhard Corp.) and ATP-funded plastics sorting technology (MBA Polymers) have reached full commercialization and profitable operations in competitive markets for natural gas recovery and engineered plastics recycling. The ATP investment in high-intensity ultraviolet lamp systems, while at a precommercial stage, also promises to help reduce levels of harmful mercury wastes in the context of unsubsidized commercial operations.

Beyond the two detailed case studies and three mini-studies, the ATP has funded many other high-risk green process technologies. Some prominent examples include the following:

- High-performance biodegradable PHA (polyhydroxyalkanoates) polymers: PHA polymers, made from renewable feedstocks, provide yet another example of plant-based chemicals poised to replace petroleum-based polymers PET and polypropylene. The successful ATP-funded innovation to reduce PHA production costs led to the formation of a joint venture between Metabolix (ATP awardee) and Archer Daniels Midland Corporation (ADM) for the construction of a new PHA plant in Clinton, Iowa to produce 50,000 tons of bio-based polymer per year. Among other PHA based products, the Clinton plant will manufacture biodegradable anti-weed sheets for farmers to lay over their tilled fields, with sheets turning into water and carbon when the growing season ends. An equivalent amount of petroleum-based polymer will be replaced, reducing the need for expensive petroleum imports. The landfilling of polymer wastes at the end of product life will also be avoided.

- Aqueous Phase Reforming (APR): With ATP funding, Virent Energy Systems developed the new APR catalyst and reactor process technology to produce hydrogen from a wide range of oxygenated compounds, such as ethylene glycol, biomass-derived glycerol, sugars, and sugar alcohols. In particular, Virent Energy Systems used ATP funding to develop a process for the production of hydrogen/alkenes mixtures to fuel internal combustion engines. It is expected that at Virent's 70 percent targeted efficiency levels for the APR process, hydrogen will be produced at approximately $4 per kilogram. In contrast, hydrogen generation from the electrolysis of water currently costs $6.5 per kilogram. When fully commercialized, the APR process technology will displace equivalent amounts of petroleum-based transportation fuels.

- Innovative film coating technologies: A joint venture of 3M and Lockheed Martin received ATP funding to develop polymer films to replace aircraft exterior paints. The 3M Aerospace and Aircraft Maintenance Division Website lists three paint replacement tape products whose utilization will lead to a combination of green benefits, including reduced volatile organic compounds and ozone depleting chemicals from conventional paint processes, reduced corrosion and associated maintenance costs, and reduced jet fuel consumption from surface treatments reducing in-flight drag.

- "Smart Windows": A joint venture of Sage and 3M Corporation received ATP funding to develop fabrication methods using electrochromic materials. Smart windows are electronically controlled to automatically lighten or darken depending on the amount of sunlight, time of day, and the seasons. This innovative technology is currently moving toward commercialization with the construction of a production facility. Green benefits will include reduced levels of winter heating and summer cooling loads, leading to energy savings and the reduction of harmful emissions resulting from avoided natural gas and electricity use.

- Low-pressure plasma for fluorescent lamps: With ATP funding, General Electric Lamp Division set out to eliminate toxic mercury—used as conductive plasma in fluorescent lamps—with environmentally safe, low-pressure plasma sources. While the research project was unable to demonstrate mercury-free fluorescent technology, the research led to the development of advanced coatings that can be used to limit mercury absorption and thereby reduce (but not eliminate) toxic mercury wastes from end-of-life product disposal.

- Innovative industrial wastewater treatment for commercial-scale aquaculture: With ATP funding, Kent Sea Farms developed a set of technology solutions for solids removal, suspended ammonia removal, managed wetlands, and passive aeration ponds for the cost-effective recycling of treated industrial process water. According to the U.S. Department of Agriculture, the United States is heavily dependent on imported seafood. Over 40 percent of U.S. fish and shellfish consumption is supplied by other nations and the U.S. seafood trade deficit is the largest for any agricultural commodity, and the second largest after petroleum, for any natural product (ARS, 2006). Water is a valuable and often scarce resource for aquaculture. More cost-effective wastewater treatment is expected to facilitate continued growth in the U.S. aquaculture industry and help reduce energy costs and waste disposal costs.

ATP has funded a broad spectrum of green process technology projects. Some of these ATP investments—including NatureWorks, wTe, MBA Polymers, and Engelhard—have led to tangible benefits. Other ATP-funded green process technologies have yet to reach commercialization but show promise of doing so and of generating future benefits.

INDUSTRY AND INVESTOR VALIDATION OF ATP GREEN INVESTMENTS

ATP's early leadership in supporting the development of high-risk, innovative green process technologies is increasingly validated by recent trends in the agricultural and chemical industries, which are focusing significant new product development efforts on plant-based chemicals. In addition, there are increasing levels of green investments by venture capital firms and institutional investors.

> Two-thirds of global chemical production depends on oil or gas as its raw ingredient. If crops, farm waste, or wood pulp were to replace fossil fuels in only 10 percent of the chemical supply, biochemicals would be a $150 billion industry, up from $30 billion today. Carbon is carbon. It doesn't matter if it was sequestered in an oilfield 100 million years ago or six months ago in an Iowa cornfield (Dolan, 2006).

Reflecting the growing realization that carbon is carbon, large corporations in the agricultural and chemical industries, which are able to bring about large-scale changes in feedstock utilization from petroleum-based to plant-based chemicals, are increasingly placing investment "bets" on the commercialization of cost-effective green process technologies. Examples include the following:

- Cargill has made significant investments to commercialize a cost-effective green process technology for PLA production, developed with ATP funding.
- Archer Daniel Midland and Metabolix have made investments to commercialize a green process technology for PHA production, developed with ATP funding.
- Chevron Corporation has launched a new biofuels business for ethanol and biodiesel production (EERE, 2006).
- DuPont, in joint venture with U.K. sugar company Tate & Lyle, has invested in a $100 million plant in Loudon, Tennessee to "use engineered bugs to turn corn glucose into chemicals, for making clothes and cosmetics" (Dolan, 2006).

In addition to major industry players betting on new green process technologies, venture capital and institutional investors are also exhibiting growing enthusiasm for a broad range of green technology investments. For example, $513 million in venture capital green investments were recorded in the first quarter of 2006, providing financial backing for 67 start-up companies offering green technology solutions (Calvey, 2006).

Private sector investments in green process technologies are expected to continue at increasing rates, as remaining externalities (associated with petroleum and other nonrenewable resources and with harmful emissions from their use) are increasingly internalized in market price structures.

As an example of the expected gradual internalization of remaining externalities, many U.S. electric utility executives are convinced that the United States is likely to join Europe in placing mandatory caps on carbon dioxide emissions—leading to more active trading of carbon futures at substantially higher price levels than currently experienced in the United States (Foss, 2006).

> The results of the two detailed case studies and three mini-studies, as well as the review of a sample of additional ATP investments in green process technologies, point to an emerging pattern of success in the reduction of harmful emissions, the increased utilization of renewable resources, and increased U.S. industrial competitiveness.

7. Conclusions

ATP provided early and sustained leadership for the development of green process technologies, focusing on practical solutions to be achieved with new, high-risk technologies. Advances in green process technologies have broad implications for U.S. industrial growth and competitiveness in agriculture, metals, plastics, energy, and water treatment.

From its early days, ATP has funded high-risk, innovative green process technologies. Investments tended to follow the tenets of Green Chemistry and aimed at providing practical, technology-based solutions to cut harmful emissions and at the same time improve U.S. industrial competitiveness. ATP investments also focused on replacing the use of depleting natural resources, such as petroleum-based feedstock, with renewable industrial feedstock, thereby reducing waste, promoting recycling, and simultaneously reducing industrial process costs.

To investigate ATP's effectiveness in meeting these objectives, five ATP-funded green process technologies were selected for study. Selection criteria included the successful technical completion of specific green technology investments and the degree of progress toward commercialization. Two of these projects were singled out for having achieved initial commercialization and having highly probable, near-term prospects for generating substantial additional benefits:

- Renewable-Resource-Based Plastics Manufacturing (NatureWorks)
- High-Speed Identification and Sorting of Nonferrous Metal Scrap (wTe Corp.)

Detailed case studies were conducted for these two projects in addition to mini-studies for three ATP-funded green projects.

Analysis over the 2003–2017 period points to substantial public returns on ATP investments as well as other important benefits, including the avoided use of 13.8 million barrels of imported petroleum, reduced greenhouse gas emissions, and increased domestic employment.

Benefits to industry users of ATP-funded green technologies were formulated as cash flows, which were then used to estimate the following performance metrics:

- For the Renewable-Resource-Based Plastics Manufacturing project, base case results indicate benefits of $11 for every dollar of ATP investment and $21 million in net present value. For a step-out scenario, reflecting substantially higher future petroleum price projections, benefits are projected at over $24 for every dollar of ATP investment and the present value at $50 million.

- For the High-Speed Identification and Sorting of Nonferrous Metal Scrap project, base case benefits of $11 are projected for every dollar of ATP investment and $20 million in net present value. For a step-out scenario, benefits of $14 are projected for every dollar of ATP investment and net present value at $25 million.

A 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 returns), indicating that the value of these projects to society at large is significantly greater than their value to the companies receiving public cost-share funding (see Table 20).

Given that these projects would not have been undertaken at all or could not have been effectively sustained without public funding, ATP funding enabled both the public and private benefit components of reported social rates of return. Estimated levels of the spillover gap tend to validate 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 green process technologies.

In addition to quantitative performance metrics for public and social returns, analysis also points to additional broad-based benefits including reduced carbon dioxide emissions and adverse climate impacts, reduced landfilling of end-of-life product wastes, and reduced import dependence for industrial raw materials.

This study targeted only two ATP-funded projects for quantitative analysis. It is likely that other ATP-funded green process technologies, including the three projects for

Table 20: Social Rate of Return for Two Case Study Projects

Project	Social Rate of Return	Spillover Gap
Renewable-Resource-Based Plastics Manufacturing	17%	4% to 11%
High-Speed Metal Scrap Sorting	36%	23% to 30%

which mini-studies have been completed and other projects, will also generate public and private benefits. Over time, these additional benefits can be expected to result in further upward adjustments of performance metrics presented in this study.

Green Technologies Accomplish Multiple Objectives

Case studies and mini-studies point to an emerging pattern of success, indicating that ATP-funded innovative green technologies can simultaneously provide economic benefits to innovators and society and also meet "green" objectives, even at market prices that do not fully internalize the costs of pollution and growing U.S. reliance on imported petroleum. If these externalities were successfully internalized in market price mechanisms, even higher levels of benefits could be traced to ATP-funded green technology solutions.

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