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The Office of Industrial Technologies: Enhancing the Competitiveness, Efficiency, and Environmental Quality of American Industry through Technology Partnerships

In the year 2010, the Department of Energy (DOE) uses its leadership in energy, science and technology to help industry sustain long-term economic growth that has created high-wage jobs and a cleaner environment.

— *Vision Statement from Department of Energy Strategic Plan, April 1994*

Located within DOE's Office of Energy Efficiency and Renewable Energy, the Office of Industrial Technologies (OIT) supports research, development and demonstration (RD&D) efforts that can improve our nation's energy future. OIT concentrates its efforts on improving energy efficiency and productivity in the industrial sector of the economy. Virtually every industrial process uses more energy than necessary.

Inefficient energy use is also frequently associated with the generation of industrial waste, pollution and their related costs. Reducing the amount of waste materials generated also reduces the amount of energy used in the processes that created the waste. Hence, supporting RD&D activities that can prevent pollution and reduce waste is another important objective of the OIT program.

OIT's RD&D projects not only improve industrial energy efficiency and reduce waste; simultaneously, they frequently reduce the capital, operating and maintenance costs of industrial technologies, improve productivity and product quality, and consequently enhance the competitiveness of U.S. industries. This in turn contributes to increased U.S. exports, greater national value-added and wealth, and higher wages for American workers.

The OIT program, in other words, is strategically positioned to assist DOE in achieving its vision of the future. This report describes the context, content, and potential benefits of the OIT RD&D program.

THE INTRODUCTION

- Describes the characteristics of industrial energy use and identifies the most energy- and waste-intensive industries in the U.S. economy, that is, the materials and process industries;
- Discusses and explains the unique, essential and often overlooked role that these industries play in the economy of linking the natural resource industries to the value-adding assembly and fabrication industries.

CHAPTER ONE

- Provides a brief history of the Office of Industrial Technologies, and describes its location and role in the Department of Energy and its mission, strategy, organization and principal methods of operation;
- Explains the Industries of the Future initiative, an industry-led and OIT-facilitated method for identifying the technology needs of industry and laying the groundwork for public-private sector partnerships;
- Provides examples of important ongoing OIT-private sector partnerships that illustrate the typical structure, operation, and potential benefits of these activities.

- Identifies some of the most important OIT commercial success stories and quantifies the energy, environmental, jobs, and other real-world benefits of these technologies.

CHAPTER TWO

- Analyzes the patterns and trends of energy use in the materials and process industries and the rest of the industrial sector;
- Describes and quantifies the economic significance of the materials and process industries;
- Explains the close relationships that exist between industrial energy use and waste and pollution generation.

CHAPTER THREE

- Describes and explains the major OIT programs targeting the industry-specific technologies of such energy-intensive industries as chemicals, steel, aluminum, paper and others;
- Quantifies the potential energy, productivity and environmental benefits of these programs.

CHAPTER FOUR

- Describes the major OIT programs targeting cross-cutting industrial technologies such as electric motors, cogeneration, combustion, heat exchangers, industrial applications of solar energy, and various waste reduction and recycling technologies;
- Quantifies the potential energy, productivity and environmental benefits of these programs.

CHARACTERISTICS OF ENERGY USE IN INDUSTRY

Energy is an essential ingredient in the production of goods and is used by industry for a wide variety of purposes. Energy resources are used to generate heat and steam for industrial processing, to power machines, to produce chemicals and plastics, to light and heat factories, to provide materials for roads, and to fuel vehicles. In 1993, industry consumed about 30.8 quadrillion Btu (quads) of primary energy, or about 37% of all the energy used in the United States that year. Net energy use, the amount of energy actually consumed by industry which excludes electric utility generating and transmission losses, was 23.6 quads.

Though primary energy use has been rising in industry almost steadily since 1983 when it was 25.8 quads, total industrial energy use in 1993 was below the record peak of 32.6 quads consumed in 1979. Going back two decades to the first oil embargo in 1973, industrial sector energy usage has grown more slowly than that of the residential/commercial and transportation sectors. Since 1983, however, growth in industrial energy usage has been at about the same rate as that of the other two principal sectors (Figure I-1).

INDUSTRIAL SECTOR ENERGY USE EXCEEDS OTHER SECTORS

Moreover, industrial sector primary energy use in 1993 of 30.8 quads exceeded that of the residential/commercial sector (30.3 quads) and transportation (22.8 quads). In comparison to the other sectors, energy use in industry is also more widely diversified among a greater number of fuel and power sources. Most of the energy needs of the residential/commercial sector are met by natural gas and electricity while more than 90% of transportation energy needs are supplied by petroleum products. By contrast, industry relies on a larger mix of energy sources. Although natural gas

Figure I-1
U.S. Primary Energy Use by Sector

Source: EIA, 1994

and petroleum are the principal sources of industrial energy, industry also consumed more than 3 quads of electricity and 2 quads each of coal and renewable energy in 1993.

Not only is the industrial energy input stream much more diverse than the other two sectors, but the number and complexity of energy using processes and technologies in industry are much greater as well. Broadly speaking, industrial energy use is consumed in industry-specific processes (such as iron blast furnaces, petroleum refining, pulp and papermaking, and beer brewing) and cross-cutting technologies such as electric motors, and boilers that have widespread use among a number of industries.

INDUSTRIAL SECTOR ENERGY USE CONCENTRATED IN SIX MATERIALS AND PROCESS INDUSTRIES

About 87% of industrial energy is used in the manufacturing sector (Figure I-2). Non-manufacturing industries, including mining, oil and gas extraction, construction, and forestry and agriculture, account for about 13%. Within manufacturing, industries primarily engaged in fabrication and assembly account for about 15% of industrial energy use. The

Figure I-2
Primary Energy Consumption by Industry, 1991

Total Primary Industrial Energy Use = 29.6 Quads

Source: EIA

balance of industrial energy use—about 71%—is consumed by a total of just six highly energy-intensive industries. Those industries include petroleum refining, chemicals, pulp and paper, metals, ceramics (stone, clay and glass), and food processing.

By and large, these materials and process industries are also the predominant focus of OIT's RD&D program.

It is not a coincidence that firms in this handful of industries share many other attributes in addition to their large appetite for energy. For example, they are often characterized by high material throughput, large water usage, heavy capital intensity, and a strong propensity for scale economies. Most important of their many common attributes, however, is their shared role in converting the raw materials supplied by the extractive industries such as mining, farming, and forestry into materials and other inputs useful to a broad range of other industries. Often simply called the basic industries, these are the materials and process industries.

CRITICAL LINKS IN THE MANUFACTURING FOOD CHAIN

The finished materials and other inputs supplied by these industries constitute the beginning of the long and intricate food chain of the manufacturing sector of the economy. While some of the products of the materials and process industries—gasoline and packaged foodstuffs for example—are sold more or less directly to consumers, the overwhelming

preponderance of their products are inputs to other manufacturing industries. Indeed, a lengthy list of such industrial products as chemical feedstocks, fibers, polymers, sheet metal, castings, lumber, and glass require further manufacturing operations before they are transformed into consumable goods.

As shown in Figure I-3, the products and output of the energy-intensive materials and process industries are converted by other value-adding fabrication and assembly industries into a complex array of consumer, industrial and national defense-related goods ranging from textiles and clothing, books and newspapers, furniture and household appliances, and computers and telephones to beverage cans and grocery bags, automobiles and aircraft, tractors and machine tools, tanks and submarines, and drugs and medical equipment.

Figure I-4 is adapted from an article by Robert Ayres entitled "Industrial Metabolism." It identifies the principal stages of transforming raw materials into manufactured goods. The goods-producing process typically begins with the extraction of raw materials that are

subsequently refined by what are generally energy-intensive processes designed to separate out impurities. These intermediate pure materials are then recombined (or synthesized) into finished materials. Typically this process entails the chemical or physical blending of multiple pure materials (or ingredients) to yield the specific properties desired by the industrial customer. Finished materials are then cast, machined or otherwise fabricated into parts or components that can be assembled into manufactured goods. Ultimately, manufactured goods are either recycled or disposed as waste.

Energy Data

The Energy Information Administration (EIA) collects data from several sources, including surveys of petroleum refiners, electric utilities, and manufacturers. The presentation of data collected by EIA varies however. For example, the consumption by fuel in Figure 2-2 is based on apparent consumption data, such as shipments of natural gas to manufacturers, provided by energy suppliers; whereas the consumption by major industry in Figure 2-1 is largely based on the Manufacturing Energy Consumption Survey (MECS), which surveys individual manufacturers. This can create some discrepancies, especially in renewable energy use. For example, on-site wood and solar energy use are generally not captured by the apparent consumption data collection, but would be captured under surveys of manufacturing or residential energy consumption.

Additionally, some data and figures in this document refer to end-use consumption while others refer to primary consumption. End-use consumption refers to energy used at an application, whereas primary consumption associates electricity generation and transmission losses with an application. EIA presents data using both end-use and primary consumption. Apparent consumption is used for most industrial sector data, and the manufacturing sector is based on the MECS.

Figure I-3
Role of Materials and Process Industries in the Economy

Unfortunately, the critical role of the materials and process industries in the economy is often overlooked by the national media and misunderstood by the broader society. Because their products largely lose their identity in the process of being converted into usable consumer goods, mass media advertising is not widely practiced by many firms in these industries (the oil and food companies who retail directly to consumers are important exceptions). Thus, firms in these industries often are not widely recognizable household names, which in turn contributes to lack of public appreciation of their roles in the economy. But from an economic and physical standpoint, these essential industries quite literally underpin the entire industrial infrastructure.

ENVIRONMENTAL PROBLEMS RELATED TO SEPARATION AND SYNTHESIS ROLES

The materials and process industries possess at least one other common attribute—their daunting environmental problems. These problems derive from their unique role in the economy of linking the extractive industries to the fabrication and assembly industries. Processing raw materials into usable industrial materials involves a large variety of energy- and waste-intensive separation and synthesis processes. Separation breaks apart molecules and synthesis

recombines them into more useful substances. They are intrinsically energy- and waste-intensive processes, and make the industries that employ them—the materials and process industries—the largest energy users and waste generators in industry.

As the Congressional Office of Technology Assessment has pointed out, the largest energy-using industries are those such as oil refining, chemicals, primary metals, pulp and paper, food, and ceramics and glass that chemically or physically transform matter. These industries employ technologies that rely on the direct application of heat to break and rearrange molecular bonds through chemical reactions. Massive amounts of energy are required to do the work of breaking up and rearranging molecules—the essence of what the materials and process industries do. Because of the central workhorse role that energy-intensive separation processes play in the materials and process industries, they typically account for 40% to 70% of the capital and operating costs in many of these industries. Nearly 45% of the energy consumed in the chemical and petroleum refining industries, for example, is used in separation processes.

Separation processes (Table I-1) not only require huge amounts of heat; they routinely produce large quantities of low-value waste products as

well. This is because the objective of these processes is to separate the desirable (or useful) from the undesirable (or useless). Examples of separation processes include distillation, metal smelting, flour milling, evaporation, and chemical reduction. By their very nature, separation processes are meant to be weight-reducing. A sizable portion of the raw material is not required in the final material and must be separated and discarded (or, if possible, recycled or a separate use developed for the waste). This is why firms in the materials and process industries often locate their plants in the general vicinity of the extractive industries whose raw materials

Figure I-4
Principal Stages in the Processing of Raw Materials into Manufactured Goods

What Is the Industrial Sector?

The Standard Industrial Classification (SIC) system is the official structure used by the federal government to classify all industrial statistics. It contains 83 major industrial groups that may be divided into three broad components: goods producing industries, transportation industries, and service industries. The goods producing industries are classified in SIC groups 1-39, the transportation industries include SIC groups 40-49 and the service industries include SIC groups 50-99.

DOE defines the industrial sector to include the goods producing industries. This includes both nonmanufacturing industries, that is, agriculture (SIC 1-9), mining (SIC 10-14), construction (SIC 15-17), and manufacturing industries (SIC 20-39). In 1993, the industrial sector consumed 30.8 quads of energy, 37% of the total U.S. primary energy use. The balance was consumed by the transportation sector (including SIC groups 40-49 and all privately owned vehicles, boats, planes and so on) and the residential/commercial sector (including privately owned dwellings and SIC groups 50-99).

Sources: *Industrial Metabolism*, Robert Ayres
Industrial Ecology: A U.S./Japan Perspective,
National Academy of Engineering

they separate into useful and useless constituents. It simply makes little economic sense to transport large quantities of valueless (or, at best, low value) waste materials great distances.

Synthesis is the process of combining elements or intermediate materials into substances possessing the properties needed by industrial customers or end-use consumers (Table I-2). It, too, is intrinsically energy- and waste-intensive, though generally less so than separation. Examples of common synthesis processes include blending molten constituents (metal alloys and glass), catalysis, polymerization, and manufacturing of most beverages and confectionary foods. In practice, it is usually not possible to synthesize products without wasting some of the feedstock or intermediate material input. This would require synthesis processes that are 100% efficient. While many processes exceed 90% efficiency, technical constraints and increasing costs prevent achievement of the theoretical maximum efficiency. The problem arises when multiple processing steps are required, that is, when many intermediate processing steps are needed to yield the desired chemical or other product. For example, a product requiring two sequential, 90% efficient processes has an overall process efficiency of 81%; one requiring three such steps is only 72% efficient. Obviously, in a tonnage commodity business, multi-step processing of numerous intermediate products can generate large amounts of waste.

LARGE POTENTIAL FOR ENERGY EFFICIENCY IMPROVEMENTS AND WASTE REDUCTION

Though separation and synthesis processes are intrinsically energy- and waste-intensive, they also present enormous potential for energy improvement and waste reduction. Because conventional processes typically operate far from the theoretical maximum efficiency, advances in science and technology have the

Table I-1

Common Separations in the Materials and Process Industries

Industry Group	Constituents Being Separated	Separation Process
Chemicals—Organic	Ethylene from Ethane	Cryogenic (low-temperature) Distillation—components are separated (distilled) at very cold temperatures according to differences in their physical properties.
Pulp and Paper	Black Liquor Solids from Cooking Chemicals	Evaporation—black liquor, a pulping process byproduct, is concentrated to boost solid content and recover cooking chemicals. Concentrated solids used as fuel in pulping mills.
Primary Metals	Iron from Iron Ore	Reduction and Smelting—a combination of chemical/thermal processes separate iron from iron oxide before carbon is added to make steel.
Petroleum Refining	Fuel Products from Crude Oil	Atmospheric Distillation—fuel products, such as kerosene, diesel oil, heavy gas oil, and lighter hydrocarbons, are separated from heavy crude oil by differences in their boiling points. Some undergo further refining to produce gasoline, petrochemical feedstocks, and fuel oils.
Stone, Clay, and Glass—Cement	Fines from Larger Pieces of Rock	Mechanical Sifting—sieves or grates are used to separate dust and small particles from larger rock pieces before clinker is produced in cement making.

Relationship of Materials and Process Industries to the Natural Resource Industries

The size, performance and health of the U.S. materials and process industries are closely related to those of the upstream industries that supply them their essential inputs—the natural resource industries. A large upstream supply capacity (natural resources) and large downstream demand (from fabrication and assembly industries and consumer markets) require a materials and processing capability of suitable magnitude to link the two.

Farmers and ranchers provide crops and meat to the food processing industries. The forestry industry harvests timber and supplies feedstocks for paper products, furniture and a diversity of building materials. Crude oil and natural gas serve as raw materials for gasoline and other refined petroleum products and feedstocks for the chemical industry. Nonfuel mining provides raw materials for metals, cement, bricks, and glass that are widely used in manufacturing and construction.

The size and economic significance of the U.S. materials and process industries derive from our nation's historic strength in natural resources, especially compared to most of our industrialized competitors. Like such other physically expansive countries as Australia, Brazil, Canada

and the former Soviet Union, the United States has been blessed by an abundant supply of arable farmland, forests, and energy and mineral resources. In contrast, most Western European countries and Japan are physically smaller and more densely populated with more mature societies than the United States. Hence, these countries either lack large natural resource supplies or their best indigenous resources have already been consumed by their higher-density population bases over time. Unfortunately, however, the historic U.S. strength in natural resources is showing signs of diminishing. Oil imports have risen sharply over the past two decades and now supply nearly half of U.S. needs. Imports of iron ore, copper and other minerals have also increased and on a value basis now account for about a quarter of total U.S. supplies. The United States remains a net exporter of forest products, but prospects of more limited timber harvests portend a possible reduction in this surplus. Though farm products, coal and fertilizer materials seem likely to continue as important export commodities, the overall reduction in U.S. natural resource self-sufficiency will place added strains on the domestic materials and process industries.

potential to improve energy efficiency considerably. Simultaneously, such advances could reduce the generation of waste material, increase the recycling of waste or find new uses for the waste materials that are the unavoidable byproducts of separation and synthesis processes.

Table I-2
Common Syntheses in the Materials and Process Industries

Industry Group	Product Being Synthesized	Synthesis Process
Chemicals—Organic	Polyethylene	Ethylene, solvent, and catalyst are reacted together under increased temperature and pressure. Polymer chains are formed, the polymer is centrifuged and precipitated, and then it is dried to yield the end product, polyethylene.
Pulp and Paper	Paper Stock	Wood pulp is refined and blended, and chemicals are added to form a stock with unique properties (strength and color) which are then formed and pressed into paper products.
Primary Metals	Brass	Copper and zinc, along with other alloying elements, are placed in a furnace. The molten metals are blended to allow even distribution of the components. The molten metals are then poured into the desired form and allowed to cool and solidify.
Petroleum Refining	Methyl-tertiary Butyl Ether (MTBE)	MTBE is produced in refineries by a chemical reaction of isobutylene and methanol. Used commonly as a blending component in making reformulated (less polluting) gasoline.
Stone, Clay, and Glass	Molten Glass	Silica, limestone, soda ash, and additives are blended together, melted in a furnace to produce chemically and physically homogenous molten glass, then formed into sheets or containers.

The Department of Energy, in partnership with its customers, is entrusted to contribute to the welfare of the Nation by providing the technical information and scientific and educational foundation for the technology, policy and institutional leadership necessary to achieve efficiency in energy use, diversity in energy sources, a more productive and competitive economy, improved environmental quality, and a secure national defense.

— Mission Statement from Department of Energy Strategic Plan, April 1994

THE NEXUS OF FEDERAL TECHNOLOGY PROGRAMS IMPACTING HEAVY INDUSTRY

OIT is located within DOE's Office of Energy Efficiency and Renewable Energy (EE). EE has the overall mission of leading the nation to a stronger economy, a cleaner environment, and a more secure future through development and deployment of sustainable energy technologies. EE is the principal organization in DOE responsible for research, development, demonstration and deployment programs targeted at the demand side of our nation's overall energy situation. Within EE, three offices are responsible for major technology programs intended to promote energy efficiency in the U.S. economy's three principal sectors: transportation, buildings/commercial and industry. OIT fulfills this role for the industrial sector.

In carrying out its duties, OIT is the leading organization within DOE responsible for the development and transfer of advanced industrial technology. OIT promotes industrial competitiveness by improving the energy and materials efficiency of industrial

processes. It also supports the creation of technologies that will lead to the emergence of new industries and contribute to thousands of new jobs, higher wages, increased exports, and improved profits.

MISSION AND HISTORY

OIT's mission is to develop and deploy, through cost-shared partnerships with industry, government, and non-governmental organizations, advanced energy efficiency, improved productivity, renewable energy, and pollution prevention technologies. OIT accomplishes its mission through a variety of technology research, development, testing, evaluation, demonstration, and deployment programs designed to assist U.S. industry.

History of OIT

Following the energy crises of the early 1970s, the nation came to realize the importance and power of efficiency as a mechanism to protect the future security of energy supplies. Legislation was crafted and quickly passed to put into place measures to constrain energy consumption and improve efficiency of energy use. The foundation of the U.S. energy conservation and efficiency programs is based on two laws that were passed at that time: the Energy Policy and Conservation Act (EPCA), and the Federal Non-nuclear Research and Development Act (FNRDA). These Acts each gave birth to new Federal agencies: the Federal Energy Agency (FEA), and the Energy Research and Development Administration (ERDA).

By 1977, fledgling efficiency programs were in place in both agencies. Each program had a component dedicated

to industrial energy efficiency that recognized the critical role of this sector of the economy in any nationwide efficiency effort. With the passage of the Department of Energy Organization Act of 1977, all FEA and ERDA programs were effectively merged. This created, among other things, the Office of Industrial Programs (OIP), OIT's organizational predecessor.

From the beginning, OIP recognized the relationship between energy efficiency and industrial waste generation and was structured to emphasize the relationship. Two major organizational elements, the Division of Waste Energy Reduction (WER) and the Division of Improved Energy Productivity (IEP), formed a matrix structure of complementary technology activities. In effect, the IEP addressed the basic process technologies (i.e., industry-specific technologies) while the WER addressed the process peripherals (cross-cutting technologies). Because budget limitations constrained the number of opportunities that could be addressed at any given time, project selection was based on maximizing portfolio benefit-cost ratios. Industrial participation in the planning and execution of programs was considered essential, and was assured through private sector cost participation. Strong evidence that these principles work can be found in the high success rate of early projects sponsored by OIP.

As OIT's experience and success in energy efficiency RD&D projects grew, the objectives of its programs gradually began to respond to the changing needs and priorities of its principal customers in the materials and process industries. As the international competitiveness of these

heavy industries was threatened in the 1980s, OIT's projects began to emphasize productivity, capital efficiency, and quality in addition to energy efficiency. Because the huge costs of environmental regulations jeopardize the competitiveness of OIT's customers, industrial waste reduction

and pollution prevention also have become critical elements of its RD&D portfolio. OIT's ability to successfully respond to the changing needs of its customers has thrust the organization into a leadership role in federal technology programs impacting heavy industry.

- Contributing to the continued growth and health of the U.S. economy, the prosperity of its citizens, and a secure national defense.

ORGANIZATION

OIT Technology Programs: Industry-Specific and Crosscutting Technologies

To exploit an almost unlimited number of opportunities for improved energy efficiency, productivity, product quality, pollution prevention and competitiveness in the materials and process industries, OIT employs what is essentially a two-pronged organizational approach. On one hand, OIT concentrates on supporting the development and deployment of more efficient and cleaner industry-specific technologies and processes. On the other, OIT supports the development of innovative crosscutting technologies and processes that are used in several, if not all, materials and process industries as well as other manufacturing and goods-producing industries.

The industry-specific thrust of the OIT program seeks to develop key breakthroughs in such central work-horse technologies as:

1. Separations in chemicals and petroleum refining;
2. Black liquor recovery and paper drying in the paper industry;
3. Coke oven, iron blast furnace and refining technology in the steel industry;
4. Alumina refining, smelting and fabrication processes in the aluminum industry;
5. Melting and refining in the glass industry; and,
6. Melting and casting in the metal foundry industry.

The industry-specific component of the OIT program addresses the highly unique nature of the raw materials, core technologies and principal products of these industries. To successfully

The Energy Policy Act and the Office of Industrial Technologies

Since 1992, OIT programs have been strongly influenced by The Energy Policy Act of 1992. The Act (commonly referred to as EPACT) was the first comprehensive U.S. energy legislation enacted in more than a decade. It contains a wide variety of energy-related mandates including several provisions intended to promote industrial energy efficiency. In particular, Sections 201, 210, 211, and 220 address industry or technology-specific developments. On the other hand, the requirements of Sections 131, 132, and 133 involve non-technology deployment policies that encourage energy-efficient practices in industrial facilities and processes. Key EPACT requirements addressing the OIT program include:

- Supporting natural gas end-use technologies (EPACT Section 2014);
- Advances in pulp and paper technologies (EPACT 2103);
- Development of more efficient electric drive technologies (EPACT Section 2105);
- Continuing steel, aluminum and metals research (EPACT Section 2106);
- Pursuing opportunities for identifying pollution prevention technologies (EPACT Section 2108);
- Developing high efficiency heat engines (EPACT Section 2112);
- Advanced manufacturing and materials initiatives (EPACT Sections 2201 and 2202);
- Deployment of a wide range of energy efficient technologies (EPACT Sections 131, 132, 133); and
- Other activities related to energy-intensive industries (EPACT Section 2107).

OBJECTIVES

OIT is currently developing a strategic plan and, consistent with its standard method of working closely with its customers, OIT will solicit customer input to its planning process. Though OIT's strategic plan is not yet ready for publication, the following discussion addresses numerous routine aspects of the organization's way of doing business that will be incorporated into the spirit of the plan, if not its specifics.

The objectives of OIT's RD&D portfolio include:

- Improving energy efficiency and energy security;
- Increasing use of renewable and alternative sources of energy;
- Making better use of energy that is now lost as waste or heat;
- Enhancing fuel flexibility;
- Improving productivity, product quality and reducing manufacturing costs;
- Preventing industrial pollution, reducing greenhouse gas emissions, and eliminating toxic and hazardous waste;
- Minimizing waste generation, enhancing in-plant recycling, and improving use and recyclability of waste materials;
- Advancing U.S. technological leadership;
- Improving the competitive position and profitability of American industry in the global marketplace;
- Stimulating job formation, wealth creation and higher wages; and,

develop and deploy next generation core technologies in these industries requires the intensive and committed application of highly specialized knowledge. OIT's industry-specific technology programs are discussed in detail in Chapter 3 of this report.

The crosscutting thrust of the OIT program addresses such technologies as advanced materials, electric motor systems, cogeneration and advanced turbine systems, heat exchangers and heat pumps, industrial boilers and combustion processes as well as an extensive number of pollution prevention and waste reduction technologies and practices. The crosscutting component of the OIT program recognizes that while such technologies have applications throughout industry, often these technologies must be tailored to suit the unique needs of different industries and processes. OIT's crosscutting technologies are discussed in greater detail in Chapter 4.

Expert Teaming

OIT employs program managers in each of the major industry-specific and crosscutting technology areas. In many instances, the specialization required to adequately address OIT's technology areas dictates the use of multiple program managers. As a result, OIT program managers typically possess a considerable depth of knowledge and expertise that helps promote productive relationships, partnering and exchanges with the organization's private sector clients and customers. OIT program managers are able to understand

industry's problems, and relate to industrial points-of-view. This enables OIT to shape its programs to provide maximum benefit to its industrial customers and the Nation as a whole.

To become even more responsive to the needs of its customers in major industries such as the paper industry, OIT is currently in the process of reorganizing to place a much greater emphasis on teaming. OIT's industry teams include managers from both its industry-specific (paper, steel, chemicals and so on) areas as well as its crosscutting program areas (e.g., advanced materials, motor systems, and waste reduction). Furthermore, experts from other areas in DOE (such as Energy Research and Fossil Energy) as well as DOE's national laboratories typically join OIT's industry teams. By creating such teams, the scope of OIT's paper industry program, for example, goes beyond its important black liquor recovery and impulse drying projects. It also

includes such technologies as motor systems, cogeneration and pollution prevention that can substantially benefit the paper industry.

Technology Deployment and Transfer

OIT has long been committed to promoting technology deployment through a variety of technology transfer activities. These activities are vital to promoting the adoption of cost effective, state-of-the-art techniques for industrial facilities to improve their energy efficiency and minimize waste products. Technology transfer occurs when technology, know-how, or information first produced in one organization or area is applied in another organization or new area. The philosophy of promoting deployment of OIT products throughout industry is woven into all OIT activities. By emphasizing cost-shared, collaborative work, OIT ensures that its projects are relevant to industry partners and will be quickly implemented.

OIT: Focus on the Materials and Process Industries

DOE's Office of Energy Efficiency and Renewable Energy concentrates on the demand-side of the U.S. energy picture, and OIT addresses the huge and diverse industrial component of the U.S. energy demand equation. Despite the great size and complexity of the industrial sector, a total of just six two-digit SIC industry groups account for almost 80% of the industrial sector's end-use energy consumption. These industries—commonly referred to as the materials and process industries—include the chemical, petroleum refining, pulp and paper, food processing, metals, and ceramics and glass industry groups. By and large, these materials and process industries are also the predominant focus of OIT's research, development, demonstration and deployment program.

In addition to high energy intensity, other prominent characteristics of these industries include:

- They account for over 95% of the volume of all waste and pollution generated in manufacturing;

- Collectively they employ about 4.2 million workers whose hourly wages exceed those of manufacturing overall by about 8% and are double those of the average retail worker;
- They account for about one-fifth of all U.S. merchandise trade and their continued competitiveness is an essential factor in the competitiveness of all of U.S. industry;
- They directly account for about one-twelfth of U.S. gross domestic product (GDP);
- They are indispensable links between such natural resource industries as farming, forestry, mining, and oil and gas extraction and such value-adding assembly industries as automobiles, aerospace, construction and electronics;
- Their continued health and robustness are critical to the maintenance of a sound national defense posture.

To Obtain Further Information About OIT Publications and Workshops

Write to OIT at the following address:

Office of Industrial Technologies,
EE-223
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Through OIT's technology transfer program, industry gains ready access to energy-efficient and pollution prevention technologies. New and underutilized technologies and process improvements that have been created through federally-sponsored research efforts are publicized, transferred to and commercially developed for industry. To close the information

gap between technology developers and potential users, OIT uses a variety of mechanisms targeted at a wide range of stakeholders. The Office undertakes significant outreach efforts, including education and communications, to achieve effective adoption and diffusion of new technologies and industrial process improvements.

OIT publishes numerous fact sheets, brochures, and case studies about new programs and specific DOE-sponsored research that can help industries reduce their energy use and prevent pollution, while improving their productivity. In addition, OIT sponsors technical workshops that bring together energy technology producers, users and OIT program managers and scientists to discuss industry needs and the possible RD&D opportunities to address these needs. These meetings are often held in cooperation with industry trade associations and technical societies.

OIT actively supports technology deployment partnerships to overcome the barriers to market acceptance of new, energy-efficient technologies. Barriers include high capital cost and perceived risks of new technologies, and the lack of reliable information on the application and performance of these technologies.

OPERATION

Industry Defines Its Research and Development Needs

At its essence, the OIT program supports a more energy efficient, productive, cleaner and competitive future for a major segment of U.S. industry. But to focus effectively on the future, a vision of that future is needed. By working with its clients in the materials and process industries, OIT learns about their needs, challenges, and industry's views or visions of the future. This process enables OIT to shape its RD&D portfolio to carefully address the needs of its customers as industry scopes out its vision of the future (see Figure 1-1).

As part of the process, OIT's industrial customers describe their manufacturing processes and products, energy use profiles and environmental problems, as well as their overall productivity and profitability. The process also informs OIT about the technical, competitiveness, and regulatory

Energy Analysis and Diagnostic Centers

Another OIT deployment-focused program is its Energy Analysis and Diagnostic Center (EADC) program. The EADC program began in 1976 to provide small- and medium-size manufacturers with individual analyses of their plants' use of energy. In addition to energy audits, the program is expanding to provide environmental support to manufacturers in the form of energy, waste, and productivity assessments. These combined assessments are performed by Industrial Assessment Centers (IACs). Centers are located at universities throughout the country. In 1994, there were 30 fully operational EADC sites, including six IACs. Audits are performed for plants within a 150-mile radius of center sites by senior- and graduate-level engineering students, under the direction of tenured engineering faculty. Each fully operational EADC conducts 30 audits a year.

Photo by Jeff Uhrhlaub

Students at Colorado State University conduct an energy analysis.

For a plant to become a client, it must have products within SIC Codes 20-39, gross annual sales of \$75 million or less, employ no more than 500 people, and have no technical staff to do an energy analysis. A one-day audit will identify inefficiencies and cause minimal disruption to the plant's operation. Sixty days after the audit the plant receives a formal, confidential report containing recommendations for specific actions and their estimated costs and payback periods. There is no cost to the plant's owner for the audit. The audit results are entered into a national database. This data base has been successfully used by Baltimore Gas & Electric Company to assist demand-side management planning.

Each year the EADC program audits about 900 plants. On average, each audit identifies approximately 4 billion Btu of potential energy savings, with total cost savings of \$40,000. Almost 50% of the recommendations have been implemented by the client plants. Since its inception, the program has conducted approximately 4,500 audits, generating energy savings of 94 trillion Btu and dollar savings of \$517 million.

Energy Analysis and Diagnostic Center Locations

Texas A&M-College Station	University of Massachusetts	San Diego State University
Arizona State University	University of Maine	San Francisco State Univ.
Bradley University	Univ. of Missouri-Rolla	University of Tennessee
Colorado State University	Mississippi State Univ.	Univ. of Arkansas—Little Rock
South Dakota State Univ.	North Carolina State Univ.	University of Dayton
Georgia Tech	Notre Dame University	University of Florida
Research Institute	University of Nevada	University of Louisville
Hofstra University	Old Dominion University	Univ. of Mich.-Ann Arbor
Iowa State University	Oklahoma State University	Univ. of Wisc.-Milwaukee
Texas A&M - Kingsville	Oregon State University	West Virginia University

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OIT's Industries of the Future Initiative is a fundamentally new approach to aligning federal investments in technology research, development, and deployment with the needs and expectations of technology users in the private sector. It aims to shrink the time required to move innovative industrial technologies from concept to marketplace. A central theme of the Industries of the Future process is helping manufacturers reduce costs and improve efficiency. For example, U.S. manufacturers spent nearly \$30 billion in 1992 on pollution abatement and control. Without significant changes in approaches to reducing waste, these nonproductive expenditures are expected to increase sharply by 2000, creating an unnecessary drain on corporate resources. The program deepens and strengthens collaboration between industry and government by facilitating integrated planning and implementation by all participants, by fostering cooperative planning among different organizations in DOE, and by fostering a more holistic perspective through intra- and interagency alliances within government.

Industry Identifies Its Technology Needs...

Industry participants begin the process by creating a vision that reflects the dynamic impact of market, business, social, and regulatory drivers in their industry. The vision is developed by industry, for industry, and provides a framework for shaping major advancements in technologies according to their potential for improving industrial process efficiency, energy and materials use, and environmental protection. DOE then shapes a portfolio of near-, medium-, and long-term technology research, development, and deployment activities to address the unique challenges each industry faces.

The Industries of the Future approach has grown out of 18 years of successful industry-government technology development led by OIT, which is ideally suited for the role of catalyst and facilitator in the Industries of the Future process. As the primary federal interface with the Nation's materials and process industries, OIT has developed in-depth knowledge of industries' concerns. OIT has also established many long-term relationships with industry leaders and organizations as well as with the DOE laboratories. OIT has been developing the Industries of the Future approach since 1992, building upon this necessary foundation.

Private-sector participants include industrial companies and trade associations, universities, private research institutions, and environmental and public-interest groups. Government participants—in addition to DOE groups such as Energy Efficiency and Renewable Energy, Fossil Energy, Energy Research, Defense Programs, Environmental Management, and DOE laboratories—may include the Environmental Protection Agency, the National Institute of Standards and

Technology (Department of Commerce), the Department of Agriculture, state agencies, and others as appropriate.

...To Help Shape a Leveraged, High-Utility RD&D Portfolio

The Industries of the Future approach will develop and use technologies that can increase energy efficiency and lower the costs of environmental protection and regulatory compliance in the materials and process industries. In chemicals and petroleum refining, for example, advances in separation sciences and catalysis promise to improve yields of high-quality products, increase energy efficiency, and reduce the need for pollution control equipment. Examples of other promising areas include improved fluid-bed catalytic crackers in the petroleum industry; alternative bleaching and high-efficiency drying processes in the pulp and paper industry; methods for reducing electricity consumption in the aluminum industry; and direct ironmaking and net-shape forming in the steel industry.

The Industries of the Future approach adds up to a new way of doing business for government and industry. The partnerships establish coordinated teams for planning and implementation, including a clear government point of contact for industry. The approach also provides the framework for coordinated budget planning, identifies gaps and areas of potential collaboration with existing programs, facilitates alignment with the industries' visions, and enables the integrated leveraging of joint resources.

OIT Cooperative Programs—Partners in Progress

A close working relationship with industry, professional organizations, and other groups has been a hallmark of OIT programs since they were established in the 1970s. Industry is a partner in planning and implementing OIT-sponsored projects. This cooperative effort helps to ensure that new technologies are relevant to industry's needs and encourages industry acceptance. Currently, OIT is involved in a broad range of partnerships involving more than 100 industrial firms, 10 national laboratories, 7 states, 20 universities, 10 utilities, 5 government agencies, the Electric Power Research Institute, the Gas Research Institute, and several trade associations. Table 1-1 contains a partial listing of several public, private and not-for-profit organizations that are currently (or were recently) involved in OIT program partnerships.

Technology deployment partnerships are designed to overcome the barriers to use more productive, energy-efficient technologies that have caused a large gap between the possible energy savings in industry and the savings that are actually realized. This gap exists despite the economic and environmental benefits accompanying energy-efficient technologies. Examples of OIT partnerships include the National Industrial Competitiveness through Energy, Environment, and Economics (NICE³), Energy Analysis and Diagnostic Centers (EADC), and the Motor Challenge programs.

challenges that are influencing future manufacturing technologies in these industries.

The process enables industry to identify and prioritize its research and development (R&D) needs. Technology projects and deployment activities that can help achieve industry's vision of the future are identified. An R&D plan is developed that features technologies that are adaptable to existing industry infrastructures and that, if implemented, could provide an acceptable rate of return for industry. Potentially commercializable technologies that can make a difference and that can be developed through partnerships are also a high priority.

Research and Development Partnerships

One of OIT's roles is to act as a catalyst in the development of new industrial technologies. Once industry identifies its R&D needs, then OIT cooperatively funds competitively selected projects that can contribute to more productive and cleaner manufacturing processes for the industry of the future. Industrial leadership in identifying technology needs helps pave the way for cost-shared partnerships with the private sector. OIT operates under the philosophy that if industry is willing to invest in new technology, then that technology has a good chance of overcoming the many barriers to

successful commercial deployment. OIT partnerships are key to successful federal efforts to stimulate technology development and deployment efforts in these industries.

OIT provides assistance to the materials and process industries in many forms besides direct co-funding for R&D. OIT is particularly well-positioned within DOE to assist in the transfer of national laboratory technology. It helps develop action plans for regulatory, market, legislative and financial initiatives that can address barriers to commercialization. Through its outreach programs, OIT can provide technical assistance and information to accelerate implementation of technology that it supports. It also uses awards, seals of approval, and other market stimulation techniques to encourage innovation and aggressive investment decision-making in industry.

OIT is also very active in a network of strategic alliances with other federal agencies, industry trade organizations, and non-governmental organizations to leverage development and deployment funds to the maximum benefit of U.S. industry (see Figure 1-2). Key alliances include the Department of Commerce, the Department of Defense, the Gas Research Institute, and the Electric Power Research Institute. OIT participates in partnerships between industry and regulatory agencies such as the Common Sense Initiative being led by EPA.

In effect, OIT is the nexus of technology development and deployment in the federal government for heavy industry. And the development and use of OIT-sponsored high productivity, energy-efficient, pollution-preventing technologies help sharpen the competitive edge of these vital industries while contributing in an important way to the continued growth and prosperity of the economy as a whole.

Figure 1-1
Industries of the Future Process

Funding and Partnership Mechanisms

OIT carries out a significant part of its mission by offering financial assistance to qualified organizations in the public and private sectors in exchange for products and services that meet OIT's program objectives. Financial assistance agreements are administered through formal legal instruments and take many different forms such as cooperative agreements or grants.

A financial assistance instrument is primarily used to transfer money, property, services or anything of value or use from the federal government to the recipient. Typically, financial assistance is used to fulfill a public intent of support or stimulation authorized by federal statute.

A grant would be awarded when no substantial involvement is expected between DOE and the recipient during performance of the activity, while a cooperative agreement would be used when substantial involvement between DOE and the recipient is expected. Some of the mechanisms available for industrial participation in OIT programs include the following:

Cost-Shared Financial Assistance Awards and Cooperative Agreements—A financial assistance award is a legal instrument reflecting a negotiated agreement between industry and the government and is usually cost-shared. To protect proprietary interests of private parties, the government may agree not to disseminate commercially valuable data that is generated under a cost-shared financial assistance award for a specified period of time.

Cooperative agreements may also reflect a relationship between the federal government and state or local government or universities in order to support or stimulate research. In cooperative agreements, substantial involvement is anticipated between DOE and the recipient during the performance of the contemplated activity.

Cooperative Research and Development Agreements (CRADAs)—CRADAs are agreements between government laboratories and nonfederal parties in which both participants provide personnel, services, facilities or equipment to conduct specified R&D. The nonfederal parties may also provide funds as no direct funding is provided by the laboratory. Rights to inventions and other intellectual property are negotiated between the laboratory and participant.

R&D Consortia—Consortia are arrangements involving multiple federal and nonfederal parties working together towards a common R&D objective. Funding for R&D consortia may be shared, but usually no funds are exchanged between participants.

Exchange Programs—These programs allow government or laboratory employees to work in industry facilities, and industry personnel to work in government labs and facilities. Exchange programs enhance technical capabilities and are used to support research in specific areas. Costs

Table 1-1
Partial Listing of OIT Program Partners

Private Sector Partners			Non-governmental Organization Partners
Advanced Cast Products, Inc.	General Electric	National Institute for Standards and Technology	Alliance to Save Energy
Advanced Refractory Technologies	General Motors	Department of Defense	National Resource Defense Council
Air Products and Chemicals, Inc.	Golden Technologies, Inc.	Air Force	National Association of State Energy Offices
Allied Signal Corporation	Institute of Paper Science and Technology	Army	American Council for an Energy-Efficient Economy
Allison Engine Company	Intel	Department of the Interior	National Energy Laboratory Partners
Aluminum Company of America	Intelnet Foundries	Bureau of Mines	Ames Laboratory
Alzeta Corporation	LTV Steel	Environmental Protection Agency (EPA)	Argonne National Laboratory
Amercom	Metallamics	University Partners	Idaho National Engineering Laboratory
American Iron & Steel Institute	Minnesota Mining and Manufacturing	University of Alabama-Birmingham	Lawrence Berkeley Laboratory
American Foundrymen's Society	National Center for Manufacturing Sciences	California Institute of Technology	Lawrence Livermore National Laboratory
American Plastics Council	Osmotek	University of California	Los Alamos National Laboratory
Amoco	Permea	Carnegie Mellon University	National Renewable Energy Laboratory
Babcock & Wilcox	Petroleum Environmental Research Forum	Case Western Reserve University	Oak Ridge National Laboratory
Beloit Corporation	Photonic	University of Colorado	Pacific Northwest Laboratory
Bethlehem Steel	Reliable Castings	Duke University	Sandia National Laboratories
Bioengineering Resources	Reynolds	University of Florida	
Boeing	Sandusky International	Georgia Institute of Technology	
BP America	Schuller International	Howard University	
Briggs & Stratton	Solar Turbines	University of Northern Iowa	
Brush Wellman	Stone & Webster	Massachusetts Institute of Technology	
Carborundum	Textron	University of New Mexico	
Caterpillar	Thermotrex	Ohio State University	
Center for Waste Reduction Technologies	Union Camp Paper Company	Oregon State University	
Chevron	UOP	Penn State University	
Chrysler	Vortec, Inc.	Princeton University	
Coors Ceramics	Wabash Alloys	Purdue University	
Dow Chemical	Weirton Steel	Rutgers University	
Dow Corning	Westinghouse Electric	University of Tennessee	
DuPont	Weyerhaeuser	Virginia Polytechnical Institute and State University	
Electric Power Research Institute	Federal Government Partners	Worcester Polytechnic Institute	
Gas Research Institute	Department of Agriculture		
	Department of Commerce		
	Census Bureau		

are borne by the organization sending the personnel. Intellectual property rights are set forth in the exchange agreement.

Licensing—This mechanism involves the transfer of less-than-ownership rights of intellectual property such as a patent or a software copyright to permit its use by the licensee. Licenses can be exclusive or non-exclusive, for a specific field of use or for a specific geographical area. The potential licensee must present plans for commercialization.

User Facility Agreements—These agreements permit private parties to conduct R&D at a DOE laboratory. For proprietary R&D, the laboratory is paid for the full cost of the activity. If the work will be published, the cost can be adjusted. Intellectual property rights generally belong to the private party user of the facility.

Work-For-Others (WFO)—WFO agreements accommodate proprietary work for a nonfederal party done by technically qualified government laboratory staff using laboratory facilities with full costs charged to the party. Title to intellectual property generally belongs to the party sponsoring the work. The government retains a nonexclusive royalty-free license to such intellectual property.

The Financial Assistance Process
DOE and OIT use a formal process to obtain industrial participation in R&D that supports its program mission, objectives and plans. The process of administering financial assistance begins with a formal solicitation or public announcement in which OIT describes its objectives or requirements to the business community. Several types of solicitation and public notice instruments are used by OIT to communicate information regarding its objectives, statement of work and the form of financial assistance award that it is considering.

Competitive Program Solicitations—

Most of OIT's funding for R&D is awarded through competitive program solicitations. A solicitation for financial assistance is used to request applications for DOE financial assistance awards. The solicitation may be in the form of a program rule or other publicly available document that invites submission of applications or proposals within a prescribed period of time. Proposals submitted in response to a competitive solicitation are evaluated with awards going to the most highly qualified offeror(s). Program sponsors issue competitive solicitations to involve private sector organizations in particular types of basic or applied R&D projects. Additionally, competitive solicitations covering multiple projects can be issued by more than one program office.

One form of competitive solicitation used by OIT to support private sector research is the **Research Opportunity Announcements (ROA)**. ROAs are summarized in the *Commerce Business Daily* and published in full text in the *Federal Register*. ROAs broadly define the OIT program's mission and research agenda and request proposals that offer meritorious approaches and solutions to OIT's research objectives.

Solicitations are also issued by OIT through the **Small Business Innovation Research (SBIR)** program. The purposes of SBIR are (1) to stimulate technological innovation, (2) to use small business to meet Federal R&D needs, (3) to encourage participation by minority and disadvantaged persons in R&D, and (4) to increase private sector commercialization of innovative R&D. Applications are accepted for competitive evaluation in response to a program solicitation issued once a year for the first phase of the three-phase program. Awards are made for an estimated 6-month project period in an amount not to exceed \$50,000. Phase I awardees are eligible to compete for Phase II funding, not to exceed \$500,000, for a 2-year project period to further develop

Figure 1-2
OIT Strategic Alliances

*Average industrial cost share is about 37%

their work. For the commercialization phase (Phase III) the small business must seek funding from outside the SBIR program.

Noncompetitive Financial

Assistance—When providing financial assistance, noncompetitive awards by OIT can occur as a result of the following:

- Unsolicited proposals or responses to Notice of Program Interest (NOPI).
- Eligibility that has been restricted by law or by regulation.
- The decision that only one recipient can be adequately responsive to the support and stimulation being provided by DOE.
- Broad solicitations for nonsimilar innovative responses.

An unsolicited proposal is a proposal for DOE financial assistance that is not submitted in response to a solicitation or that is submitted in response to an NOPI. An unsolicited application must propose an innovative idea, method or approach. An NOPI provides information about a particular DOE program interest in obtaining research applicable to general problem areas or program objectives. Applications submitted in response to an NOPI are evaluated as an unsolicited application.

An unsolicited proposal may be accepted by DOE if it:

- Demonstrates a unique and innovative idea, method or approach, or demonstrates a unique capability of the submitter;
- Is meritorious based on a general evaluation; and,
- Would not be eligible for financial assistance under a recent, current, or planned solicitation.

In the unsolicited proposal, the proposer must describe the objectives and pertinence of the proposed work to DOE, the rationale of the approach, the methods to be pursued, the qualifications of the investigators and the institution, if applicable, and the level of funding required to achieve the objectives. If accepted, an unsolicited proposal may result in an acquisition (contract) or a financial assistance (grant or cooperative agreement) award.

TRACKING THE PERFORMANCE AND BENEFITS OF THE OIT PROGRAM

For more than a decade, OIT has maintained a formal system to monitor and analyze RD&D projects that it has supported and that have been successfully commercialized. OIT's technology commercialization tracking system enables it to determine the market penetration of technologies it has funded and their impact on industrial energy efficiency and pollution prevention. On the basis of historical data on commercial use of OIT technologies, OIT has been very successful in facilitating the process by which federal research dollars are translated into useful technologies that benefit the U.S. economy and its industrial sector. Both industry and the nation have reaped many benefits from commercialized technologies that had their roots in OIT.

It must be emphasized that the national benefits of industrial energy efficiency R&D activities extend

beyond energy savings and waste reduction. Because energy efficiency is much less capital intensive than producing and distributing primary forms of energy, implementing efficient technologies increases the capital available for investment in other areas. Hence, OIT-supported technologies have directly improved the bottom line profitability and international competitiveness of the U.S. economy.

The results of OIT's most recent annual survey—conducted by the Pacific Northwest Laboratory—are shown in Table 1-2. The Pacific Northwest Laboratory's survey is based on telephone interviews with firms that have either bought or sold technologies and equipment that were spawned by the OIT program. The survey data indicate that 55 OIT-sponsored technologies have been implemented by the private sector. This

table reports the actual energy savings rate, the cumulative energy savings of each OIT-sponsored technology, and the type of fuel saved.

OIT Technologies Helped Reduce Industrial Energy Costs by about \$400 Million in 1993

As shown, technologies funded by OIT contributed to industrial energy savings of about 95 trillion Btu or about 0.1 quad in fiscal year 1993. At current energy price levels, this translates to an estimated energy cost savings of more than \$400 million. Hence, the value of industrial energy savings in one year alone appears to have been more than twice the total annual OIT program budget.

Table 1-2 also provides information on the cumulative energy savings of successfully commercialized OIT technologies. According to the survey, the cumulative energy savings from

Btu—The Currency of Energy

By definition, a British thermal unit (Btu) is the amount of energy needed to raise the temperature of one pound of water by 1°F. Btu are usually measured in units of million Btu (MBtu) or larger units. A quad is one quadrillion or 10^{15} Btu.

The amount of energy released in burning one match tip is about one Btu.

One 100-watt light bulb burning 8 hours a day for a year consumes about 996,300 Btu, or about 1 MBtu. (This does not include losses in generation and transmission which can increase this value by about a factor of three.)

A 30 mpg car driven 12,000 miles per year consumes about 400 gallons of gasoline each year with an energy content of about 50 MBtu.

A 2200 square foot house, on average, consumes about 113 MBtu of energy per year at a cost of \$1,340. When generation and transmission losses associated with the electricity portion of that energy are considered, the total energy required is 198 MBtu.

A million-ton-per-year integrated steel mill consumes about 24 trillion Btu (0.024 quads) per year; the steel industry as a whole uses about 1.7 quads per year, and together with aluminum and the other metals, all the metals industries use about 2.5 quads of energy (end-use) per year.

The combustion of 1 quad of coal in industry generates about 100 million tons of CO₂ (the principal global warming gas), while 1 quad of gasoline yields about 78 million tons of CO₂, and 1 quad of natural gas releases about 58 million tons of CO₂ to the atmosphere.

U.S. industry overall uses about 23 quads of energy (end-use) annually for heat, power and feedstocks at a cost of more than \$100 billion; hence, on average a quad of energy costs industry about \$4.4 billion and each quad of energy saved reduces industry's costs by more than \$4 billion.

The U.S. uses a total of about 84 quads annually (including electric power generation and distribution losses) at a cost (in 1990) of more than \$360 billion.

technologies supported by OIT is estimated at 520 trillion Btu—or about half of one quad. At current energy prices, this translates into an estimated cumulative energy cost savings of about \$2.2 billion.

But the benefits of OIT's R&D program go beyond energy savings, and the organization's survey helps quantify some of the other positive impacts of the program. Table 1-3 presents estimates of increased employment, increased capital productivity, and emissions reductions for commercialized OIT technologies. These data reveal that the manufacture, distribution, export, service and use of these technologies have contributed to an increase in employment of more than 16,000 man-years.

Technologies supported by OIT very often reduce or otherwise simplify the number of steps in a manufacturing process. By simplifying the manufacturing process, the cost of capital equipment for the new technology is often lowered in relation to the standard technology it is replacing. This, in turn, contributes to increased capital productivity. Calculations derived from OIT's survey data indicate that industry's increased capital productivity attributable to the OIT-supported technologies was about \$1.25 billion in 1993.

OIT Technologies Helped Reduce Industrial Emissions by More Than 7 Million Tons

In addition, reduced industrial emissions of harmful pollutants and

waste, and increased recycling and use of wastes as feedstocks are among the many environmental benefits of OIT technologies. OIT-supported technologies helped reduce industrial emissions of particulates, volatile organic compounds (VOCs), sulfur dioxide (SO₂) and nitrogen oxides (NO_x) by about 60,000 tons in 1993. These same technologies helped lower industrial generation of carbon dioxide (CO₂) by more than 7 million tons that year.

Although the data measuring the impacts of the OIT program are very illuminating, they do not reflect all the benefits of the program. For example, excluded are such indirect benefits of OIT research as the development of better analytical and design tools for

The NICE³ Program—Spurring Deployment of New Technologies

One of OIT's most successful programs is jointly sponsored with the U.S. Environmental Protection Agency (EPA). Known as National Industrial Competitiveness through Energy, Environment and Economics (or NICE³), it is an innovative, cost-sharing program to improve industrial energy efficiency, promote clean production, and enhance economic competitiveness in U.S. industries. The program provides grants to state/industry partnerships for projects that develop and demonstrate advances in energy efficiency and clean production technologies. The NICE³ program has an exceptional leveraging effect on industry. On average, for every dollar of OIT funding under NICE³, industry invests more than \$4 of its own funds in a NICE³ project.

The program goals are achieved through sponsored projects that:

- Demonstrate successful industrial applications of energy-efficient technologies that reduce costs to industry and prevent pollution;
- Identify and implement efficiency improvements in material inputs, processes, and waste streams;
- Develop strategies to overcome barriers that inhibit energy efficiency and waste minimization; and,

- Enhance U.S. industrial competitiveness by encouraging the use of cost-effective waste minimization and energy-efficient processes, equipment, and practices.

Industry applicants must submit project proposals through a state energy, pollution prevention, or business development office. Funds are awarded to state/industry partnerships that can match the OIT/EPA federal funds at least dollar for dollar. Awardees receive a one-time grant of up to \$400,000 for a proposed project. After the initial funding, the awardee is expected to commercialize the process or technology without federal support.

Successful NICE³ projects include the following:

- PPG Industries in Ohio has developed a system to recover and reuse paint wastewater. Waste and energy consumption is reduced by more than 90%, and payback on the investment is less than 1 year.
- AAP St. Marys in Ohio has introduced a more efficient technology for remelting the aluminum chips that result from machining cast aluminum automobile wheels. Energy consumption is reduced by 50%, waste is reduced by 90%, and simple payback is about 1.5 years.

- FMC in Texas has designed and implemented a steam distillation system to recover spent methanol in the production of hydrogen peroxide. Energy consumption is reduced by 50%, and waste is reduced by 66%, resulting in savings of more than \$350,000 per year.
- AMPCO Metal Manufacturing in Ohio modified the existing method of heating a continuously heated holding furnace (tundish) resulting in a reduction of 89% in energy use and more than 50% in waste, while paying back the investment in about 1 year.
- DuPont-Merck in New Jersey has demonstrated ultrasonic technology as a method to successfully clean storage tanks for the pharmaceutical industry. Compared to the typical solvent method for tank cleaning, ultrasonic technology has reduced energy consumption by 90% and reduced the use of toxic chemicals by 100%, while saving more than \$293,000 annually in operating expenses.

advanced industrial processes. Also inadvertently overlooked are the operating and maintenance costs and productivity benefits of successfully commercialized OIT technologies. In many instances, the non-energy operating cost reductions alone are sufficient to pay for these technologies.

Although the data provided in Tables 1-2 and 1-3 indicate the cumulative

benefits of OIT-supported technologies through 1993, the energy and non-energy benefits of these technologies will continue to accumulate in the future. Furthermore, these benefits are expected to increase sharply as several major new technologies currently being supported by OIT are commercialized.

Agenda 2020—The Forest and Paper Products Industry's Vision of the Future

Agenda 2020—the forest, wood and paper products industry's vision of the future—has advanced the furthest of the several industry visions in which OIT is involved. It is a technology road map developed by the industry to address ongoing manufacturing and environmental challenges confronting it and its customers. OIT is acting as a facilitator on behalf of the industry with a broad cross-section of other DOE organizations and federal agencies to help implement a coordinated research plan that helps leverage government R&D investment. The goals of the initiative include promoting industrial growth, energy efficiency and international competitiveness while preserving the environment.

While other industries have entered into partnerships with government before, this partnership adds a new feature: the entire forest products industry is unified behind one strategic technology plan. The industry's vision was led by a CEO-level working group headed by the Chairman of the American Forest and Paper Association and composed of CEOs representing the full range of industry products and interests. The CEO group impaneled and guided the efforts of a broad-based Chief Technology Officers' working group to refine and finalize the industry research agenda.

An Industry R&D Roadmap

The intention of the forest and paper industry vision document is to provide an overall direction for the entire industry's research and technology agenda as opposed to that of any single industry segment or company. It is a way of helping to improve the global competitiveness of the industry as a whole. The Agenda focuses on raw material, environmental, energy and

process areas of the industry and not on product research because the latter is deemed more appropriate for individual companies.

Agenda 2020 has identified six strategic priority areas for the forest and paper industry that will benefit from research:

- Sustainable forest management;
- Environmental performance;
- Energy performance;
- Improved capital effectiveness;
- Recycling;
- Sensors and controls.

Because of significant demands for capital to meet mandated environmental objectives, industry's R&D investments do not fully address its long-term needs. U.S. wood products, pulp and paper companies are currently not spending enough on R&D to remain competitive over the long-term

vis-a-vis their traditional competitors in Canada, Scandinavia and Japan as well as aggressive emerging nations such as Brazil, Chile and Indonesia.

Meeting Common Technology Needs through Partnership

Agenda 2020 is a device intended to help address this challenge. It has enabled the firms in the industry as well as those who supply it and others to identify their common technology needs—needs that no single company alone has sufficient financial and technical resources to meet. With attention to the high priority needs identified in Agenda 2020, the forest products and paper industry will continue to maintain its competitive advantage in the global market.

Agenda 2020 will help open the doors of advanced scientific knowhow throughout DOE and the rest of the federal government to help the forest and paper industry become the hallmark of sustainable development. The agenda will lay the foundation for a partnership between government funding agencies, research institutions, suppliers to the industry and the industry itself that can help accelerate the development and deployment of the needed technology. This partnership will enable the forest, wood and paper industry to create more jobs by making the industry cleaner and more cost efficient.

Photo courtesy of Ankers Photography

Department of Energy Secretary Hazel O'Leary, Senator Chuck Robb of Virginia, and James River Corporation CEO Robert Williams participated in the signing of Agenda 2020 in November 1994.

Table 1-2*Energy Savings of Commercialized OIT Technologies—FY 1993*

Technology	Current Energy Savings Rate (10 ¹² Btu/yr)	Cumulative Savings Through FY 1993 (10 ¹² Btu)	Type of Fuel Saved ^(a)
Beck Dyeing Modifications	*	120	NG
Biomass Grain Dryer	0.1	0.9	E,P
Boiler Workshops	*	42.2	F,NG
Catalytic Distillation	4.7	5.1	RG
Cement Particles Size Classification	2.2	7.4	E
Chemical Separation by Fluid Extraction	0.0	0.0	F
Cogeneration— Coal-Fired Steam Turbine	12.9	69.2	C
Cogeneration—Slow Speed Diesel	0.0	17.7	E,F
Coil-Coating Ovens	*	35.2	NG
Combination Grain Drying	*	7.3	P
Computer Controlled Oven	2.3	22.3	NG
Cupola Stack Air Injection	*	0.1	NG
Energy Analysis and Diagnostic Centers	8.6	74.4	E,F,NG
Energy-Efficient Canning	0.2	2.3	NG
Energy-Efficient Fertilizer Production (Pipe Cross Reactor)	*	2.6	NG
FBWHRS (Fluidized Bed Waste Heat Recovery System)	*	0.0	F,NG
Foam Processing	*	11.4	NG
High-Efficiency Weld Unit	2.9	10.8	E
HTBDR (High-Temperature Burner Duct Recuperator)—Bayonet Ceramic Tube	*	0.2	NG
HTBDR—Cruciform Ceramic Tube	*	0.0	NG
High-Temperature Ceramic Recuperator	1.3	20.6	F,NG
Humidity Sensor	0.0	0.0	NG
Hyperfiltration—Food	0.7	2.6	E
Hyperfiltration—Textiles	0.2	0.7	C
Improved Diesel Engines	48.5	97.1	F
Irrigation Systems	3.6	44.6	E,F,NG
Membrane Separation of Sweeteners	**	0.0	E,NG
Methanol Recovery Process	0.1	0.1	NG
Multi-Deck Board Dryer	*	0.8	NG
Nitrogen-Methanol Carburization	0.4	10.3	NG
Organic Rankine Cycle Bottoming Unit	*	0.5	E
PET Bottle Separator	*	1.2	Ch
Plating Waste Concentrator	0.7	1.5	F,NG
Recuperators (Metallic)	*	4.5	NG
Reverse Brayton Cycle Solvent Recovery	0.4	0.8	Ch,NG
Slot Forge Furnace Recuperator	1.2	9.8	F,NG
Solvent Recovery from Effluent Streams	0.3	0.3	Ch
Waste Atactic Polypropylene to Fuel	*	0.5	F,NG
Waste Energy Recovery at Honolulu, Hawaii	3.4	13.6	C
Totals	94.6	520.1	

*Precursor to a more advanced technology, **Data not available; (a) C=Coal, Ch=Feedstock Chemicals, E=Electricity, F=Fuel Oil, NG=Natural Gas, O=Other, P=Propane, RG=Refinery Gas

Source: Pacific Northwest Laboratory

Table 1-3
Other Impacts of Commercialized OIT Technologies—FY 1993

Technology	Increased Employment (Man-Years)	Increased Capital Productivity (\$ 10 ⁶)	Reduction in Pollutants (10 ³ Tons)				
			Particulates	VOCs	SO ₂	NO _x	CO ₂
Biomass Grain Dryer	31	2.7	<0.01	<0.01	0.00	0.06	4.52
Catalytic Reactor	51	(13.9)	<0.01	0.01	0.00	0.18	145.21
Cement Particle Size Classification	228	17.7	0.20	<0.01	0.74	0.28	68.34
Cogeneration—Coal-Fired Steam Turbine	526	23.0	4.64	0.03	16.13	6.13	1341.60
Cogeneration—Slow Speed Diesel	835	68.1	0.00	0.00	0.00	0.00	0.00
Computer Controlled Oven	27	2.3	<0.01	0.01	0.00	0.16	128.82
Energy, Analysis and Diagnostic Centers	2374	119.7	0.60	0.02	2.32	1.20	587.52
Energy-Efficient Canning	13	0.8	<0.01	<0.01	0.00	0.02	13.0
High-Efficiency Weld Unit	(79)	8.8	0.55	0.01	1.98	0.75	182.91
High-Temperature Ceramic Recuperator	436	37.5	<0.01	<0.01	0.05	0.09	88.37
Hyperfiltration—Food	161	11.7	0.15	<0.01	0.54	0.20	49.58
Hyperfiltration—Textiles	43	2.8	0.07	<0.01	0.24	0.09	19.76
Improved Diesel Engines	9927	800.1	0.24	0.05	3.88	3.40	3905.86
Irrigation Systems	656	105.4	0.25	0.01	0.96	0.50	243.44
Methanol Recovery Process	1	1.2	<0.01	<0.01	0.00	<0.01	2.26
Nitrogen-Methanol Carburization	527	17.9	<0.01	<0.01	0.00	0.03	24.86
Plating Waste Concentrator	26	4.4	<0.01	<0.01	0.02	0.04	39.05
Reverse Brayton Cycle Solvent Recovery	143	4.4	<0.01	4.65	0.01	0.02	17.13
Slot Forge Furnace	68	5.0	<0.01	<0.01	0.04	0.07	71.93
Solvent Recovery from Effluent Streams	183	3.1	<0.01	<0.01	0.02	0.01	15.30
Waste Energy Recovery at Honolulu, Hawaii	202	22.4	1.23	0.01	4.26	1.62	354.64
Totals	16,379	1245.1	7.93	4.80	31.19	14.85	7304.10

Source: Energetics, Inc.

OIT's Principal Customers: The Materials and Process Industries

OIT concentrates its RD&D programs on the most energy-intensive industries—those that separate and synthesize raw materials into useful materials and consumable food and fuel products. Collectively known as the materials and process industries, this group includes the chemical, metals, paper, petroleum refining, food processing, and ceramics and glass industries.

ENERGY USE IN THE MATERIALS AND PROCESS INDUSTRIES

Because they are large energy users, the materials and process industries are prime targets for improvements in energy efficiency. These industries account for 41% of all manufacturing shipments and 35% of value added by manufacturers, but nearly 90% of manufacturing energy usage (Figure 2-1). The development and application of improved technology and operating practices could have a substantial impact on the nearly 24 quads of primary energy consumed by these basic industries every year. To successfully apply technological advancements, however, the source and nature of energy consumption in these very diverse industries must first be understood.

Trends in Industrial Energy Use and Efficiency

The energy mix used by industry has changed considerably over the last two decades (Figure 2-2). The use of petroleum and natural gas by industry tends to fluctuate somewhat over time along with the availability and price of supplies, but remains within a stable range. Both have supplied between 30% and 40% of industry's energy demands for more than 30 years. It is worth noting that about half the petroleum products and 10% of the

Figure 2-1
Energy Consumption by Major Industry, 1991

Sources: EIA, *Manufacturing Consumption of Energy 1991*
EIA, *Monthly Energy Review*, October 1993

natural gas consumed by industry is used as feedstock to produce plastics, fertilizers, asphalts and similar materials rather than as heat and power.

Although use of petroleum products and natural gas has remained relatively steady over the last few decades, coal use has declined from supplying 26% of industrial energy needs in 1960 to about 12% currently. Over that same period, the use of electricity in industry doubled from 7% to 14% of the energy mix. This is partially because of the growth in fabrication and assembly industries that are more reliant on electricity for their energy needs than are the materials and process industries. The growth of electricity usage in industry has occurred despite the fact that it is considerably more expensive on a Btu basis than fossil fuel products. Among the many benefits electricity offers that help offset its higher cost compared to other forms of energy are its higher

efficiency at the point of application (less energy wasted), its cleanliness in an industrial environment, and its high degree of flexibility.

American industry has been a leader in making energy efficiency improvements. Between 1973 and 1989, the value of goods and services produced in the United States grew by 50%, but the amount of energy industry consumed actually declined by 6%. Although some of this decrease can be attributed to a shift away from energy-intensive industries, gains in energy efficiency have made a significant contribution. Studies have estimated that a little over half of all energy saved in industry since 1972 is attributed to efficiency gains, with the balance mostly because of compositional shifts in the U.S. manufacturing base.

Industry's dependence on energy is often measured by energy intensity, or the amount of energy used to

produce a unit of output (typically Btu of energy per dollar of output or contribution to gross domestic product [GDP]). Energy intensity has declined by nearly 25% since 1974, when the oil embargo and increasing energy prices started a downward trend in industrial energy consumption. However, since the fall in crude oil prices in 1986, industrial energy

consumption has risen slowly and energy intensity has remained relatively unchanged (Figure 2-3).

Sources and Uses of Energy in the Materials and Process Industries

The materials and process industries use a variety of energy sources to transform raw materials into

intermediate and finished industrial products—iron to steel, wood to paper, crude oil to plastics, sand to glass, etc. As shown in Figure 2-4, natural gas and petroleum products are the largest sources of energy for these industries. Many also make use of waste or byproduct fuels that are produced on-site, such as refinery gas, waste heat from blast furnaces, the byproducts of coke ovens, and wood waste. In the pulp and paper industry, for example, more than half of its energy requirements are met by waste fuels such as bark, wood chips, and black liquor, a byproduct of pulping.

Figure 2-2
Industrial Energy Consumption by Fuel, 1960–1992

Source: Annual Energy Review 1992, EIA

Figure 2-3
Industrial Energy Intensity, Consumption, and GDP, 1960–1992

Energy Intensity = Industrial energy use per dollar GDP

Sources: Annual Energy Review, 1992
Monthly Energy Review, October 1993, EIA

Figure 2-5 shows the principal functional uses of energy in the materials and process industries. Steam, produced in boilers and cogenerated, is the largest functional use of energy in the materials and process industries. It is particularly important in industries such as paper, food processing, and chemicals that deal largely with low temperature, organic materials. The heavy use of steam in these industries makes them particularly attractive for cogeneration systems.

Direct process heat, generated in furnaces, ovens, kilns, and similar vessels, represents the second largest use of energy in these industries. It is used for a diversity of processes that include fluid heating, metals treating, melting, smelting, forming, calcining, drying and curing. Though widely used in all the materials and process industries, direct process heat is especially important in the metal, ceramics and glass industries that work predominantly with high temperature, inorganic materials. Electricity for machine drives is the third largest use of energy, and includes power for motor drives in pumps, fans, compressors, and materials handling or processing equipment. Machine drives are an especially important use of energy in the fabrication and assembly industries. Other uses for energy include electrolytic processes (especially important in the aluminum industry), space heating, and lighting.

Large quantities of energy are also used as feedstocks in the chemical industry (petroleum, natural gas, etc.) and the steel industry where carburized coal (coke) is used as a reductant in iron blast furnaces. About half the petroleum products used in industry are consumed as feedstocks rather than fuels.

Energy Costs in Industry

Industry spent more than \$100 billion on energy in 1992, with the bulk of expenditures (about 95%) used to purchase electricity, petroleum products, and natural gas (Figure 2-6). The petroleum products used by industry are diverse and include residual and distillate fuel oil, gasoline, liquified petroleum gases (LPG), refinery gas, petroleum coke, asphalt, and many types of lubricants. About 5% of energy expenditures are used to purchase steam and metallurgical coal (used for coke production), which on a Btu basis account for about 9% of industrial energy use.

Although on an end-use Btu basis electric power accounts for only about 14% of industrial sector energy use, on a cost basis purchased electricity accounts for 44% of total energy costs in the industrial sector. Most of the electricity is used by industry to drive motors and machines. Somewhat surprisingly, however, high efficiency motor systems have not been a high priority in industry, yet there are indications this may be changing.

Although industry's total energy expenditures of about \$100 billion is a very large sum, it represents only about 3% of total costs. But, like energy usage, energy costs vary substantially throughout industry. Paralleling their role as the largest energy users in industry, the materials and process industries also have the largest energy costs. In most instances their total energy costs substantially exceed the 3% average for all industry (Figure 2-7). As the figure reveals, in such industries as steel, paper, and glass, energy costs exceed 10% of total

Figure 2-4

Energy Use by Fuel Type in the Materials and Process Industries

Note: 1988 is the latest year for which this data is available.

* For the petroleum industry, "other" includes all feedstocks and raw material inputs for the production of nonenergy products (asphalt, waxes, lubricants, and solvents) and feedstock consumption at adjoining petrochemical plants, regardless of type of energy. "Other" also includes net steam and energy other than from the sources listed that were used in the production of heat and power. Those inputs and feedstocks that were converted to other energy products (crude oil converted to residual and distillate fuel oils) are excluded.

Source: Manufacturing Consumption of Energy 1988, EIA

Figure 2-5

Energy Use by Function in the Materials and Process Industries

Source: Industrial Energy Efficiency, Office of Technology Assessment

costs. Moreover in those industries that produce nitrogen fertilizers, aluminum, cement and chloralkali, energy expenditures are greater than 20% of all costs. Such industries are constantly trying to find ways to use energy more efficiently regardless of the level of energy prices.

Because firms in the energy-intensive industries consume such large quantities of energy, they are usually able to purchase fuels and electricity in bulk quantities at discounts unavailable to firms in other industries or to individual consumers. Depending on demand and availability, quantity discount allowances can enable industrial firms to pay up to one-third to nearly one-half less for their energy supplies (on a Btu basis) than commercial and residential energy customers.

Energy prices are lower in the United States than in a number of other countries, especially our heavily industrialized international competitors. For example, Japan and Western Europe are more dependent on imported fuels than the United States, and sometimes they levy high taxes on energy sold in their countries to discourage consumption and encourage efficiency. This bestows a competitive advantage on large industrial energy users in the United States. Energy prices have a direct impact

on overall industrial energy consumption as well as the choice of fuels used. When energy prices are high, firms in energy-intensive industries aggressively seek energy conservation measures and switch fuels to lower their energy costs. When energy prices are low, as they have been for some time, the economic attractiveness of energy efficiency investments decreases relative to other corporate investments. Hence, in the current climate investments in industrial energy efficiency technologies typically also possess substantial productivity or environmental benefits as well.

Industrial Sector Energy Use Projections

DOE's Energy Information Administration (EIA) projects industrial sector end-use energy consumption to range between 29.8 quads and 32.9 quads in the year 2010. The corresponding average annual rates

of growth in industrial energy use are expected to range between 0.9% and 1.5%. Because the rate of growth in industrial energy use is expected to be lower than that of GDP, EIA forecasts industrial energy intensity to continue to decline over the next 15 years. Among the factors contributing to the expected continuing decline in industrial energy intensity include the following:

- the gradual restructuring of industry toward knowledge-intensive rather than materials-intensive products;
- higher capacity use because of improved computer controls and just-in-time manufacturing methods;
- process efficiency gains due to higher energy prices and efficiency standards.

Figure 2-7
Energy Purchases and Their Share of Production Costs by Industry, 1991

Note: Costs of purchased energy include electricity and fuels consumed for heat, power, and electricity generation. Production costs include purchased energy; materials, goods, parts, containers, scrap, and supplies for production, repair, or maintenance; contract work; bought and resold products; and labor (including wages, nonwage benefits, and social security and other legally required payments).

Source: 1991 Annual Survey of Manufacturers: Statistics for Industry Groups and Industries;
DOC December 1992

Figure 2-6
Industrial Energy Costs

Source: EIA, State Energy Price and Expenditure Report 1992

While the materials and process industries are intrinsically large consumers of energy, each has very different energy needs and potential target areas for energy efficiency improvements. The characteristics of energy use and sources of energy-intensity for each are based on specific product and process requirements as well as market considerations.

Petroleum Refining: This industry consumes the most energy of all the materials and process industries, mostly in the form of refinery gas, petroleum coke, fuel oil and LPG that are produced on-site. Nearly all steam requirements are met by boilers fired with refinery gases, and byproduct fuels provide about two-thirds of all heat and power requirements. About 80% of the products produced at refineries are fuels (gasoline, jet fuel, fuel oil), with the remainder comprised of LPG, petrochemical feedstocks, and miscellaneous lubricants and waxes. The most energy-intensive processes in refining involve separation and/or synthesis, e.g., distillation, catalytic cracking, catalytic reforming, catalytic hydrotreating, alkylation, and hydrogen production.

Chemicals: The chemical industry is the second largest energy-consuming materials and process industry and one of the most diverse, providing thousands of different finished and intermediate products for everything from plastics to pharmaceuticals to food additives to fertilizers. Most energy needs for heat and power in the chemical industry are met by natural gas and electricity. Natural gas, LPG, and refinery gas are also consumed in significant quantities as feedstocks. Natural gas is used to produce a number of important chemicals, including ammonia, hydrogen, methanol, and carbon black. LPG and refinery gas are used primarily in the production of petrochemicals

like ethylene, propylene, vinyl chloride, and others. A wide variety of processes are used to produce the many different products of the chemical industry, and many are energy-intensive separation and synthesis processes, e.g., distillation, polymerization, etc., which require large heat or power inputs. Some of the most energy-intensive products include industrial gases (nitrogen, oxygen, acetylene, carbon dioxide), alkalies (sodium hydroxide and other bases), inorganic chemicals (chlorine, sulfuric acid, aluminum, and potassium compounds) and nitrogenous fertilizers (ammonia, ammonia compounds, urea).

Primary Metals: The primary metals industries are the third largest energy consumer of this industry group. In steel-making the principal energy source is metallurgical coal that is used to produce coke, which performs both as fuel for melting iron ore and as a feedstock in the chemical reduction of iron ore to pig iron. Electricity comprises a smaller share and is used primarily in electric arc furnaces to melt scrap. Both physical and chemical separation and synthesis processes are used in steelmaking; the most energy intensive are those associated with blast, steel, heating, and annealing furnaces. Aluminum processes rely almost entirely on purchased electricity (nearly 90%); electricity also accounts for more than 25% of aluminum production costs. In aluminum production, the separation of aluminum from alumina in electrolytic cells is responsible for consuming the bulk of electrical energy.

Pulp and Paper: The paper industry is the fourth largest energy consumer of the materials and process industries, but meets more than 50% of its energy needs with self-generated and residue fuels like bark, hogged fuel, and black liquor—a byproduct of the pulping process. The pulp and paper industry also cogenerates

about 40% of its electricity from waste or byproduct fuels. Energy-intensive processes include pulping (kraft, sulfite, thermomechanical) and associated bleaching and chemical recovery processes. Papermaking is also an energy-intensive process, accounting for about 37% of the energy consumed in the pulp and paper industry.

Food Processing: Fifth in energy consumption, the food processing industry includes producers of meat, dairy, fruit, vegetables, grains, fats, beverages, and a variety of other edibles. Natural gas and electricity meet most of the energy requirements in food processing, primarily for separation processes. About half of the energy used in food processing is for direct heating; the remaining is used to generate process steam and hot water. Among the most energy-intensive food producers are wet corn millers, beet sugar processors, and malt beverage brewers. In general, processes that consume the most energy include concentration of food products from liquid streams, cooking, drying, and evaporation.

Stone, Clay and Glass: This group is the sixth largest consumer of energy and is comprised mostly of producers of cement, glass, brick, tile, ceramics, pottery, concrete, gypsum, and other stone products. Throughout these industries, natural gas is the primary energy source, and is used mostly to fire furnaces and kilns. The cement and gypsum industries are exceptions, using mostly coal to fire kilns. The largest energy consumer of this group is the cement industry, where energy makes up 25% of production costs. The most energy-intensive processes in cement-making are the kilns and associated processes used in clinker production. In glassmaking, the most energy-intensive processes are refining and melting.

Despite the expected continued decline in industrial sector energy intensity, EIA forecasts that the actual use of energy in industry will reverse its overall negative trend of the last two decades, as shown in Figure 2-8. EIA believes that industry's usage of energy will surpass its record consumption of 25.7 quads (end-use basis) set in 1979 by the year 2000 when consumption is forecast to reach 28.3 quads. EIA foresees a continuation in recent trends in the mix of fuel and energy types used by industry. The use of renewable forms of energy and electricity are expected to grow more rapidly than other sources of energy in industry while the growth in coke and coal usage will lag.

EIA's belief that the growth in industrial sector energy usage will again begin to turn positive—in contrast to the negative growth rate of -0.4% from 1980 to 1990—is consistent with other forecasts, as shown in Table 2-1. EIA's reference case forecast of 1.1% annual rate of growth in industrial sector energy consumption nearly equals that of the Gas Research Institute (GRI) at 1.3%, and exceeds those of Decision Resources Inc. (DRI) at 0.6% and Wharton Economic Forecasting Associates (WEFA) at 0.6%.

ECONOMIC SIGNIFICANCE OF THE MATERIALS AND PROCESS INDUSTRIES

Very Large But Growth Maturing

The energy-intensive materials and process industries are a huge and critical component of the economy. In 1992, they shipped a total of \$1.19 trillion worth of products. This included about \$404 billion in shipments by the food processing industry, \$306 billion by the chemical industry and \$150 billion by the petroleum refining industry. In 1992 the total value added by these industries amounted to \$492 billion, meaning they directly accounted for about 34% of all value added by manufacturing and more than 8% of all of U.S. economic output.

Despite their large size, the materials and process industries tend to be somewhat mature. Such industries as steel, petroleum refining, inorganic chemicals, paper and glass developed early in the evolution of the industrial economy. Evidence of the maturity of these industries is illustrated in Figure 2-9. Since 1980, only chemicals and pulp and paper have grown at rates faster than that of manufacturing as a whole, and none of the six major materials and process industries grew as fast as the overall GDP.

Still, most of these industries also possess selected high-growth segments. Pharmaceuticals, plastics and advanced materials in chemicals, steel minimills, fiberglass, and aluminum

foundries and semi-fabricated products are but a few examples of high-growth areas in the materials and process industries. The food processing industry, of course, is essentially a consumer goods industry that is constantly responding to changing tastes, and at any given time offers hundreds of products whose markets are either rapidly growing or contracting.

On the whole, however, the U.S. materials and process industries are cyclical industries whose long-term growth at best equals or more commonly is slightly less than that of the overall economy. The slow growth trajectories often translate into low price/earnings (P/E) ratios for the stocks of companies in these

Table 2-1

Forecast Growth in Industrial Sector Energy Demand, 1993-2010
(various sources; average annual percent growth)

Fuel	1983-1993	EIA (AEO '95)	DRI	GRI	WEFA
Petroleum	2.0	1.1	0.6	1.3	0.6
Natural gas	3.1	1.3	0.5	1.7	0.2
Coal	0.1	0.4	1.2	-1.0	0.8
Electricity	2.4	1.4	1.6	1.8	1.8
All energy	2.0	1.1	0.6	1.3	0.6

Figure 2-8

Trends in and EIA Projections of Industrial Sector Energy Use

Note: End-use energy basis

industries. Despite the lack of the glamour that often accompanies high-growth, high P/E industries, the materials and process industries underlie and support the entire manufacturing economy. The health, performance and competitiveness of these industries are tightly intertwined with those of the rest of U.S. manufacturing.

Huge and Well-Paying Employer, Especially Outside Major Metropolitan Areas

Commensurate with their large physical size, the materials and process industries are also a major source of jobs in the American economy. In 1992, total employment in the materials and process industries was about 4.2 million workers. This was

about 23% of U.S. manufacturing employment and nearly 5% of the nation's total non-farm, private sector employment.

Despite the huge size of the work force in the materials and process industries, total employment declined by about 720,000 workers between 1980 and 1992, a reduction of about 15%. The metals industries alone lost about 430,000 workers during the period, and by themselves accounted for much of the overall reduction in employment in the materials and process industries. Total job cutbacks in such industries as chemicals, pulp and paper, and food processing were proportionally much less pronounced as indicated in Figure 2-10. On the positive side, industry restructuring in response to foreign competition and recessionary cycles also resulted in increased productivity on the part of U.S. producers.

The contracting employment pool in the materials and process industries contrasts sharply with the growth of workers in wholesale and retail trade and other service occupations. For example, between 1980 and 1992, employment in wholesale/retail occupations increased about 24% (Figure 2-11). Unfortunately, wages in these jobs often average only about half of those in the materials and process industries.

Indeed, hourly wage rates in the materials and process industries typically exceed the average of all manufacturing by about 8% and the average service sector job's wages by 22%, as shown in Figure 2-12. In addition, during periods of strong economic growth, workers in these industries can often considerably boost their overall earnings with overtime pay. Moreover, health benefits are usually provided by the large corporations that account for most of the jobs in these industries. The hundreds of thousands of jobs lost in the materials and process industries over the past decade were some of the best-paying jobs in American industry. Inevitably,

Figure 2-9
Growth Trends in the Materials and Process Industries

Source: Various Census of Manufacturers and Annual Survey of Manufacturers; Economic Report of the President, February 1994

Figure 2-10
Employment Trends in the Materials and Process Industries

Source: Various Annual Survey of Manufacturers and Census of Manufacturers; Bureau of the Census

these job losses were an important contributor to the growing divergence between the high and low ends of the compensation scales of U.S. workers.

Another important attribute of the employment profile of the materials and process industries relates to the fact that they often locate relatively close to the natural resource industries whose raw materials they process. For example, petroleum refineries are often located on shipping and storage

routes used by oil producers. Pulp and paper plants are typically sited near large timber resources in the Northwest and Southeast. Several base metal smelters are situated in the Rocky Mountain and other mineral-rich districts.

The locational tendencies of many firms in the materials and process industries means that they are often especially important sources of earnings and employment outside large

metropolitan areas in rural and low-density population areas. Hence, when plants in these industries shut down, it is common for the local and regional economies to suffer extreme economic hardship including high unemployment. Some locales never recover when major plants in these industries close their doors.

Large Capital Intensity Means Big Multiplier Effect

Another compelling indicator of their role in the economy is the quantity of capital invested in the materials and process industries. Because of the huge size, throughput, and scale economies of these industries, they are among the most capital intensive of all manufacturing industries. Collectively, these industries accounted for about half of all new capital expenditures in manufacturing in 1992. Furthermore, with the exception of the food processing industry, all the materials and process industries exceeded the manufacturing average for capital expenditures as a percent of sales, as shown in Figure 2-13. These industries are also among the largest in terms of overall capital investment as measured by the value of gross stocks of fixed private capital.

The capital intensity of the materials and process industries has an important multiplier effect in creating jobs and wealth outside these industries. The Economic Policy Institute estimates that each job in the materials and process industries supports four workers employed in supplier, equipment, repair, finance, engineering, sales and even government occupations.

Around a Fifth of U.S. Merchandise Trade

The materials and process industries also play a huge role in our nation's trade picture. In 1991, when they employed 5% of U.S. workers and produced 8% of U.S. GDP, they also accounted for nearly 20% of our total merchandise trade, as shown in Figure 2-14. The huge role that trade in

Figure 2-11
Growth in Employment: Materials and Process Industries Compared to Other Industries

Sources: Statistical Abstract of the United States 1993 (Table #662); Various Annual Survey of Manufacturers 1980; Census of Manufacturers 1992

Figure 2-12
Wages in the Materials and Process Industries Compared to Other Industries

Source: 1992 Census of Manufacturers; Statistical Abstract of the United States 1993 (Table #662)

Food Processing: The food and beverage industry is the largest manufacturing industry in the United States with total shipments of \$404 billion in 1992. About 40% of industry shipments are higher value-added products such as microwavable packaged foods. Despite its huge size, between 1988 and 1992 the value of food and beverage sector shipments grew at an inflation-adjusted annual rate of only about 1%. Because of this trend, U.S. food and beverage companies are increasingly looking towards export markets for growth. The value of processed food exports was \$20.5 billion in 1993, while imports was \$16 billion. Exports of lower value-added goods (e.g., poultry, meat, butter and flour) have generally exceeded exports of higher value-added goods. In 1992 the food processing industry employed 1.5 million people. This represents a decline of 2.1% since 1980. The average hourly wage for workers in the food processing industry in 1992 was \$10.38, somewhat below the U.S. average manufacturing sector wage of \$11.94. Capital spending for the industry in 1992 amounted to \$9.9 billion while R&D spending was around \$1.4 billion.

The U.S. food processing industry is relatively mature, and the value of industry shipments is projected to rise about 1% a year over the next five years. The North American Free Trade Agreement (NAFTA) may benefit the U.S. industry as Mexico may become a major importer of U.S. food products. The industry will also be impacted by the General Agreement on Tariffs and Trade (GATT), which would allow U.S. food manufacturers to invest more easily in GATT-member nations.

Chemicals: U.S. chemical companies produce about 23% of the world's total chemical output with 1992 shipments valued at \$306 billion. In 1992, 850,000 people worked in the chemical industry with an average hourly wage rate of \$15.25, about 28% more than the U.S. manufacturing sector average. Chemical industry exports were valued at \$42.7 billion in 1993—surpassing all other U.S. industries. Its net trade balance in 1993 was \$15.5 billion. Chemical firms make large investments in new capacity to expand output, but they also continually upgrade and replace existing equipment to enhance competitiveness and comply

with environmental regulations. In 1992, the industry spent \$16.5 billion on new plants and equipment. Because of its emphasis on technology and new product development, the chemical industry is also very research-intensive. More than 80,000 scientists, engineers, and technicians are involved in chemical-related R&D. In 1992 more than \$16 billion was spent on R&D; this was about 5.5% of chemical industry sales and it exceeded the manufacturing sector average of 3%.

The U.S. chemical industry is expected to grow at a rate about 1.5% faster than GDP over the next five years. Despite this expected growth, the U.S. chemical industry will likely be heavily impacted by new environmental regulations. For example, the 1990 Clean Air Act Amendments set control standards for industrial sources of more than 40 pollutants to be met by 1995 and for 148 pollutants to be met by 2003. This means that the chemical industry will need to spend a much larger share of its plant and equipment budget on pollution abatement. Experts predict that pollution control may consume as much as 25% to 30% of the industry's fixed capital investment, up from 12% in 1993.

Primary Metals: The primary metals industrial group consists of iron and steel, non-ferrous metals (e.g., aluminum, copper, and lead) and foundries. Industry shipments for primary metals were valued at \$138 billion in 1992. Overall the industry employed 663,000 people in 1992, down about 40% from 1.1 million in 1980. The average wage for workers in the primary metals industries was \$14.71 per hour, significantly above the manufacturing sector average of \$11.94 per hour.

The value of steel industry shipments in 1992 was \$57.4 billion. Employment in both the steel products industry and iron and steel foundries is currently about half of what it was in 1980. Strong competitive pressures—both domestic and international—have forced U.S. steel producers to make investments in new technologies, close inefficient plants, and change management practices. Consequently, a leaner, more productive industry has emerged. Increased demand from the auto and construction industries helped boost capacity utilization and contributed to higher prices and profits. Steelmakers are increasingly

impacted by environmental regulations. The 1990 Clean Air Act, requiring reductions in toxic coke oven emissions, will likely force the shutdown of many facilities, although researchers are working on the development of new technologies that could assist the industry in meeting its mandated pollution targets.

The U.S. aluminum industry has also experienced a series of down years due to recessionary conditions. In addition, large exports from former Soviet Union countries have depressed prices. More favorable conditions prevailed in 1993, however, as shipments of ingots and semifabricated products increased to an estimated 8.2 million metric tons, an increase of 2.8% over 1992 levels. There was a trade deficit in aluminum in 1992, but the trade balance for aluminum semifabricated products was positive. Employment in the primary non-ferrous metals group, to which aluminum belongs, declined more than 40% between 1980 and 1992. While data on R&D expenditures for the aluminum industry are not available, researchers are developing new uses for aluminum and creating new materials such as metal matrix composites that are based on aluminum. Industry analysts forecast that aluminum shipments overall will likely increase at a compound annual rate of about 3% through 1998.

Pulp and Paper: The U.S. pulp and paper industry produces about 30% of the world's paper and paperboard. In 1993, 43.2 million tons of paperboard and 41.7 million tons of paper were produced at U.S. mills. In 1992, industry shipments were valued at \$133 billion—tenth among U.S. manufacturing industries. The paper industry is a small net importer with 1993 imports at \$10.9 billion and exports at \$9.5 billion. The principal supplier to the United States was Canada, which in 1992 was responsible for 76% of all imports. The industry is highly capital-intensive, and in 1992 capital expenditures were \$7.8 billion, about 7.5% of all capital spending in U.S. manufacturing. Environmental programs account for nearly 15% of total capital spending—more than capacity expansion spending. In 1992, the industry spent \$1.2 billion on R&D—about 0.9% of total sales, a relatively modest amount compared to most manufacturing industries. In 1992, *continued on page 29*

continued from page 28 >

there were 6,700 scientists and engineers involved in paper industry R&D, about 1% of total employment. As was the case for many other U.S. manufacturing industries, employment in the pulp and paper industry declined over the last decade. From a 1980 total of 645,000 workers, paper industry employment fell to 626,000 workers by 1992. Production workers earned an average of \$13.80 per hour in 1992 compared to the U.S. manufacturing average of \$11.94.

Shipments of paper products are expected to grow at an annual rate of more than 2% through 1998, and forecasters predict positive trade balances for the industry over the next few years. Despite overall growth in the industry, spending on capacity expansion will likely grow more slowly over the next few years as manufacturers comply with more stringent pollution control regulations. Environmental concerns may also have some positive effects on the industry, however. Paper and plastic often compete in packaging uses, and in the future the market may favor paper because it is often considered more environmentally benign than plastic.

Petroleum Refining: Estimated industry shipments by the petroleum refining industry were close to \$136 billion in 1992. Still, refined petroleum imports generally exceed exports, and in 1993 the U.S. imported about 930 thousand barrels of refined products per day more than it exported. Between 1980 and 1992 employment in the industry fell by 28%. On the other hand, productivity by refinery workers increased at a 2.5% per year rate from 1970 to 1992 while wages averaged \$19.72 per hour that year making petroleum refining the second highest-paying manufacturing industry. Environmental compliance has forced many refining companies to upgrade their facilities, which is part of the reason that capital spending for the petroleum refining industry was \$6.3 billion in 1992, up from \$3.8 billion in 1990. Such pressures caused 12 small refineries to close in 1992, contributing to a capacity reduction of 240,000 barrels a day. U.S. refiners also spent \$2.2 billion on R&D in 1991, the latest year for which data are available.

Demand for petroleum products is expected to grow at an average rate of 1.5% through 1998—a rate slightly less than that of the overall U.S. economy. Future regulatory changes will most likely force changes in the configuration of refineries and require heavy investment in downstream processes. According to the Commerce Department, more than 60 other small refineries are also at risk for closure because of the potential costs of complying with environmental regulations. Though larger refineries are expected to increase capacity, incremental additions by larger firms may not be enough to keep pace with petroleum demand. This gap will likely be filled by imports of petroleum products, which could increase by as much as 80% between 1993 and 1998.

Stone, Clay and Glass: Stone, clay and glass products are generally categorized as construction materials, which include glass, cement, ceramic tiles, gypsum products, and related materials. Industry shipments for these materials were valued at \$62.5 billion in 1992. Overall, the industry employed 470,000 people in 1992, down 23% from 1980. The average wage for workers was \$12.14 per hour, slightly higher than the manufacturing average.

The glass industry is made up of companies that make unfabricated glass and those that form glass into various products. In 1993, the value of shipments for flat glass was \$2.1 billion. About 57% of flat glass output is consumed by the construction industry, and the auto industry accounts for about 25%. In 1992, the flat glass industry employed an 11,900 people—down from 15,300 workers in 1982. The average hourly wage for these workers was \$16.80 in 1992, well above the manufacturing average. U.S. glass producers have expanded into foreign markets to increase market share. Exports in 1992 were \$723 million, while imports were \$485 million. Major markets include Canada, Mexico, and Japan. The industry is expected to continue to make advances in the development of two new technologies: switchable glass (in which opacity is changed by electronic and other means), and energy-saving low emissivity glass.

Both may experience strong demand growth in coming years. Producers will also focus on expanding market share abroad.

In 1992, the value of shipments for the cement industry was \$4 billion, and the industry employed 17,000 people, down from 19,100 workers in 1987. The average hourly wage for workers was \$15.08 in 1992, well above the manufacturing average. The United States is by far a net importer of Portland cement because of the sheer size of its market, limited domestic capacity, and prices that are higher than world prices. Exports in 1992 were \$49 million while imports were \$250 million. However, imports as a percent of U.S. consumption have been decreasing since 1987 and further declines are expected because of decreasing U.S. demand, trade (dumping) cases, and stronger world demand. Experts predict domestic consumption should rise 3% annually through 1999 in the absence of a large U.S. infrastructure and renewal program.

Table 2-2
Salient Economic Statistics for the Materials and Process Industries, 1992

Industry	SIC Code	Employees (Thousands)	Value Added (Billions)	Shipments (Billions)	Capital Expenditures (Millions)	Average Wages (\$/hour)	Production Hours (Millions)	Production Wages (Millions)
Food and Kindred Products	20	1504.8	\$2156.80	\$ 403.80	\$ 9932.80	\$10.38	2250.0	\$ 23,364.80
Paper and Allied Products	26	626.2	\$ 59.90	\$ 133.00	\$ 7813.90	\$13.80	1018.3	\$ 14,048.50
Chemicals and Allied Products	28	850.3	\$ 165.10	\$ 305.80	\$16,525.60	\$15.25	1007.7	\$ 15,368.00
Petroleum and Coal Products	29	114.4	\$ 23.80	\$ 150.00	\$ 6677.00	\$17.67	165.4	\$ 2922.40
Petroleum Refining	2911	74.8	\$ 19.10	\$ 136.30	\$ 6263.00	\$19.72	109.4	\$ 2157.40
Stone, Clay, and Glass Products	32	469.9	\$ 34.60	\$ 62.50	\$ 2467.00	\$12.14	743.6	\$ 9027.70
Flat Glass	321	11.9	\$ 1.30	\$ 2.10	\$ 148.20	\$16.80	20.5	\$ 344.50
Glass and Glassware	322	66.2	\$ 5.90	\$ 9.10	\$ 577.40	\$14.47	114.8	\$ 1660.70
Products of Purchased Glass	323	55.5	\$ 3.80	\$ 7.00	\$ 277.40	\$10.51	88.1	\$ 925.90
Mineral Wool	3296	19.2	\$ 1.90	\$ 3.20	\$ 115.10	\$14.75	32.5	\$ 479.30
Glass	Total	152.8	\$ 13.00	\$ 21.30	\$ 1118.10	\$13.33	255.9	\$ 3410.40
Primary Metal Industries	33	663.0	\$ 51.80	\$ 138.30	\$ 5368.20	\$14.71	1,067.9	\$ 15,707.30
Blast Furnaces and Steel Mills	3312	171.7	\$ 16.60	\$ 42.30	\$ 2217.30	\$18.94	278.8	\$ 5281.60
Steel Wire and Related Products	3315	25.1	\$ 1.80	\$ 4.30	\$ 126.60	\$11.98	41.1	\$ 492.40
Cold Finishing of Steel Shapes	3316	15.9	\$ 1.80	\$ 5.80	\$ 119.60	\$17.06	23.7	\$ 404.30
Steel Pipe and Tubes	3317	23.2	\$ 1.70	\$ 5.00	\$ 108.00	\$13.24	37.4	\$ 495.10
Steel	Total	235.9	\$ 21.90	\$ 57.40	\$ 2571.50	\$17.52	381.0	\$ 6673.40
Primary Aluminum	3334	19.8	\$ 1.50	\$ 5.90	\$ 215.10	\$18.06	31.1	\$ 561.70
Aluminum Sheet, Plate, and Foil	3353	24.4	\$ 3.20	\$ 10.60	\$ 418.30	\$17.98	39.9	\$ 717.40
Aluminum Extruded Products	3354	25.7	\$ 1.40	\$ 3.70	\$ 150.40	\$10.66	42.9	\$ 457.20
Aluminum Rolling and Drawing	3355	1.6	\$ 0.10	\$ 0.80	\$ 14.90	\$11.00	2.8	\$ 30.80
Aluminum	Total	71.5	\$ 6.20	\$ 21.00	\$ 798.70	\$15.14	116.7	\$ 1767.10
Iron and Steel Foundries	332	123.1	\$ 6.90	\$ 11.90	\$ 468.70	\$13.68	205.1	\$ 2805.10
Nonferrous Foundries	336	73.8	\$ 3.90	\$ 6.90	\$ 256.90	\$11.22	119.6	\$ 1342.00
Foundries	Total	196.9	\$ 10.80	\$ 18.80	\$ 725.60	\$12.77	324.7	\$ 4147.10
Materials and Process Industries	20, 26, 28-9, 32-3	4228.6	\$ 492.10	\$ 1193.30	\$48,784.50	\$12.86	6252.9	\$ 80,438.70
Manufacturing	20-39	18,253.3	\$ 1428.7	\$ 3006.3	\$103,656.2	\$11.94	23,590.7	\$ 281,737.2
Materials and Process Industries Percent of Manufacturing		23.17%	34.44%	39.69%	47.06%	107.72%	26.51%	28.55%

Source: 1992 Census of Manufacturers Preliminary Report Summary Series, issued October 1994; Bureau of the Census

commodities and products manufactured by the materials and process industries plays in our nation's total trade picture underscores the necessity that these industries maintain a high degree of competitiveness.

Some U.S. materials and process industries such as food processing, organic chemicals, pharmaceuticals, and pulp mills are considered among the most technologically advanced and competitive in the world. Large trade surpluses in such merchandise

as chemicals and food products contributed to total exports of about \$101 billion by the materials and process industries in 1993.

On the other hand, other industries such as steel and petroleum refining struggle intensely with foreign competition—despite extensive modernization and restructuring over the past decade. These industries are important contributors to our nation's overall trade deficit. Heavy reliance on foreign suppliers of refined oil

products and steel among many other items helped boost total imports of commodities produced by the materials and process industries to \$93 billion in 1993 (Figure 2-15).

Regardless of their current trade balance, however, the bottom line is that virtually all the materials and process industries face strong international competition. In some foreign countries, the large number of workers in these industries translates into strong political support and subsidies. In addition, the relative maturity of these industries and their often highly cyclical nature sometimes lead to worldwide overcapacity and depressed prices, as has been the recent case in the steel and petrochemical industries. The U.S. materials and process industries are also facing increasingly intense competition from resource-rich developing countries that want to add greater value to raw commodities such as oil, minerals, and lumber.

In addition to this competition, the materials and process industries are facing increasingly stringent environmental regulations. By the mid-1990s, amendments to the Clean Air Act of 1990 will require large capital investments at petroleum refineries, chemical plants, steel mills, and the electric

Figure 2-13
Capital Expenditures in the Materials and Process Industries

Source: 1992 Census of Manufacturers, Bureau of the Census

Figure 2-14
*U.S. Merchandise Trade in 1993:
Role of the Materials and Process Industries*

Source: Statistical Abstract of the United States 1994 (Table # 1332), Commerce Department

Figure 2-15
Trade Balance for Materials and Process Industries, 1993

Source: Statistical Abstract of the United States 1994 (Table # 1332), Commerce Department

utilities that supply fossil-based electricity to aluminum smelters. This is on top of already high levels of investment for pollution abatement and control in these industries. For example, the chemical industry spent \$7.2 billion for pollution abatement in 1992, about 44% of its total capital investment.

Research and Development Levels Considerably Below Average

Because of the large employment of the materials and process industries, the magnitude of international trade in their products, their contribution to GDP, and their critical linking role between the extractive and fabrication and assembly industries, it is essential that this sector of the economy remain highly competitive. Innovative technology to improve the energy efficiency, productivity and product quality of the materials and process industries is critical to maintaining their international competitiveness.

Unfortunately, R&D spending in these high wage, high employment, high multiplier industries—with the lone exception of the chemical industry—averages out to only about 1% of sales. This is fully two-thirds below the average of all manufacturing as indicated in Figure 2-16. Consistent with its innovation-and-growth culture, the chemical industry by contrast spends nearly twice as much on R&D as the average of all U.S. manufacturers. In general, however, the below average R&D spending by the materials and process industries is indicative of mature markets and mature technologies. In addition, the scale-economy nature of these industries translates into large capital requirements, long payback periods, high risk and conservative innovation strategies.

Yet continuous innovation and improvement are increasingly necessary for success in the competitive global economy. The characteristic tendencies of many firms involved in making and processing food products, fuels, and materials suggest a strong

need for joint participation among multiple companies and federal partners in collaborative research and technology development partnership.

INDUSTRIAL WASTE AND POLLUTION: THE ROLE OF THE MATERIALS AND PROCESS INDUSTRIES

Energy and Waste: The Connection

There is a strong relationship between energy use and waste production in manufacturing. As the guardian to the gateway of the manufacturing sector, the materials and process industries are responsible for separating useful constituents from those that are not useful in the raw materials produced by the extractive industries. The potentially useful substances are then recombined (or synthesized) into consumable foodstuffs, fuels and industrial materials (see Figures I-3 and I-4). Separation and synthesis of materials are intrinsically energy- and waste-intensive processes. Figure 2-17 shows that the six materials and

process industries—chemicals, pulp and paper, primary metals, petroleum, food, and stone, clay and glass—account for more than 95% of the waste generated in manufacturing.

With the exception of the petroleum refining industry, the materials and process industries show a close relationship between energy use and waste generation. Petroleum refining shows much higher energy consumption relative to waste because many of its waste products are consumed as energy. These industries also use processes that tend to require very large amounts of water. This greatly increases the weight and volume of their waste streams. For example, the pulp and paper industry—which shows high waste levels relative to energy consumption—generates huge amounts of wastewaters that may overstate the weight of their waste streams relative to other industries.

When industry generates waste, valuable energy is often wasted. This wasted energy is accounted for in the

Figure 2-16
R&D Expenditures in the Materials and Process Industries

*Estimated

Sources: Research and Development in Industry, 1992, National Science Foundation;
1992 Census of Manufacturers, Bureau of the Census

Figure 2-17*Waste Generation in the Materials and Process Industries*

Sources: *Manufacturing Consumption of Energy 1991*; EIA
National Biennial RCRA Hazardous Waste Report 1989; EPA
Report to Congress: Solid Waste Disposal in the United States; EPA 1988

embodied energy of unused or poorly used raw materials, in the energy content of waste streams, and in the energy required to manage and dispose of wastes. This is especially true for the energy-intensive materials and process industries, where waste generation and excessive energy consumption present opportunities for more efficient processes. When a process is inefficient, scarce energy resources are not being used effectively. When waste is created, materials, as well as energy, are not being used efficiently.

Because they are so closely linked, decreased energy use and waste reduction can be complementary goals. Promoting pollution prevention in industry through various means will reduce fuel consumption within industrial processes as well as the energy used to treat and dispose of wastes. To find potential targets in industry where both waste and energy reductions can be achieved, it is necessary to identify and quantify the major sources of waste, and how they are linked to the energy-intensive materials and process industries.

The Genesis of Industrial Waste

As industry transforms materials into useful products, numerous byproducts are created. When these byproducts have economic value, they are sold as secondary products or further transformed to create other useful

materials. Unfortunately, an enormous amount of industrial byproducts has little or no economic value and is discarded as waste.

The genesis of industrial waste perhaps can be best understood by considering the flow of materials through industrial systems. Each industry, company, or facility acquires input materials, transforms these materials into finished outputs, and discards useless byproducts (waste). Wastes can be calculated as the difference between the mass of all inputs and the mass of the useful outputs—a conceptually simple materials balance. With this perspective, waste reduction becomes synonymous with efficient materials use.

Large quantities of raw materials are needed to create most of the products we use and consume. Production inputs consist of primary raw materials, known as active inputs, and secondary materials, known as inactive inputs. Active inputs include the major ingredients needed for the final product—iron ore for steel, wood pulp for paper, etc. Inactive inputs include those such as water and air that are required for production but are a minor component of the finished product.

As products and materials move from the extractive industries through the materials and process industries to the fabrication and assembly industries,

more of the active inputs are used in the final product. Hence, in mining, for example, very large quantities of unwanted mineral impurities are discarded in isolating the desired elements. Often, 80% of the mass of the ores consist of undesirable constituents; 99% in the case of copper. In later production stages, such as in the transformation of iron to steel and in the subsequent forming of sheet metal for consumer products, smaller amounts of active inputs are discarded and less waste is generated.

Examples of the principal material balances for several major U.S. materials and process industries are shown in Figure 2-18. These balances, which were based on available production data, indicate that as much as 95% to as little as 11% of active inputs wind up in these industries' finished products.

Industrial Waste and Pollution: How Much and What Type?

Information on which to base estimates of the quantity of waste generated by industry is generally poor and must be pieced together from a variety of sources that have widely differing definitions of wastes. For example, agricultural byproducts that are returned to the soil may be viewed as a waste or a useful product. Differing reporting periods and methods of accounting for water content create additional problems. Because most wastes contain large quantities of water, some may argue that an entire stream is a waste while others may not consider the water component to be a waste. Conflicting definitions combined with the scarcity of reliable data create confusion over the magnitude of industrial wastes and the opportunities to reduce them.

Considering these substantial caveats, the best available estimates suggest that U.S. industry generates more than 14 billion tons of waste each year (Figure 2-19). These wastes include gaseous emissions, solid wastes, sludges, and huge amounts of wastewater. Most of the wastes

originate in the manufacturing sector which generates roughly 9 billion tons per year. The remaining industrial wastes—about 5 billion tons per year—come from coal and nonfuel mining, oil and gas extraction, and agriculture. This estimate is at best a rough approximation of the true extent of waste generation.

The following discussion of the principal types of industrial waste and pollution is based on data synthesized from a variety of data sources. It is focused primarily on the principal categories of waste and pollution as defined by various environmental statutes. These wastes include the major hazardous and nonhazardous waste streams of manufacturing, toxic

waste, greenhouse gases, other airborne pollutants and unclassified (i.e., exempt or nonmanufacturing) waste. The discussion provides a broad overview and introduction to the principal categories of waste and suggests ways that they might be interrelated from the standpoint of their various industrial sources.

It is important to bear in mind that this discussion is focused on the quantitative dimensions of industrial waste. But from a legal, human health, or cost perspective, the qualitative dimensions of a million tons of highly toxic waste in many respects far outweigh the quantitative significance of a billion tons of essentially inert nonhazardous waste.

Nonhazardous wastes make up the largest category of industrial wastes. Manufacturers generate an estimated 6.5 billion tons of nonhazardous waste per year. These wastes are defined as solid wastes by legislation, but have been estimated to contain roughly 70% water by weight. The data reported on nonhazardous wastes is derived from numerous sources, many of which are more than 10 years old. As a result, data for this waste type has the greatest degree of uncertainty and inconsistency.

Within manufacturing, more than 90% of the nonhazardous waste is produced by five industries: chemicals; primary metals; pulp and paper; stone, clay and glass; and food products (Figure 2-20). About 97% of this waste is disposed of in surface impoundments at the plant site where it was generated. Very little is known about the characteristics of these wastes except what has been studied within specific industries (such as the chemical and petroleum industries) that collect waste data through their respective industry trade organizations.

Hazardous wastes make up a smaller portion of the total industrial waste stream, but they represent a greater risk to the environment and human

The Critical Role of the Materials and Process Industries in Supporting National Defense

The materials and process industries not only provide the foundation of our nation's industrial base; they are also essential in supporting a secure national defense. If high-tech industries such as aerospace, transportation equipment, and microelectronics supply the muscle and central nervous system of our national defense, then the materials and process industries provide the backbone and lifeblood to support our nation's military needs. Tanks and all-terrain vehicles, missiles and bombs, small arms and ammunition, fighter aircraft and helicopters, nuclear submarines and aircraft carriers, radios, computers and communications systems, intelligence and logistical systems are all fashioned from materials and propelled by fuels manufactured by the materials and process industries.

Indeed, the materials and process industries are essential to national defense in two fundamental ways:

- On one hand, they convert raw materials into durable items like metal alloys and polymer composites that are used to make the weapons and supporting systems necessary to conduct successful combat operations;
- On the other hand, their products help sustain military operations anywhere in the world with such essential non-durable supplies as food, clothing and fuel.

A lengthy list of expert panels and reports have testified to the critical roles of the materials and process industries as suppliers to both the military directly and the industries that manufacture weapons and other military hardware. For example, the General Accounting Office (GAO) has identified more than 200 four-digit SIC

code industries as being defense-critical. These industries provide supplies and weapon systems to meet threats to the nation ranging from incidents of terrorism to full-scale global conflicts. According to GAO, in efforts to assess the viability of defense-critical industries, DOD has repeatedly identified the major materials and process industries including paper mills, various chemical products, petroleum refining, primary and fabricated metals and machinery.

As recent efforts to define defense-critical technologies have become more refined—and focused on computers, microelectronics, advanced propulsion systems and sensors—DOD has continued to emphasize materials and manufacturing as critical areas. For example, in DOD's influential Defense Critical Technologies Plan, 21 critical technologies were identified and classified into five clusters, including materials and manufacturing. The materials and manufacturing cluster includes composite materials, high-energy density materials, and flexible manufacturing.

Further evidence of the national defense significance of the materials and process industries comes from the National Critical Technologies Panel that was authorized by the Defense Authorization Act of 1990. The panel identified 22 technologies as critical to national economic prosperity and to national security. Materials synthesis and processing were prominently identified on the list because the panel felt that they are fundamental to the technological progress of many key industries including microelectronics, aerospace, transportation, and energy.

Chemicals: The chemical industry produces more than 2 billion tons of waste each year. It is a major waste generator in every media and is the major source of hazardous waste in industry, accounting for 91% of these wastes in 1989.

Chemicals, which are used by nearly every industry and are found in many consumer products, contribute to waste streams throughout manufacturing. While the industry is dominated by about a dozen large, integrated companies, it also includes thousands of smaller chemical companies, creating a large and diverse waste profile. The vast majority of wastes are generated by a few sub-industries: plastic materials and resins, cyclic crudes and intermediates, and other industrial organic chemicals. Most of the chemical industry's waste is process wastewater, both hazardous and nonhazardous. The industry also faces major challenges to reduce various air pollutants, particularly VOCs and oxides of sulfur and nitrogen. The chemical industry spends the most for pollution abatement and control—\$6.5 billion in 1992. However, because of its economic vitality, this industry is less burdened by these costs than other industries (about 3.5% of value added).

Because this industry produces such significant waste streams, investments in pollution prevention R&D within the chemical industry could yield very large environmental and economic benefits. To meet the waste challenge, many large chemical companies have pioneered advances in pollution prevention technologies. Shifts to aqueous-based cleaners, solvent recycling technologies, and better operating practices are some of the steps that have helped to reduce wastes in chemical manufacture and use. Advanced separation technologies are viewed as having the greatest potential for reducing large waste streams economically.

Pulp and Paper: The pulp and paper industry is the largest waste generator in manufacturing. Most of these wastes—

2.3 billion tons—are nonhazardous. The industry accounts for less than 10% of hazardous, toxic, air and greenhouse gas wastes in manufacturing. Solid wastes from the pulp and paper industry are generally nonhazardous wastewaters that are low in metal content. Major waste streams include bark and wood wastes, spent pulping chemicals, and wastewater treatment sludges. Water-borne pollution is a major concern of the industry, especially controlling the formation of dioxin at kraft pulp mills. The pulp and paper industry recycles large amounts of wastepaper, recovering an estimated 36% of wastepaper in 1992. This industry also uses a part of its waste stream as boiler fuel, such as wood wastes and pulping liquor. Pollution abatement and control costs for pulp mills are relatively high, representing 17% of capital expenditures and 12% of value added.

Petroleum: The American Petroleum Institute estimates petroleum refining wastes to be about 16 million tons per year—about one-tenth of EPA's estimate. The petroleum refining industry produces relatively little solid waste. Roughly three-fourths of solid waste from refining is aqueous wastes, with the remainder consisting of contaminated soils, oily sludges, spent catalysts, and chemicals and inorganic wastes. Major pollutants include air emissions (sulfur oxides, nitrous oxides, and carbon monoxide), heavy metals, VOCs, toxic air emissions, spent solvents and catalysts, and naturally occurring radioactive materials. The biggest waste challenge faced by petroleum refiners is controlling air-borne emissions of key pollutants. This is reflected in the very high expenditures for pollution abatement and control—\$5.3 billion in 1992. This represents more than 15% of the value added for this industry (compared to 1.7% for all manufacturing). Implementation of the Clean Air Act Amendments of 1990 is expected to create additional costs and technical challenges for refiners.

Primary Metals: Waste streams from the metals industry include a diverse collection of solid, liquid, and gaseous byproducts. Steelmaking and iron blast furnaces produce slag, iron oxide scale, coke breeze, waste pickle liquor, and a variety of sludges and dust. Foundries and metal casting operations also produce large amounts of waste sand that contain metal constituents. Many types of iron wastes are recovered and recycled throughout the iron and steelmaking process. Other wastes include toxic air emissions from coke ovens and wastewater sludges.

The production of non-ferrous metals, including aluminum, copper and zinc, generates a variety of solid wastes. The major source of wastes in aluminum production are in potliners, scrap furnace brick, black and white mud from potliner reprocessing, and various sludges. Copper production results in significant furnace slag and miscellaneous slurries. Zinc production yields kiln residue from smelters and clinker waste from zinc oxide plants.

Stone, Clay, and Glass: The major wastes in these industries are inorganic, nonhazardous byproducts, mostly in the form of fines and dust of the primary product. Because these industries produce little or no hazardous and toxic wastes, pollution abatement and control costs are average for manufacturing. Most of the wastes produced include substances found in the feed material, such as silica, soda ash, lime, clay, and stone and cement dust. One of the largest sources of solid waste is cement kiln dust. These wastes are currently exempt from hazardous waste regulations pending further study by EPA. Because of the high heat produced, cement kilns burn some hazardous (e.g., solvents and waste oils) and nonhazardous wastes as secondary fuel (about 15% of Btu needs are from wastes). Combustion of these hazardous substances has created concern regarding the characteristics of cement kiln dust.

Figure 2-18
Material Flows for Several Industrial Processes

MMT = Million Short Tons

Note: Data not available for all processes.

Source: Use of Materials Balances to Estimate Aggregate Waste Generation and Waste Reduction Potential in the United States; Robert Ayres, and Leslie Ayres

Figure 2-19
Industrial Waste Categories

Sources: Manufacturing Consumption of Energy, 1991, EIA
National Biennial RCRA Hazardous Waste Report, 1989, EPA
Report to Congress: Solid Waste Disposal in the United States, 1988, EPA

health and are therefore more closely regulated. Hazardous waste is characterized as having toxic, corrosive, reactive, or ignitable properties. In addition, mixtures containing specific (listed) substances are considered hazardous. According to EPA, in 1989 about 193 million tons of hazardous solid waste were managed in treatment, storage, and disposal facilities regulated under the Resource Conservation and Recovery Act (RCRA). Although data collection covered 20,732 sites throughout the United States, many hazardous wastes are managed outside the scope of the RCRA permitting system. Analysis of the hazardous waste data for 1987 indicates that the reported wastes represent only about 40% of the total estimated hazardous waste stream in industry. This suggests that all of industry generated close to 500 million tons of hazardous waste in 1989.

Much of the hazardous waste generated in the United States is concentrated in a small number of large manufacturing complexes. Of the 20,732 sites covered in the 1989 RCRA report, 60 sites (less than 0.5%) accounted for 93% of all wastes. Of these sites, 40 are in the chemical industry, which accounts for 91% of hazardous waste generation in manufacturing. Other industries that contain large hazardous waste generators are petroleum refining, electronic and electric equipment, fabricated metal products, and primary metals. More than 90% of the weight of hazardous wastes are wastewaters.

Toxic waste emissions from manufacturing are of special interest because of their potentially severe impact on the health of workers, local communities, and the environment. In 1991, U.S. companies released and transferred 3.2 million tons of toxic wastes (Figure 2-21). The chemical industry was responsible for the largest portion of these wastes, followed by primary metals and the petroleum refining industries. Together these three industries account for nearly two-thirds of

the total toxic waste stream. Topping the list of toxics was ammonium sulfate, which is often used as an agricultural fertilizer and is also a co-product of some chemical processes and a byproduct of steel coke ovens. Other major toxics included widely used commodity acids (e.g., sulfuric, hydrochloric) and commonly used solvents and chemical building blocks (e.g., methanol, toluene, acetone, xylene, trichloroethane, etc.).

Greenhouse gases comprise a group of gaseous wastes that are associated with global climate change. Major contributors include carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs). Carbon dioxide, the largest source of greenhouse gases, is produced by fossil fuel combustion and certain industrial processes (including cement manufacture, lime manufacture, limestone in steelmaking, carbon dioxide manufacture, soda ash manufacture and use, and aluminum production). In 1991, an estimated 2.3 billion tons of CO₂ was emitted by industry. Industrial methane emissions, which result from agricultural activities and energy production and use, were estimated at 18 million tons in 1991. Although significant uncertainty still remains about the magnitude of future climate change from greenhouse gases, the potential effects of sustained temperature rises (e.g., rising sea levels, availability of water, etc.) continue to be a cause for concern and study.

In addition, industry manufactures all of the CFCs in use and emits some waste CFCs. CFCs are associated with the depletion of the stratospheric ozone layer, which normally filters the ultraviolet radiation that can be harmful to human health and the environment. Although CFCs remain in wide use, international agreements have already been adopted to control and eventually phase out the use of harmful CFCs entirely over the next 10 years.

Figure 2-20

Industrial Hazardous and Nonhazardous Wastes by Industry

Sources: National Biennial RCRA Hazardous Waste Report, 1989, EPA
Report to Congress: Solid Waste Disposal in the United States, 1988, EPA

Figure 2-21

Industrial Toxic Wastes by Industry

Source: 1991 Toxic Release Inventory, EPA May 1993

Airborne pollutants are gaseous byproducts of fossil fuel combustion and other industrial activities. Several of these pollutants—particulates, SO_x, NO_x, VOCs, and CO—contribute to poor urban air quality and regional air problems like acid rain. EPA has estimated that industrial sources account for more than 40% of all reactive VOC emissions, about 15% of SO_x emissions, and about 3% of NO_x emissions in the United States.

Elevated levels of these pollutants can lead to a variety of adverse health effects, and have also been blamed for reduced crop yields and stunted forest growth. Ozone, for example, produced through chemical reactions that involve both NO_x and VOCs, is a major component of smog. Acidic deposition, or acid rain, occurs when pollutants (primarily SO_x, NO_x, and VOCs) form acidic compounds in the atmosphere and are later deposited on the earth by

Figure 2-22*Air Emissions from the Materials and Process Industries*

Source: National Air Pollution Estimates 1990-1991, EPA October 1992

Figure 2-23*Nonmanufacturing Wastes*

Source: Energetics

rain, snow, or fog. The detrimental effects of these acidic compounds on aquatic systems, forests, and human health are of major concern to the public. In 1990, air emissions from the manufacturing industries reached more than 10 million tons (Figure 2-22). The highest producers of airborne pollutants are the chemical, petroleum refining, primary metals, pulp and paper, and stone, clay and glass industries.

Exempt wastes (as classified by RCRA) include those originating in mining and agriculture. Though the quantities of these wastes are significant, they are classified as exempt wastes because the task of defining

what constitutes waste is not always straightforward. For example, some have argued that removing and replacing overburden in mining or plowing under dried corn stalks in farming should not be considered part of the industrial waste stream. Mining wastes considered for this report include wastes from oil and gas extraction and production, metal mining, and nonmetallic minerals (except fuels); coal mining wastes are not included. Agricultural wastes consist mainly of feedlot wastes and crop wastes. EPA estimates the upper limit of agricultural wastes at one billion gallons per day, which translates to 1.5 billion tons per year (Figure

2-23). Overall, nonmanufacturing wastes represent about 40% of the total industrial solid waste stream.

Costs of Waste Management and Pollution Control

The Department of Commerce estimates that all of American industry—including manufacturing, electric utilities, mining, and a variety of service and nonmanufacturing industries—spent \$53 billion for waste management and pollution control in 1992. These costs represent direct outlays for equipment purchases, operations, and maintenance but do not include a wide variety of indirect costs associated with waste management as described below.

Manufacturing sector pollution abatement operating cost/capital expenditure data are collected by the Census Bureau in a survey of companies. Preliminary estimates indicate that manufacturers spent roughly \$27 billion on pollution control equipment and operations in 1992—about 1% of the total value of all manufacturing shipments (Figure 2-24). However, pollution control costs do not fall evenly among industries. Five materials and process industries account for about 70% of total costs.

Several measures can be used to assess effects that pollution control costs have on U.S. competitiveness. One approach is to consider pollution control costs as a portion of sales and value added. On average, manufacturers spend 0.8% of sales and 1.72% of value added on pollution control expenditures. However, once again, the average is misleading because of the great variance of these expenditures among industries. For example, the petroleum refining industry spends much more than this average—2.25% of sales and 15.4% of value added—on pollution control. Other materials and process industries that spend more than the average include pulp mills, blast furnaces, inorganic chemicals, chemicals, and primary metals.

Another, even more compelling indication of the impact of pollution control costs on U.S. competitiveness is the portion of capital expenditures that is allocated to this activity. In 1991, 7.9% of all capital expenditures by manufacturers were for pollution control equipment. However, once more the average is misleading. Four materials and process industries—petroleum refining, chemicals, metals and paper—allocated on the average about 15% of their total capital expenditures to pollution control. U.S. petroleum refiners spent over 25% of their capital on pollution control. In contrast, most fabrication and assembly industries including those such as textiles, automobiles, and machinery devoted only about 2% or 3% of their capital expenditures to pollution control (Figure 2-25).

In addition, the Congressional Office of Technology Assessment believes that manufacturers' pollution abatement expenditures may be substantially under-reported. OTA has indicated that such factors as interest expenditures, productivity losses, product quality degradation, indirect labor costs, legal fees, liability costs, indirect material and energy costs, interest expenses, research and development costs, and opportunity costs of alternative investments are all under-reported in calculating actual pollution control costs. For estimation purposes, OTA suggests a rough figure of 25% underestimation. Using this factor, actual pollution control expenditures for manufacturing may amount to about \$30 billion per year—further exacerbating the negative impact of pollution control expenditures on the competitiveness of U.S. industries, especially the materials and process industries.

Moreover, U.S. firms spend more than their international rivals on pollution control. From 1974 to 1990, U.S. companies spent between 0.8 and 0.95% of GDP on pollution control while other OECD countries spent considerably less. The comparable estimates ranged from about 0.3% for France to 0.8%

for Germany. Though differences in how countries account for pollution control costs detract from the reliability of these data, the available evidence indicates that the United States spends more than Japan, Germany, the Netherlands, and other leading environmentally active countries in the portion of capital expenditures that are used for pollution control equipment.

A final perspective on these costs considers the amount spent on pollution abatement and control compared to other corporate costs. Pollution

control expenditures are about half of what industry spends on all corporate R&D and is equal to what they spend on all employee training. To the extent that pollution control diverts money from these other important activities, the competitive disadvantage is further intensified.

Figure 2-24

Pollution Abatement Costs and Expenditures, 1973–1992

Source: Pollution Abatement Costs and Expenditures, 1992, DOC March 1994

Figure 2-25

Pollution Control Expenditure Ratios, 1991

Sources: Pollution Abatement Costs and Expenditures 1991, DOC Annual Survey of Manufacturers 1991, DOC

The Chemical Industry

TURNING TECHNOLOGY TO ADVANTAGE IN A KEYSTONE U.S. INDUSTRY

The U.S. chemical industry is exceptionally large, complex and diverse. In 1992 its total shipments were valued at \$306 billion and it employed 850,000 workers. It produces more than 60,000 different products ranging from basic organic and inorganic commodity chemicals such as ethylene and sulfuric acid to mass-market consumer goods such as drugs, detergents and paints. The preponderance of its products, however, are inputs to other manufacturing industries as well as agriculture and mining. Export markets are also a significant outlet for chemical industry products, accounting for about 14% of total industry sales (Figure 3-1).

Chemical industry products improve the productivity and quality of goods produced by other industries. For example, fertilizers produced in the chemical industry enable U.S. farmers to be the most productive in the world. Steel industry basic oxygen furnaces are dependent on oxygen supplied by the chemical industry. Paints and plating compounds made in the chemical industry protect all kinds of metallic structures from autos to bridges and extend their useful lifetimes. Because of its basic, keystone role as a supplier to so many manufacturing and other industries, the performance and competitiveness of the chemical industry are both dependent on and contribute to the performance and competitiveness of the rest of the industrial economy.

Table 3-1
*Chemical Industry Profile**

Value of Shipments	\$306 billion
Total Employment	850,000 jobs
Capital Expenditures	\$16.5 billion
Net Trade Balance	\$15.5 billion
Energy Consumption	5.05 quadrillion Btu
Waste Generation	1.84 billion tons
Average Hourly Earnings	\$15.25

*Data for latest year available

The chemical industry is simultaneously a traditional smokestack industry and a high-tech industry. It possesses both high growth and mature industry segments. It is one of the largest energy-consuming and waste-generating industries while simultaneously it houses the knowledge- and technology-intensive pharmaceutical industry and much of the fledgling biotech and advanced materials industries.

Industry's Success Based Largely on R&D and Innovation

A key to the success of the U.S. chemical industry—and a feature that largely distinguishes it from other materials and process industries—has been its traditionally large R&D funding and its strong propensity to innovate. It was one of the first industries to support company-owned research labs, and more than 80,000 scientists, engineers, and technicians are employed in chemical-related R&D. In 1992 more than \$16 billion was spent on R&D, an amount equal to about 5.5% of total chemical industry sales. This compared to a manufacturing sector average of 3%. Only the transportation equipment industry group—including both the auto and aerospace industries—had higher R&D expenditures.

Figure 3-1
U.S. Chemical Industry Markets, 1993

Source: Chemical Manufacturers Association

One particularly successful class of products that in many respects exemplifies the technology-based culture of the chemical industry is plastics. Through the development and application of complex synthesis and processing methods, chemical industry technologists have been able to create hundreds of different plastic materials. Typically, synthetic polymer materials can be produced at competitive costs with properties that are comparable or even superior to such traditional materials as steel, paper, wood, and glass. Such favorable qualities combined with aggressive marketing have propelled the U.S. plastics market at greater than a 6% annual rate of growth for well over a decade.

The chemical industry's proficiency in innovative technologies and products such as polymer materials has contributed much to its huge success in the global market. The chemical industry is the largest exporting industry in the U.S. economy with 1993 exports valued at \$42.7 billion. Its trade balance (exports minus imports) in

Because of the complexity of the chemical industry, it is difficult to characterize its principal technologies and processes in a simple yet meaningful manner. But in the broadest sense, chemical industry manufacturing processes convert starting materials (feedstocks) into products, byproducts, and their associated wastes. Most chemical manufacturing processes fall into one of two major categories: unit processes or unit operations. In addition, process controls are widely employed in the industry and are integral components of most chemical manufacturing processes.

Traditional chemical engineering has taught two views of a chemical process. First, each process consists of one or more unit processes such as nitration, oxidation, pyrolysis, amination, epoxidation, chlorination, or electrolysis. Management of the chemistry of unit processes typically involves modeling and analysis of reaction kinetics and thermodynamics.

Second, each process requires one or more unit operations such as distillation, absorption, extraction, evaporation, centrifugation, filtration, heat transfer or pumping. Management of the heat and mass transfer aspects of unit operations typically involve equipment systems and the modeling and analysis of transport properties and thermodynamics.

Process control refers to the systematic collection and integration of information about a chemical process, and the use of that information to adjust the process. Many chemical industry processes are virtually fully automated—operator intervention is needed only in the event of extreme process variability or malfunction. Improved controls enhance efficiency by stimulating adjustments to the process that reduce variability between actual operating conditions and design specifications. Sensors are an essential part of control systems. They detect changes in variables such as temperature, pressure, flow, density, viscosity, chemical composition and moisture content that trigger appropriate process adjustments.

1993 was \$15.5 billion. Because of the large value of chemical exports, the industry plays an especially critical role in the nation's overall trade picture. It is essential that the industry retain its traditionally strong competitive stance at the risk of severely aggravating our country's chronic and disturbing trade deficit.

Is Chemical Innovation Slowing?

Still, there are growing concerns about the ability of the industry to sustain its traditional commitment to R&D as a mechanism for maintaining its above average growth and competitive edge. As the chemical industry has diversified into such high-tech fields as pharmaceuticals, biotechnology, and advanced materials, its R&D focus has shifted increasingly toward new product development and away from more fundamental breakthroughs. Chemical companies are investing more heavily in product line extensions, upgrades and technical service at the expense of their historical commitment to new chemistry and novel processes. Central research laboratories are refocusing on near-term goals, being downsized, or even eliminated.

In addition, an ever-lengthening and more costly litany of environmental regulations is threatening the competitiveness of the chemical industry as they require an increasingly large share of the chemical industry's available investment capital. For example, the 1990 Clean Air Act Amendments set standards for industrial sources of more than 40 pollutants that must be met by 1995 and for 148 pollutants that must be met by 2003. The risk of such regulations inhibits the chemical industry's traditional drive to develop new materials and other products that underlie its growth and contribute to its competitiveness. Moreover, experts predict that in the near future, such measures will force the industry to spend a much larger share of its investment capital—as much as 25% to 30%—on pollution activities.

Continued growth and international competitiveness of the chemical industry depend on continued increases in productivity stemming in large measure from R&D and upgrading plants and equipment. But environmental regulations that discourage new investment in R&D and in more efficient, competitive and environmentally friendly manufacturing processes and facilities could lower the U.S. industry's competitiveness and its long-term growth.

THE MANUFACTURING PROCESS: E PLURIBUS PLURIBUS

In comparison to other materials and process industries such as steel, paper and petroleum refining, the chemical industry relies on a wider range of raw material inputs to make a much longer list of products. Whereas the steel, paper and petroleum refining industries may each produce several hundred different products, the chemical industry makes as many as 60,000 different products. Inevitably, with wider ranges of raw material inputs and product outputs, chemical manufacturing processes are considerably more complex than those of most other materials and process industries.

Figure 3-2 provides one perspective about how the principal components of the chemical industry relate to one another. As shown, the industry's raw materials are supplied by agriculture, fossil fuel extraction and mining. These raw materials are processed into basic and intermediate chemicals that become the basic building blocks for a broad range of chemical additives and functional chemical products. For example, the organic chemical ethylene—the building block for polyethylene—is used in the production of several intermediate chemicals that are then processed further. Other chemical elements and chemical compounds, such as chlorine and oxygen, are often incorporated in or used to facilitate the manufacture of these chemicals (Figure 3-3).

Organic chemicals are mainly petrochemicals (i.e., produced from oil or other fossil fuel feedstocks) and by definition contain carbon atoms. Like other basic chemicals, basic organic chemicals are large volume commodities that typically sell at low prices. Products made from organic compounds are found in almost every

kind of manufactured good. Organic compounds include (among others) ethylene which is used largely to manufacture polyethylene plastics, benzene (used to make styrene) and toluene which is consumed largely to refine gasoline to boost octane levels.

Benzene, ethylene, xylene and other basic organic chemicals are also synthesized in various combinations to produce other organic chemicals that are slightly more complex and specialized. These are called intermediate chemicals because they usually require further processing into new compounds before they can achieve their full functionality. A few of the larger volume intermediate organic chemicals include ethylene dichloride, ethylbenzene, methanol and vinyl chloride.

Inorganic chemicals are typically recovered from metallic ores or non-metallic minerals. Examples of some of the larger tonnage inorganic compounds include sulfuric acid, chlorine and soda ash, among others. The inorganic segment of the chemical industry is less complex than the

organic segment, and a relatively limited number of commodities account for the bulk of production and sales. Inorganic chemicals have been among the most widely used products of the chemical industry since its inception. Hence, in general their markets are fairly mature with only moderate rates of growth.

An important distinction between inorganic and organic chemicals is that organic compounds often wind up in polymer materials that are used in manufactured goods. Inorganics, on the other hand, are used primarily as catalysts or processing aids and, as a result, are not usually embedded in manufactured goods. This dissipative nature of inorganic chemicals has important environmental implications.

Industrial gases such as oxygen, nitrogen and argon are manufactured by the liquefaction and fractionation of air using ultra-low temperature technology. Other industrial gases, such as acetylene and carbon dioxide, are made by chemical methods. Most oxygen is used in steelmaking while a large proportion of nitrogen is reacted with hydrogen to produce ammonia. Carbon dioxide is used largely in dry ice, and almost all acetylene is consumed in metal welding, cutting and similar applications.

Chemical additives are often specialized chemicals that perform a wide variety of functions and are manufactured by many types of technologies. They can be classified into two broad categories: end use (with typically industry-specific applications) and multi-purpose (generally used in numerous products or industries). Among the largest consumers of end-use specialty chemical additives include the plastics, petroleum refining, food, textile, paint and electronic industries among many others. Generic or multi-purpose chemical additives include paints and pigments, dyes, detergents and other surfactants, flame retardants, corrosion inhibitors, enzymes and many others.

Figure 3-2
Principal Components of the Chemical Industry

Source: Kline Guide to the Chemical Industry

Figure 3-3
The Ethylene "Family" of Basic and Intermediate Chemicals

Note: Numbers in parentheses refer to the production ranking of that chemical in the United States.

Source: Brief Characterizations of the Top 50 U.S. Commodity Chemicals, OIT

Functional chemicals are products that are used by one or many industries for a particular application. Polymers manufactured from organic petrochemicals are by far the largest class of functional chemical products, and include plastic materials as well as synthetic resins, fibers and rubbers. Agricultural chemicals, including fertilizers and pesticides, are the second most important category of functional chemicals. Other functional chemicals include industrial cleansers, explosives, adhesives and catalysts.

Energy

In 1991, the chemical industry consumed about 5.1 quads of energy. About 53% of chemical industry energy use was for fuel and power and the remainder was used for feedstocks. Some segments of the chemical industry are very energy-intensive; for example, energy costs in the industrial gas segment of the industry account for 40%-50% of total operating costs. On the other hand, other industry segments use energy less intensively. For example, energy use in the production of inorganic chemicals accounts for less than 10% of production costs. Overall, however, four segments of the chemical industry—inorganic chemicals, organic chemicals, plastics and fertilizers—consumed 86% of all fuel and electricity used in the chemical industry in 1991 (see Figure 3-4).

The overall efficiency of energy use in the chemical industry has improved by 51% since 1974. This is because of improved technology and energy management as well as a general shift toward the production of less energy-intensive products. Simultaneously, the proportion of energy used for feedstocks in the chemical industry has grown from 39% in 1970 to 48% presently. Much of this increase can be attributed to growth of the plastics business.

Figure 3-4

Sources and Uses of Energy in the Chemical Industry, 1991 (in Btu quads)

*Excludes industrial gases

Source: EIA

Environmental Profile

The chemical industry produces about 2 billion tons of waste per year, most of which is wastewater. It is a major source of hazardous waste in industry, accounting for 91% of these wastes in 1989. The industry also faces major challenges to reduce various air pollutants, especially VOCs and oxides of sulfur and nitrogen. The vast majority of chemical industry waste is generated by just a few industry segments including plastic materials and resins, tonnage basic and intermediate chemicals, and other industrial organic chemicals.

It is instructive to consider the ultimate application of various types of chemical products. Chemicals are used as catalysts, detergents and cleaning agents, paints and dyes, enzymes, solvents, fertilizers, pesticides, water and sewage treatment agents, food and gasoline additives, explosives, bleaching agents, abrasives and drugs. All of these uses are dissipative in nature. That is, chemicals become widely dispersed in very small concentrations making recycling virtually impossible, at least from an economic viability standpoint.

The fact that so many chemical products are used dissipatively has important environmental implications. Although released in small quantities, dispersed chemicals can eventually begin to accumulate in concentrations sufficient to be potentially harmful to human health and

the environment. The chemical use of lead in paints and gasoline are examples of the potentially harmful nature of chemical dissipation. Dissipation is less pronounced in polymers, of course, which are used in textiles, fiberglass, and plastics in ways similar to most traditional materials. Still, the large number of grades of plastics, the tendency for plastic materials to degrade when melted and re-used, and the difficulties of recycling fiber-reinforced plastics tend to limit the amount of plastics recycling compared to many other materials.

THE OIT CHEMICAL PROGRAM

The major components of the OIT chemical program include alternative feedstocks, advanced separation technologies (including membranes), catalysis, bioprocessing and a variety of waste reduction projects that target chemical industry processes and products. Because the organic chemical industry is based almost entirely on petroleum and natural gas feedstocks, the alternative feedstocks program is seeking to develop renewable substitutes for these depletable inputs. A series of commercial biomass technologies are being developed that convert hydrocarbons from renewable agricultural and forestry resources such as switchgrass, woody crops, and corn.

The membrane program is developing systems that act as permeable barriers to separate or concentrate the

components of chemical process streams. In comparison to conventional chemical separation processes, advanced membranes are very energy efficient because they do not require large amounts of thermal energy; rather, only electrical energy is needed to force the material through the membrane. The bioprocessing program has two components: biological technologies and chemical technologies. The primary focus of the biological technologies R&D efforts is to introduce biotechnology into the chemical industry through adopting biological systems to operate in organic media and develop high-volume, high-capacity engineering systems. The primary focus of the chemical technologies R&D efforts is to reduce the time it takes to introduce catalysts into industry process operations by developing models that guide catalyst and process design.

Alternative Feedstocks

The goal of the Alternative Feedstocks Program is to develop economically feasible, environmentally sound processes for producing chemicals from renewable (biomass) resources such as corn and other farm crops,

wood, or biomass recovered from wastes. Currently, nearly all organic chemicals are made from either crude oil or natural gas. Renewable resources have the potential to be used as feedstocks for a number of high-volume intermediate chemicals, from which many diverse chemical products are made. The use of biomass feedstocks in the chemical and petroleum industries should be desirable from just about any point of view—energy, economic, and environmental. The ability to derive chemicals from renewable resources will help these industries respond to changing world markets and feedstock availability, as well as promote life-cycle environmental stewardship.

Biologically Produced Organic Acid Derivatives: A New Route to Chemical Intermediates

(Oak Ridge National Laboratory, Argonne National Laboratory, National Renewable Energy Laboratory, Idaho National Engineering Laboratory, Pacific Northwest Laboratory, Michigan Biotechnology Institute)

Organic chemicals are typically produced in a series of steps involving the production of one or more chemical intermediates—chemical building blocks that can then be converted into

An Important Note about OIT Technology Benefit Estimates

The data contained in these tables are derived from a process that OIT is implementing to help bring more discipline to its planning activities. To give a more consistent representation of the possible advantages of OIT-supported technologies, quantitative estimates of the potential benefits of many of these projects have been developed. Although these estimates represent the best judgment of expert program managers who are highly informed about these technologies, the tentative nature of these estimates must be emphasized. The potential benefit tables in this report are not statements of fact—rather, they are forecasts about the future. As such, they are subject to influence by many uncertainties relating to such factors as competing technologies, end product demand, energy prices, interest rates, government regulations and foreign competition. An appendix to this report describes the methodology used to derive the benefit estimates in greater detail.

the final product. Typically, organic chemical intermediates are derived from hydrocarbon feedstocks such as petroleum or natural gas. This OIT program is investigating new ways of producing chemical intermediates using biological methods.

The initial target of the program is succinic acid, which is mainly produced from a petroleum-based feedstock in a number of energy-intensive and costly steps. But the acid can also be produced by a biologically derived route—fermentation. This process uses glucose derived from corn syrup as the feedstock. However, the conventional biological separation process produces an undesirable waste byproduct, gypsum. For biological production methods such as fermentation to become competitive with current petroleum-based production methods, technological improvements are needed to decrease the costs. This can be achieved by eliminating undesirable byproducts, increasing yields,

Table 3-2

Annual Benefits of Biologically Produced Organic Acid Derivatives

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	6178	5676	502	502
Total Cost (\$1000)	80,056	44,151	35,905	35,905
Energy Cost (\$1000)	35,313	12,737	22,576	22,576
Capital Cost (\$1000)	30,743	18,962	11,781	11,781
O&M Cost (\$1000)	14,000	12,452	1548	1548
Emissions (metric ton)				
CO ₂	465,717	427,258	37,858	37,858
NO _x	392	360	32	32
SO _x	3517	3231	286	286
Particulates	9203	8455	748	748
Solid Waste (1000 short tons)	—	—	112	112
Risk				
Technical		HIGH		
Market		MEDIUM		
Year of Maximum Market Share		2007		

allowing for continuous chemical reaction, and improving purification techniques.

The AFP's national laboratory consortium has undertaken a joint R&D project, guided by industrial input, to demonstrate the feasibility of a fermentation bioprocess to produce succinic acid, and various derivatives, without gypsum production. The proposed process uses a corn-base (an abundant feedstock) sugar. The sugar is mixed with new microorganisms developed by industry in a vessel, known as a bioreactor. These microorganisms have demonstrated the capability of producing improved yields and concentrations of succinic acid. The resulting succinic acid product will then be separated and concentrated from the mixture using an advanced technique, membrane electrodialysis. A recently performed economic analysis shows a reduction in the overall production cost of approximately \$0.06/lb, compared to those of conventional fermentation organic acid recovery processes. The program continues to re-evaluate, and revise its economic projections based on its actual R&D results.

Succinic acid is just the chemical intermediate. The final use of succinic acid will be to build through catalysis, other higher-valued chemicals, such as butanediol. Butanediol is used for plastics applications. The national laboratory consortium is also working on this, as part of the succinic acid project. Industrial producers or users of the butanediol and related chemicals are being sought to lead the demonstration effort.

Clean Fractionation: Laying the Foundation for a Biomass Refinery
(*National Renewable Energy Laboratory*)
Like the petroleum cracking process, which separates a chemically complex crude oil mixture into predictable starting materials for industry, the fractionation process separates a single lignocellulosic (woody) feedstock into its three major components—cellulose, hemicellulose, and lignin.

The fractionation process could be used to derive these three valuable materials from biomass feedstocks including a variety of agricultural wastes. Markets already exist for these products—particularly in the pulp and paper and chemicals industries—and many new market opportunities are envisioned. To date, the fractionation process has not been proven technically and economically feasible with lignocellulosic materials.

A current OIT project is attempting to remedy this situation with the development and demonstration of a clean fractionation process that uses a proprietary solvent mixture to dissolve the lignin and hemicellulose components, producing solid cellulose. After further processing, the lignin is separated as a solid, leaving a solution of hemicellulose and water. The process is simple, recovering up to 95% of the components in the feedstock at high purities. The aspects of the clean fractionation process that appeal the most to potential industrial users include the high purity and easy bleaching of the cellulose obtained, as well as the ease and simplicity with which the lignin can be separated. The results to date have already stirred the interest of many private-sector businesses who see a number of market opportunities. For example, the cellulose derived from the process could be used for producing ethanol or could be upgraded to other higher value products, reducing the amount of chemicals produced from petroleum-based feedstocks. The lignin could find applications in the production of pulping catalysts, as well as certain other chemicals and products.

Membranes

A membrane is a semi-permeable barrier that can be used to separate a mixture into its individual components by discriminating on the basis of physical or chemical attributes such as molecular size or solubility. Membrane separation processes have been shown to be promising alternatives for many industrial applications.

Although conventional separation processes are very energy intensive, typically requiring large amounts of steam, membrane separation processes require only the electricity to pump the mixture through pipes to and from the membrane. The OIT membrane program includes efforts directed at developing new membrane systems and applications with the goal of reducing energy use in chemical production and petroleum refining processes.

Catalytic Membrane Reactor for Chemicals Production: Better Yield for Less Energy

(*Golden Technologies, Inc., Media and Process Technology, Inc.*)
Organic chemicals—those containing the element carbon—are produced from petroleum and natural gas in refineries and other chemical production facilities. Most chemical production processes require the input of thermal energy (usually in the form of steam heat) to carry out the desired chemical reactions and separations. The yield of these reactions is often limited to 50% or less, which means that the process must be repeated several times to get the desired amount of product. The dehydrogenation (removal of the hydrogen) from the petrochemical ethylbenzene to produce styrene (a chemical used to make plastics and rubber) provides a good example of the problems associated with conventional thermal processing. This reaction requires high temperatures (and thus a lot of energy) and an expensive catalyst, but the yield is low and the reactor vessel takes a terrible beating.

A membrane separation process that uses a porous ceramic membrane impregnated with a catalyst has been developed for use in the conversion of ethylbenzene to styrene. In the new membrane reactor, the unwanted hydrogen radiates outward through the tubular membrane, while the desired styrene component passes straight down the center and out the other end for further processing. Because the hydrogen is removed

through the membrane wall as it is formed, it cannot re-react with the styrene to produce the original ethylbenzene again, a problem that lowers the conversion rate of the conventional process.

The use of a membrane reactor to carry out dehydrogenation reactions would have numerous associated benefits, including reduced capital and operating costs. The higher conversion rate of the membrane process means that fewer passes through the system are required to get the same amount of product. Energy requirements are significantly reduced because the membrane process can take place at lower temperatures than the conventional process and because downstream processing requirements are lessened. Lower reactor temperatures may have the added benefit of allowing the use of less expensive catalysts in the membrane.

Active Transport Membranes for Gas Separations: An Elusive Technology is Finally Mastered

(Air Products and Chemicals, Permea)

Active transport membrane processes differ from other membrane separation processes because they involve specific chemical reactions rather than filtration or differences in solubility of the components of a mixture. An active transport material is embedded into a membrane, where it selectively extracts a component of the mixture being fed into the system and transports it through the membrane for release on the other side. Because active transport membrane systems contain a reactive carrier species (transport material), they are typically much more selective than other membrane separations and can be used as an alternative to gas absorption and liquid extraction processes. One potential application being investigated is removing hydrogen during the production of ammonia.

Ammonia is a commonly used chemical throughout both manufacturing and agriculture, serving as a feedstock

in the production of commodities ranging from plastics to fertilizers. Current process steps to separate hydrogen from ammonia during its production are relatively slow and inefficient. Research is underway to develop active transport materials to accelerate this separation, as well as the separation of other gases from mixtures containing hydrogen. The

transport materials being developed belong to a specific family of polymers; these materials are then encapsulated within layers of the membrane. Active transport membrane systems can replace or be used in combination with existing technologies to expand their applicability. Total energy savings of 42 billion Btu have been estimated for a number of

Photo courtesy of Golden Technologies Company, Inc.

The innovative catalytic membrane reactor uses state-of-the-art membranes for varying applications.

Table 3-3
Annual Benefits of Catalytic Membranes for Chemical Production

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	60	54	7	325
Total Cost (\$1000)	637	554	83	4148
Energy Cost (\$1000)	165	147	18	893
Capital Cost (\$1000)	472	407	65	3255
O&M Cost (\$1000)	N/A ¹	N/A	0.0	0
Emissions (metric ton)				
CO ₂	3167	2824	343	17,153
NO _x	4	3	1	21
SO _x	0.016	0.015	0.002	0.1
Particulates	0.079	0.071	0.009	0.4
Solid Waste (1000 tons)	—	—	—	—
Risk				
Technical	HIGH			
Market	MEDIUM			
Year of Maximum Market Share	2007			

¹ O&M costs not available. OIT cost expected to be approximately equal to current technology.

these applications. Other benefits of this novel separation process include faster processing speed, lower capital costs, and reduced environmental impact because it does not rely on solvents, as do the conventional gas separation processes it replaces.

Bioprocessing

The goal of OIT's Bioprocessing Program is to provide experimental evidence of the technical and economic feasibility of advanced chemical and biological concepts that can improve the energy efficiency, productivity, and environmental soundness of a variety of processes throughout the chemical and petroleum refining industries. Toward this end, the program sponsors efforts to apply the fundamental principles of biology and chemistry to make or modify products, and to apply engineering principles to develop cost-competitive bioprocesses. Cornerstone activities focus on the development of new and improved catalysts and biocatalysts that improve the rates and yields of chemical reactions commonly found in the chemical and petroleum refining industries. Similarly, a necessary complement to the development of

new biocatalysts is the design and testing of bioreactor systems to carry out the reactions.

Biological Technologies: Tremendous Potential for Producing Common Chemicals

(Oak Ridge National Laboratory,
Lawrence Berkeley Laboratory, California
Institute of Technology, Massachusetts
Institute of Technology, AlliedSignal)

Bioprocessing techniques are already being used in the production of some low-volume chemicals. The use of such techniques for the production of high-volume commodity chemicals has yet to be demonstrated. Part of the problem is that current bioprocessing methods are relatively slow and do not lend themselves well to operations requiring high levels of productivity. In addition, conventional water-based bioprocesses are not applicable to many chemical production processes. Because of the great potential of bioprocessing systems, however, the chemical industry is interested in evaluating them for use in developing new products, adding value to current chemical intermediates, and eliminating the chemical waste streams associated with traditional methods of producing chemicals.

The goal of OIT's biological technologies research is to advance the state of the art in bioprocessing capabilities in order to facilitate the introduction of biotechnology into the production of commodity chemicals. As part of the program, scientists are examining possible approaches to overcoming barriers to the widespread application of biotechnology in industry. Activities are underway to improve yields from enzymes and microorganisms through protein, metabolic, and genetic engineering; increase productivities in bioprocesses to permit continuous (as opposed to batch) operation; improve recovery of dilute products; and design and engineer biocatalysts for operation in unnatural environments (e.g., certain temperatures, pressures, and organic solvents). For example, researchers are using computer-aided molecular design methods to design synthetic analogs of enzymes for use in producing such common chemicals as methanol and methane, with the ultimate goal of using sunlight as the energy source for the reaction. In another project, new bioreactors for continuously producing certain chemicals are being developed and tested. Enzymes that could be used as catalysts in organic solvents (rather than in water) are also being investigated and refined in several ongoing projects. By carrying out chemical production processes using renewable resources rather than petroleum-based resources, biological technologies will reduce the energy use and chemical waste associated with current methods of chemical production.

OIT's bioprocessing technologies offer fundamentally new alternatives to many conventional chemical processing technologies. Unlike most other OIT programs that mainly target specific, widely used industrial processes, bioprocessing technologies are more generic in nature with possible applicability among many conventional chemical processes—a few of which are indicated in Table 3-6. But because of their more generic

Table 3-4

Annual Benefits of Active Transport Membranes for Gas Separation

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	0.11	0.08	0.03	42
Total Cost (\$1000)	1037	472	566	56,566
Energy Cost (\$1000)	0.3	0.2	0.1	115
Capital Cost (\$1000)	472	81	391	39,059
O&M Cost (\$1000)	565	390	175	17,500
Emissions (metric ton)				
CO ₂	5.5	4.1	1.4	2217
NO _x	0.007	0.005	0.002	3
SO _x	0.00003	0.00002	0.00001	0.01
Particulates	0.0001	0.0001	0.00004	0.06
Solid Waste (1000 tons)	—	—	—	—
Risk				
Technical	HIGH			
Market	MEDIUM			
Year of Maximum Market Share	2004			

nature, it is difficult to estimate the potential energy, cost and environmental benefits of these technologies vis-a-vis their conventional counterparts in a quantifiably meaningful way. While such comparisons might be done on a process-by-process basis, most OIT bioprocessing technologies are far removed from the demonstrations that would begin to yield reliable process and operational data on which to base estimates of their potential economic and other benefits.

Improved Catalytic Processes: Eliminating the Trial and Error Approach to Catalyst Design
(Los Alamos National Laboratory, ARCO, Lawrence Berkeley Laboratory, Pacific Northwest Laboratories, Ames Laboratory)
Of the top 50 chemicals (by volume) produced in the United States, 33 are produced in processes involving the use of catalysts. Overall chemical conversion efficiencies range from as low as 10% to as high as 99%, depending on the catalyst and process. The majority of these processes are energy intensive, and many generate polluting waste streams requiring treatment or disposal. The development and design of a catalyst is typically a labor-intensive, trial-and-error procedure whose results more often than not turn out to be something slightly different than was initially intended. Modern theoretical tools offer the hope of reducing the time and effort associated with the catalyst screening process, while designing catalysts that work better and faster.

OIT's chemical technologies research will provide industry with the modeling tools it needs to improve the entire catalyst design, development, testing, and commercialization sequence. Several major catalyst types—zeolite, metal oxide, and metallic catalysts—are being targeted because of their prominent use in many chemical production, petroleum refining, and automotive applications. For example, filling in the gaps in knowledge about the catalytic process used in the conversion of methanol to gasoline is the focus of one project. Fundamental

investigation of the process is expected to improve its yield and selectivity, which will ultimately lead to higher productivity and energy savings. In another project, scientists are using models to prepare complete descriptions of various industrial catalyst systems, leading to increasingly better prediction of their behavior in particular applications. The benefits of the chemical technologies research could include an annual energy savings of as high as 8 trillion Btu.

Other Programs

Other OIT programs are involved in research that impact the chemical industry, such as the industrial waste program and the heat pump program. An example of a project from the industrial waste program that impacts the chemical industry is described below.

Biological/Chemical Caprolactam Production Process: Microorganisms at Work in Your Carpet

(Allied Signal)

A large portion of the carpets manufactured in the United States are made from Nylon 6, a polymer that consists of repeating units of the chemical caprolactam. Nylon 6 can

Table 3-5

Bioprocessing: Partial Listing of Potential Candidate Chemical Processes

Acetic acid	Isopropanol
Acetone	Malic acid
Butanol	Propionic acid
Butyric acid	Propylene glycol
Glycerol	Succinic acid

also be produced from caprolactam's cousin caprolactone. Although this alternative production method is much more efficient and produces considerably less waste than the conventional method, it is unfortunately very costly because of the high price of caprolactone. The development of a new, cheaper method of producing caprolactone is being pursued to make the production of Nylon 6 an economically viable alternative to the conventional process.

The new caprolactone production method uses a novel biological process to convert caprolactone's precursor, cyclohexane, into caprolactone. The process relies on microorganisms—tiny living organisms such as bacteria—to react with the cyclohexane and convert it into caprolactone. This reaction takes place in a

Table 3-6

Annual Benefits of Improved Catalytic Processing Technologies

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	1695	1610	85	8541
Total Cost (\$1000)	21,247	20,719	528	52,802
Energy Cost (\$1000)	6328	6009	319	31,884
Capital Cost (\$1000)	10,714	10,715	-1	-106
O&M Cost (\$1000)	4205	3995	210	21,024
Emissions (metric ton)				
CO ₂	120,923	114,830	6093	609,301
NO _x	235	223	12	1182
SO _x	173	165	9	874
Particulates	38	36	2	189
Solid Waste (1000 short tons)	-	-	-	-
Risk				
Technical		HIGH		
Market		MEDIUM		
Year of Maximum Market Share		2020		

Table 3-7
Annual Benefits of Biological/Chemical Caprolactam

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	13	7	6	3890
Total Cost (\$1000)	1183	1041	141	84,811
Energy Cost (\$1000)	185	92	93	55,517
Capital Cost (\$1000)	98	49	49	29,294
O&M Cost (\$1000)	900	900	0	0
Emissions (metric ton)				
CO ₂	2330	1165	1165	699,026
NO _x	2	1	1	648
SO _x	18	9	9	5241
Particulates	45	22	23	13,464
Solid Waste (1000 tons)	N/A	N/A	0.02	13
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		2018		

large vessel known as a bioreactor; additional steps must then be taken to isolate and purify the caprolactone. The potential benefits of using the alternative method of producing Nylon 6 will include energy savings of 4 trillion Btu and reductions of 26 million pounds of waste chemicals. The success of biological caprolactone production may have other environmental implications as well—the chemical has also been shown to be applicable to the production of biodegradable polyester.

The Petroleum Refining Industry

RIISING TO THE CHALLENGE OF ENVIRONMENTAL STEWARDSHIP

The petroleum refining industry produces a wide range of products used in transportation, industry, electrical generation, heating and so on that have a major impact on the U.S. economy and trade balance. The principal products include transportation fuels and raw materials for the manufacture of many chemicals from carbon black and ammonia to synthetic fibers and plastics. Refineries employ a variety of physical and chemical processes to extract hydrocarbon streams from crude oil and convert them to the desired products. The industry thus engages in hydrocarbon engineering.

Lifeblood of the Transportation Sector, Vital Supplier to the Manufacturing Sector

The petroleum refining industry is critical to the economic stability and energy security of the United States. Except for food and clothing, no organic industry is more important to an industrialized economy than the petroleum industry. The industry supplies 97% of the energy for the travel and freight needs of the nation. The fuel needs of more than 190 million automobiles, trucks, and buses as well as all aircraft are met by petroleum products.

The annual value of all product shipments from the petroleum refining industry is about \$136 billion. The refining process increases the net value of crude oil feedstocks by \$19.1 billion. In addition, refined petroleum products contribute significantly to the \$165 billion value added by the chemicals industry, the \$29.9 billion value added by the textiles industry, and the \$58.5 billion value added by the rubber and miscellaneous products industry.

The refining industry directly employs 75,000 of the 1 million oil and gas industry workers. Since 1980, refinery

industry jobs have declined by 28%. These lost jobs were in high-wage occupations. The average worker in the refining industry realizes an annual income of \$38,600, versus the average annual income of all industries of around \$27,000.

U.S. Refineries: Larger But Fewer

Substantial changes in the structure and configuration of U.S. refineries have occurred during the past 25 years. The number of operating refineries has decreased from about 285 in the 1960s to 187 in 1993, while the average capacity has steadily increased from 35,000 barrels per day (bpd) to more than 80,000 bpd at present. Major dislocations occurred in the 1970s when a historic high of 324 refineries were in operation. The decline in operating refineries from this peak, which occurred in 1981, has been due primarily to closing simple refineries that cannot process heavier oils nor afford to make the necessary investments to comply with the 1990 Clean Air Act Amendments (CAAA) regulations. Approximately 65 small refineries with a distillation

capacity of about 1 million bpd continue to be at risk. Despite extensive investment in individual refineries during the 1980s, no grassroots refineries have been built in the United States for more than a decade, reflecting both over-capacity during the early 1980s and regulatory/cost hurdles during the latter part of the decade.

The refining industry currently has a distillation capacity of about 15 million bpd (see Figure 3-5). This includes downstream processing charge capacity—a measure of processing flexibility. Although their

Table 3-8
Petroleum Refining Industry Profile

Value of Shipments	\$136 billion
Total Employment	75,000 jobs
Capital Expenditures	\$6.7 billion
Net Trade Balance	-\$3.7 billion
Energy Consumption	5.97 quads
Waste Generation	180 million tons
Average Hourly Earnings	\$17.67

*Data for latest year available

Figure 3-5
Operable U.S. Refinery Capacity, Crude Oil Inputs, and Petroleum Demand, 1970-1992

Source: EIA

number has declined, refinery complexity has increased. U.S. refining capacity currently accounts for 21% of the world total. About 70% of domestic capacity (which is among the most sophisticated in the world) is owned by 20 companies.

About 28% of U.S. Refining Capacity is Foreign-Owned

Ownership of U.S. refineries changed appreciably in the 1980s as mergers, takeovers, and foreign investments altered the structure of the industry. A significant proportion of the domestic industry has been purchased by or entered into joint ventures with foreign refiners. Among the 10 largest refinery capacity owners in the United States, four are foreign. Countries represented include the Netherlands, Great Britain, Saudi Arabia, Venezuela, and Mexico. To a large extent foreign refining firms have purchased U.S. capacity for strategic reasons. As market forces eroded the Organization of Petroleum Exporting Countries' (OPEC) ability to sustain high oil prices, members sought ways to develop and secure more stable markets for their crude oil. State-owned energy companies built large refineries in their own countries and invested in existing refining and marketing operations in industrialized countries.

Overall, imports of foreign crude oil and refined petroleum products supply almost half the U.S. market. U.S. imports of refined products generally serve market niches that develop for a variety of reasons: logistical considerations, regional shortages, and long-term trade relationships between suppliers and refiners. Exports—primarily distillate and residual fuel oils and petroleum coke—constitute 4% to 6% of U.S. refinery output.

Finished petroleum products accounted for 64% of all U.S. oil-related imports in 1992, with other liquids (primarily unfinished oils) and natural gas liquids accounting for 27% and 9%, respectively. Nearly 80% of

finished petroleum-product imports are delivered to the East Coast. Residual fuel oil, motor gasoline, and distillate fuel oil accounted for 86% of the imported products delivered to the East Coast.

The Future Challenge: Provide Environmental Stewardship while Remaining Competitive

Environmental constraints, in the form of government regulations and public opposition to expansion, are an ever-increasing burden on U.S. refiners. Recent public policy and regulatory developments have generally had a negative impact on the industry. Typically they have increased refining costs by requiring significant capital investments with uncertain returns to meet new product quality mandates.

The two regulatory developments that will have the most profound impact on the industry are the CAAA and the Phase II reformulated gasoline and diesel fuel specifications adopted by the California Air Resources Board (CARB). As a result of these regulations, the quality of gasoline and diesel fuels will change dramatically between now and 2000. Title IV of the CAAA mandated reduced SO_x and NO_x emissions from power plants that

will also impact the refining industry. These provisions are expected to contribute to declines in high-sulfur fuel oil demand and increases in low-sulfur fuel oil demand. They will also require some refineries operating in non-attainment zones to undertake process modifications to reduce their SO_x and NO_x emissions.

The proposed rules for implementing the CAAA's reformulated gasoline (RFG) provisions stipulate target compliance levels for volatility,

Photo courtesy of Stevie Grand

The structure and configuration of U.S. refineries have changed during the past 25 years.

Figure 3-6

Foreign Ownership of U.S. Petroleum Refining Capacity

Source: EIA

benzene and oxygen content. Other gasoline properties—such as aromatics, sulfur content, olefin content and T90 distillation point—are not clearly specified, but will be incorporated in the complex model that will be used to determine a gasoline's allowable VOC emissions beginning in 1997. There is still a great deal of uncertainty surrounding the CAAA's RFG specifications because they have not yet been finalized. Also, the details of the complex model that will apply to Phase II RFG in 2000 will not be finalized until more emissions testing data becomes available in a year or two.

An estimate of the refining industry's cost of compliance with environmental regulations between 1991 and 2010 was developed in a comprehensive study by the National Petroleum Council (NPC). The main areas addressed in the study were safety and health, air control emissions, wastewater, and solid waste including coke. The council concluded that the total cost will exceed \$150 billion with the capital component of that cost estimated at \$36 billion. By comparison, this exceeds the industry's existing capital base of only \$31 billion.

The environmental challenge will most likely force petroleum refiners to alter refinery configurations and invest heavily in downstream processes. In some instances, it may be more economic for certain refineries to close partially or entirely, rather than upgrade facilities to meet the new standards. Hence, there are strong incentives to develop and adopt innovative approaches and cost-effective technologies to ensure that the industry will remain competitive. Unless cost-effective solutions are found, the competitiveness of U.S. refiners could be severely impaired and the general viability of the industry threatened. If the industry does not maintain its competitiveness, refined product imports could increase sharply. The number of regulations is expected to increase in the future and further exacerbate the problem.

THE REFINING PROCESS: SEPARATE, CONVERT, REMOVE IMPURITIES, AND BLEND

Refinery configurations are based on the quality of the crude oil being processed and the types of products to be refined. Refinery complexity is related to the types and amount of processing needed to convert crude oil into finished products. Crude oil is not a homogenous substance, rather it is a mixture of an almost countless variety of hydrocarbons—molecules comprised of at least one atom of carbon in chemical association with hydrogen atoms. Refinery processing is generally divided into four categories: separation and conversion of hydrocarbons, and treatment and blending of products.

Separation: Dividing Crude Oil Molecules by Weight

The first step in the refining process is to separate the crude into different hydrocarbon groups (or fractions) that have varying boiling points. While there are many ways to accomplish separation, fractional distillation (illustrated in Figure 3-7) is the most common process. Lighter products such as gasoline have lower boiling points and are condensed and collected at the top of the tower; heavier products such as residual fuel oil have higher boiling points and are drawn off at the bottom.

The separated, lighter boiling products are referred to as straight run liquids. Both atmospheric (most prevalent)

and vacuum distillation units are used. Vacuum distillation is used primarily on the heavy (highest boiling fraction) atmospheric residuum to achieve further separation. The boiling temperature is lowered under a vacuum and additional separation can be achieved before the heavy hydrocarbons crack or break apart. The use of vacuum distillation allows the refinery to produce more of the high-value, light-end distillates generally referred to as white products.

Conversion: Heavy Hydrocarbons into Lighter Products

Converting heavy hydrocarbons into lighter products involves altering the carbon/hydrogen ratio and the number of carbon atoms in the molecules. Heating causes the molecules to break up or crack, reducing the number of carbon atoms per molecule and thereby lightening the fuels. Using a catalyst can accelerate and lower the overall stress of the process. Alternatively, the number of hydrogen atoms can be increased by introducing hydrogen into the process with the aid of a catalyst. Processes based on these approaches are designed to increase the yield of the desirable transportation fuels (white products) and improve their quality. Conversion processes generally fall into three categories: cracking, combining, and rearranging the hydrocarbon molecules.

Cracking is a process in which large hydrocarbon molecules are cracked into smaller molecules that can be used to blend lighter products such as gasoline and diesel fuel. Cracking can be done with heat (thermal cracking) and/or a catalyst (catalytic cracking). In thermal cracking, a combination of high temperature and pressure causes bonds between carbon and hydrogen atoms in the large hydrocarbon molecules to break thus producing the lighter, smaller distillate molecules. The resulting mixture of product molecules is then separated by injection into a flash chamber. Feedstocks for thermal cracking are residuum

Figure 3-7
Schematic of Crude Oil Distillation

Source: William L. Lefter, *Petroleum Refining for the Non-Technical Person*

and heavy gas oils; products derived include butane gasoline blend stock, naphtha, gas oils, and coke.

Fluid catalytic cracking (FCC) is similar to thermal cracking except that a catalyst is used to accelerate the cracking reaction under conditions of moderate temperature and pressure. Catalysts generally used are a mixture of alumina, zeolites, and processed clay held together with a binder. FCC is one of the most important processes used in refineries because it converts a high fraction of the feed into gasoline stock; FCCs produce about 50% of all U.S. gasoline.

Several processes are used to combine small molecules into larger molecules. The most common processes are alkylation and polymerization. In the alkylation process, either olefinic propylene or butylene is combined with isobutane with the aid of a catalyst to produce a branched hydrocarbon product that is generally referred to as an alkylate, one of the highest quality gasoline components. In the polymerization process, olefinic gases recovered from cracking are combined with the aid of a catalyst to produce a high octane gasoline blend stock. Hydrocarbon molecules can also be rearranged to alter their characteristics and make them more desirable as gasoline blending stocks. Two processes used most frequently for this purpose are catalytic reforming and isomerization.

Treatment: Removing the Impurities

A number of product streams contain impurities (e.g., sulfur, nitrogen or heavy metals) that must be removed. The process most frequently used to remove impurities is hydrotreating. In hydrotreating, hydrogen is mixed with the product stream to be treated and with the aid of a catalyst chemically reacts with impurities such as sulfur and nitrogen to produce hydrogen sulfide and ammonia. The metals present attach themselves to the catalyst

and are removed when the catalyst is regenerated and recycled. Hydrotreating thus helps purify gasoline, aviation fuel and fuel oil blend stocks.

Blending: Combining the Products to Meet User Specifications

Refinery products must meet specifications for octane rating, sulfur content and other factors that can vary with season and geographic location. Refinery products are thus derived by combining the various blend stocks described above to meet specifications. Once the desired product composition is determined, appropriate volumes of individual blend stocks are withdrawn from holding tanks through metering devices and passed into the pipeline for distribution. Analyzers continuously monitor the product to ensure conformity to specifications; adjustments are made as necessary.

A schematic of a typical complex refinery is presented in Figure 3-8, and illustrates how all these processes are integrated to produce the slate of products that are derived from the refining process.

Refinery Energy Use and Efficiency

Petroleum refining involves both chemical and mechanical energy changes. Although some conversion processes are exothermic, most are endothermic and require large amounts of heat, e.g., distillation, cracking, hydrotreating, reforming, and alkylation. A large amount of mechanical energy is also needed for pumping, transportation, compression of gases, and the like. Over half the energy needed in the refinery comes from in-house refining streams in the form of refinery fuel gas.

The refining and organic chemicals industries are inextricably linked (thus, the petrochemicals industry) and together account for more than 40% of industrial sector energy use: 5 quads of this energy is feedstock that is converted to non-energy product; the remaining 6.7 quads are used in refining oil and processing feedstocks. In addition, 22 quads of transportation fuels pass through the refining industry and are consumed in the transportation sector.

Improved energy efficiency has been a major priority of the petroleum refining industry since the sharp

Figure 3-8
Simplified Flow Chart of a Complex Refinery

Source: Adapted from National Petroleum Council, U.S. Petroleum Refining

Table 3-9
Projected Refinery Industry Emissions
Based on Overall Material Balance, Year 2000

Air Emissions		lb/Day
CO		695,000
NO _x (0.35 lb/10 ⁹ Btu)		976,000
SO _x (60 kg/1000 barrel)		1,660,000
Particulates		174,000
VOCs		220,000
Solid Wastes		
Oily Sludges		23,800,000
Spent FCU Catalyst		1,110,000
Spent Refining Catalyst		12,800
Spent Hydrocracker Catalyst		5480
Spent Resid Treating Catalyst (2000 lb resid/lb catalyst)		58,000
Spent Hydrotreat Catalyst		104,000
Inorganic Waste (neutralized HF)		51,000
Liquid Wastes		
Waste Water		13,500,000*
Waste Water—Toxic Materials		1590
Waste Water—Toxic Organics		5480
Spent Sulfuric Acid		12,800,000

*Barrels per day.

Source: Argonne National Lab

increase in energy prices in the 1970s. Total energy consumption per barrel of crude processed has been estimated at 584,000 Btu in 1990, down from a reported 673,000 Btu in 1973. Of course, the actual efficiency gain is considerably higher than indicated by this 15% improvement because the industry has become considerably more complex since 1973, and in effect produces much higher quality products.

Environmental Profile

The refining process yields a spectrum of solid, liquid, and air emissions—many of which are subject to control in accord with existing rules or regulations. The refining industry's expected emissions in the year 2000 are shown in Table 3-10. In addition, many more effluents will be subject to planned or proposed rules (typical refinery emissions and the applicable regulations are illustrated in Figure 3-9). Principal contaminants entering refineries include: sulfur, nitrogen,

Figure 3-9
Refinery Emissions and Applicable Regulations

Source: EPA Petroleum Refinery Cluster Project, 1991

nickel, vanadium, sodium chloride, silicon, fluorine, potassium, and catalytic metals such as tungsten, cobalt, molybdenum, and platinum.

Sulfur is the major contaminant entering the refinery in the crude oil charge at a rate of 48 million lbs/day. Organosulfur compounds either remain at various levels in the refined products, are burned to SO₂, or converted to H₂S in a hydrotreating unit from which they proceed to a sulfur plant where they are converted to elemental sulfur.

Nitrogen either leaves in the refined product or is removed in hydrotreating. Nickel and vanadium enter with the crude and concentrate in the bottoms. If the bottoms are hydroprocessed, these metals deposit on the hydrotreating catalyst; if fed into an FCC unit, they deposit on the cracking catalyst. Otherwise, they end up in #6 fuel oil and marketable coke. Nickel and vanadium are commonly recovered from spent catalysts. Cobalt and molybdenum catalysts are not usually reclaimed because they are not worth enough to justify the cost.

Currently they are often landfilled, but this may change in the future and metals reclaimers may be handling these spent catalysts. Platinum and rhenium catalysts are always reclaimed because of their high value. For many years, silica-alumina cracking catalyst was sent to landfills. More recently, refiners in environmentally sensitive areas are sending spent cracking catalyst to cement plants where it is used.

THE OIT PETROLEUM REFINING PROGRAM

OIT's Petroleum Refining Program sponsors R&D of cost-effective, energy-efficient processes and technologies for helping U.S. petroleum refiners stay competitive in the world market while complying with stringent U.S. environmental regulations. As part of its strategy, the program is characterizing petroleum refinery emissions to develop a base of understanding leading to the development of improved refinery technologies. Advanced technologies that are capable of producing the cleaner fuels required in the future—while

maintaining or exceeding the energy efficiency of current technologies—are also being sponsored, as are novel methods of utilizing refinery wastes.

Hybrid Membrane Separation for Propylene Recovery: Low-Energy Membrane Unit Replaces High-Energy Distillation Tower
(BP America, University of Colorado, University of Virginia)

Petroleum refineries typically use a number of physical and chemical processes to convert crude oil into gasoline and hundreds of other products. One process—catalytic cracking—is used to increase the yield of lighter and more valuable products such as gasoline. The waste gases from the catalytic cracking process contain propylene, a potentially valuable compound used to make plastics. To recover propylene, the components of the waste gas are separated using a two-tower distillation system. The distillation process is very energy-intensive, with energy efficiencies seldom exceeding 10%. For years, researchers have been trying to improve the efficiency of propylene separation and recovery through the use of membranes. OIT has sponsored the development of a propylene recovery system that combines a membrane unit with a single distillation column.

The new hybrid membrane/distillation system has shown substantial cost savings in both retrofitted operations and new facilities. Because the membrane unit is cheaper than a distillation column, the hybrid system is expected to have capital costs of as much as 25% less than the conventional distillation system; similar savings are expected in operating and maintenance costs. In a recent pilot plant operation, the hybrid system was shown to recover propylene with purities exceeding 99%. Current research to refine the membrane system should further reduce the cost of the system and make it more resistant to contamination by components of the waste gas stream.

Table 3-10

Annual Benefits of Hybrid Membrane Separation of Propylene

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	10	10	0	0
Total Cost (\$1000)	3550	2697	852	852,401
Energy Cost (\$1000)	26	26	0	0
Capital Cost (\$1000)	1758	1338	419	419,401
O&M Cost (\$1000)	1766	1333	433	433,000
Emissions (metric ton)				
CO ₂	499	499	0	0
NO _x	0.6	0.6	0	0
SO _x	0	0	0	0
Particulates	0.01	0.01	0	0
Solid Waste (1000 short tons)	—	—	—	—
Risk				
Technical	MEDIUM			
Market	LOW			
Year of Maximum Market Share	2014			

The Origin and Disposition of Toxic Combustion Byproducts in Process Heaters: Minimizing Petroleum Refinery Emissions
(Sandia National Laboratories, Lawrence Livermore National Laboratory)

The boilers and process heaters used in petroleum refineries burn natural gas and a fuel known as refinery fuel gas. Beginning in the year 2000 these boilers and heaters, which emit hazardous air pollutants, will be regulated by provisions in the Clean Air Act Amendments of 1990. According to this legislation, 189 species or classes of species of pollutants, many of which are carcinogenic, were identified as hazardous. Unfortunately, little is understood about the formation of these pollutants. Current emission control techniques are prohibitively expensive. New burner designs and combustion process modifications are needed that can minimize the formation of these hazardous emissions.

To help the petroleum refining industry prepare for efficient compliance with the upcoming regulations, OIT is sponsoring research on air toxic emissions from refinery boilers and process heaters using various burner technologies. Goals of this work

include the establishment of the current state of such emissions, development of an understanding of their origin and eventual disposition, and development of an understanding of the mechanisms of their formation and destruction so that new operating conditions and burner technologies that produce fewer toxic emissions may be developed. Both natural gas and RFG will be tested during the research. The results of this project should facilitate the development of advanced burner concepts capable of reduced air toxic emissions in time to enable the refining industry to comply with Clean Air Act regulations efficiently and cost-effectively.

Production of Ethanol from Refinery Waste Gases: Reducing Pollution While Making Cleaner Fuel
(Bioengineering Resources, Inc.)

Petroleum refineries discharge hydrogen, carbon monoxide, and carbon dioxide waste gases to the atmosphere. Converting these waste gases into useful chemicals would reduce pollution while decreasing the amount of these chemicals that would otherwise have to be produced from non-waste feedstocks. Scientists are currently examining the feasibility of producing the

chemical ethanol from crude oil refinery waste streams. More than 1 billion gallons of ethanol are produced in the United States each year, much of which is blended with gasoline to reduce vehicle emissions. Currently ethanol is produced from fermented corn at a cost of about \$.90 per gallon just for raw material (corn) costs; substantial tax credits are applied to keep the cost of blended fuel economical. However, sharp growth is expected in the demand for blended fuels as vehicle emission restrictions are tightened, and the corresponding increase in ethanol production to meet this demand is expected to significantly raise prices.

The production of ethanol from waste refinery gases will significantly reduce ethanol costs, allow expansion of the markets for blended fuels, reduce air pollution from both refineries and vehicles, and reduce fuel imports. The conversion process being investigated uses bacteria to convert the gases to ethanol, followed by purification steps similar to those used in the corn-based process. The new process captures the energy content of the waste gases, potentially saving up to 450 trillion Btu annually by the year 2010. With an expected conversion of gas into ethanol of about 75%, the reduction in emissions of H₂, CO, and CO₂ that same year could exceed 30 million tons. The addition of a waste gas conversion plant to a refinery also offers substantial economic incentive, yielding an annual after-tax return on investment of 50% to 100%. The process can also be applied to other processes with waste carbon monoxide and hydrogen streams, such as the production of the chemicals methanol and ammonia and coke-making ovens in the steel industry.

Advanced Fluid Catalytic Cracker (FCC): Advancing FCC Technology to Produce Cleaner Fuels (Argonne National Laboratory)

The manufacture of designer gasolines (reformulated gasolines that reduce emissions) as prescribed by the 1990 Clean Air Act Amendments

will have a profound impact on the operation of petroleum refineries. Particular attention is being given to the FCC unit; regulatory mandates can be achieved most effectively by altering the FCC unit to produce more oxygenates (which have low emissions when combusted) and olefins, while reducing the yield of

undesirable products such as heavy gasoline. The key to modifying the FCC process is to develop a more fundamental understanding of its physical and chemical behavior.

With OIT and industry sponsorship, researchers are developing advanced technology for the next generation of

Table 3-11

Annual Benefits of the Production of Ethanol from Refinery Waste Gases

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	7806	2013	5793	451,854
Total Cost (\$1000)	83,139	18,673	64,466	5,028,358
Energy Cost (\$1000)	29,480	5428	24,052	1,876,086
Capital Cost (\$1000)	14,159	5045	9114	710,872
O&M Cost (\$1000)	39,500	8200	31,300	2,441,400
Emissions (metric ton)				
CO ₂	562,870	109,119	453,751	35,392,539
NO _x	1102	130	972	75,812
SO _x	830	18	812	63,367
Particulates	186	48	138	10,738
Solid Waste (1000 short tons)	—	—	—	—
Risk				
Technical		HIGH		
Market		HIGH		
Year of Maximum Market Share		2010		

Table 3-12

Annual Benefits of Advanced Fluid Catalytic Cracking

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	1695	1675	19.7	788
Total Cost (\$1000)	21,902	21,888	15	582
Energy Cost (\$1000)	6983	6902	81	3248
Capital Cost (\$1000)	10,714	10,820	-106	-4243
O&M Cost (\$1000)	4205	4165	39.4	1577
Emissions (metric ton)				
CO ₂	133,283	131,733	1550	61,992
NO _x	284.5	270.3	14.2	132.0
SO _x	241.4	229.3	12.1	112.0
Particulates	51.4	50.8	0.6	24
Solid Waste (1000 short tons)	—	—	—	—
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		2020		

FCC units, technology that will be able to tailor product yields to more closely match the mandated gasoline formulas. Using computer models, the design of current FCC units will be modified to decrease the use of catalysts, increase the production of light gasoline fractions, reduce capital and operating costs, and reduce levels of aromatics and sulfur in the gasoline fraction. The new fuels and other products that will be produced will reduce emissions of SO_x , NO_x , CO, and particulates; increase thermal efficiency, achieve higher yields of transportation fuels per barrel processed; and improve cost competitiveness. In the long term, the advanced FCC technology will be extended to the processing of petroleum crude (to eliminate the primary crude distillation unit and reduce energy use and emissions), recycled refinery wastes, plastic feedstocks, and used motor oil.

The Pulp and Paper Industry

BACKBONE OF THE INFORMATION ECONOMY

The U.S. pulp and paper industry is recognized worldwide for producing a large volume of high-quality, low-cost products. The industry benefits from a large consumer base, a modern technical infrastructure, a good supply of raw materials, and a highly skilled labor force. The industry processes cellulose fibers, primarily from wood, into consumer goods such as stationery and paper tissues, and industrial products such as cardboard for packaging and paper for newsprint and books.

Just as steel is often considered the backbone of the industrial economy, in many respects, the paper industry plays a parallel role in supporting the information economy. Newspapers, magazines, books, newsletters, letters, memoranda, computer printouts and reports are the media used to get much of this information into the hands of its users. Our economy's appetite for information is such that U.S. per capita paper consumption is the highest in the world (Figure 3-10). Because the paper industry supplies mainly consumers, as opposed to capital goods markets, its growth rate closely parallels that of the overall economy as shown in Figure 3-11, in contrast to several other more mature and cyclical materials and process industries.

The paper industry is divided into two principal sectors. The mill sector processes raw materials, such as wood and recycled paper, into sheets of paper and paperboard. The converting sector further processes the sheets of paper into other finished products, such as envelopes or boxes. Like the other major materials and process industries, the largest energy using processes in the paper industry are in separating the usable fibers from the unusable lignin and then refining the

resulting pulp through a series of process steps into paper. Hence, paper mills account for more than 90% of the energy consumption in the industry with paper products producers and fabricators (the converting sector) accounting for the balance.

The Most Capital-Intensive Manufacturing Industry

The pulp and paper industry output grew from about 61 million tons in 1980 to about 85 million tons of paper and paperboard products in 1993—

on average about 700 pounds for every man, woman and child in the United States. The 85 million tons were nearly equally divided between paper and paperboard products.

The industry has invested heavily in new equipment in the past decade, with capital expenditures averaging about 10% of sales, about twice as high as those of the manufacturing sector as a whole. On average the paper industry has invested more than \$120,000 per worker—more

Figure 3-10

Per Capita GDP versus Per Capita Consumption of Paper and Paperboard, 1990

Figure 3-11

Paper Use Compared with GDP

Table 3-13
*Pulp and Paper Industry Profile**

Volume of Products	85 million tons
Value of Shipments	\$133 billion
Total Employment	626,000 jobs
Capital Expenditures	\$7.8 billion
Net Trade Balance	\$-1.4 billion
Energy Consumption	2.5 quadrillion Btu
Waste Generation	2.25 billion tons
Average Hourly Earnings	\$13.80

*Data for latest year available

than any other manufacturing industry. Notably, environmental improvements have replaced additions to capacity as the driving force behind capital-spending plans. Otherwise, equipment is replaced only when necessary due to the large capital costs of new equipment in this high productivity, scale-economy industry.

A Strong International Competitor
Currently, the United States possesses about 30% of the world's paper capacity. Our country's vast domestic forest resources have historically underpinned our major role in the world paper industry. Exports represent about 8% of total shipments of finished paper, with most exports going to Canada, Mexico, and Japan while imports (primarily from Canada) account for about 9% of U.S. consumption of paper. Hence—especially in comparison to most other G-7 nations—the U.S. paper industry is a strong international competitor.

However, domestic forest resources are becoming more limited and less accessible to some extent, and competition from developing countries with large forest resources, such as Brazil, is increasing substantially. Moreover, domestic paper manufacturers are also prone to cyclical fluctuations in the economy, while foreign competition is often supported by government subsidies during periods of soft demand and low prices.

Figure 3-12
Kraft Papermaking Process

Source: Adapted from *The Paper Yearbook*

THE MANUFACTURING PROCESS: FROM LOGS TO PAPER

The papermaking process entails five principal steps: (1) wood preparation, (2) pulping, (3) bleaching (if desired), (4) chemical recovery, and (5) papermaking (Figure 3-12). Although wood fiber is the predominant ingredient in paper, trees cut for manufacturing paper provide only slightly more than half of the fiber used. The remaining fiber is obtained from recycled newsprint, spent packaging, other waste paper, and waste residues of lumber operations and saw mills.

Pulping: Isolating the Fibers

After wood preparation, during which tree bark is removed and the wood is chipped into small pieces, the pulping process breaks apart the fibers in the wood and cleans the fibers of unwanted wood residues. The principal methods use chemical techniques, mechanical techniques, or a combination of the two. Currently, chemical pulping techniques are used in 80% of U.S. production. These methods involve tradeoffs in terms of cost, yield, and paper quality.

During chemical pulping, the wood chips are cooked in a chemical solution at high temperature and pressure. Chemical processes dissolve most of the lignin (the glue that holds the fibers together) and frees the cellulose fibers. The most widely used technique, the kraft process, uses a solution of sodium hydroxide and sodium sulfide. The resulting pulp is then washed to remove the chemicals. The spent solution, often referred to as black liquor, contains organic material dissolved from the wood and inorganic chemicals.

Bleaching: Making Paper White

Most pulps are relatively dark in color, similar to the brown color of a grocery store bag. The color is attributed to the remaining lignin in the pulp. Bleaching is used to alter or remove the residual lignin from the pulp, to brighten the color of the final paper product. Bleaching is accomplished by the alternating treatment of pulp with oxidizing agents and alkali solutions. Chlorine compounds are often used for this process and contribute to the generation of dioxins, the industry's most acute environmental problem.

In effect, consumer preference is a major contributor to the dioxin problem. If American consumers were more willing to purchase and use less-white or off-white paper products, or conversely, if manufacturers were more willing to use more expensive methods to bleach the pulp, the paper industry could reduce its use of chlorine bleaching agents in the paper-making manufacturing process.

Chemical Recovery: Recycling and Black Liquor

The chemical pulping processes use large quantities of chemicals to separate the cellulose fibers from the lignin. Regenerating these chemicals for reuse is important for economic and waste-disposal reasons. In addition, it enables wood waste—a renewable resource—to serve as an important source of energy. When the chemicals are recovered from black liquor, enough energy is extracted from the organic wood byproducts to make many paper mills largely energy self-reliant.

In chemical recovery, black liquor is concentrated in evaporators, then burned in boilers, many of which are connected to steam turbine cogeneration systems. The wood residues fuel the boiler while the spent chemicals remain behind as smelt at the bottom of the boiler furnace. The chemicals are then processed to be reused in the pulping process.

Papermaking

The papermaking stage consists of several steps including stock preparation (beating), sheet forming, pressing, and drying. The fibers are pounded and squeezed to increase their flexibility during the beating stage; if the paper is to be colored, pigments or dyes are added during this step. Once prepared, a dilute suspension of pulp is ready to be formed into paper sheets. The fibers are deposited in a sheet on a screen, drained and pressed to remove the bulk of the water, and then dried, all in a continuous process.

Energy: Heavy Reliance on Renewables

In 1991, the paper industry consumed 2.5 quads of energy, making it the third largest energy consuming industry in the United States. On average, about 31 million Btu are currently used to produce a ton of paper. The three most energy-intensive steps account for 83% of the energy consumed by the industry: pulping accounts for

26%, chemical recovery requires 19%, and papermaking consumes 38% (Figure 3-13).

It is perhaps not widely recognized but the paper industry makes extensive use of renewable resources to supply needed process energy. Indeed, almost two-thirds of all renewable fuels consumed by the U.S. industrial sector is accounted for by the industry's use of black liquor,

Photo courtesy of Donald Meadow, TAPPI Journal

Logs are cut to size on a truck at a plant that produces corrugating medium and linerboard.

Figure 3-13

Major Energy Flows in the U.S. Paper Industry

bark, and wood for fuel. Also, the industry generates almost 40% of the total on-site electricity generated by U.S. manufacturing industries by using cogeneration. Even with this use of renewable sources, the industry spent nearly \$5.5 billion on purchased energy in 1991, or nearly 4.3% of the value of its shipments. For the mill sector, this percentage nearly doubles to 8.2%.

Environmental Profile

The pulp and paper industry also generated more than 2.25 billion tons of waste in 1991, most of which was non-hazardous waste water and sludges. However, the waste streams from chlorine bleaching can contain toxic materials, including dioxins. Water-pollution control is the major environmental issue facing the industry. Major sources of pollutants include: digester and evaporator condensates, bleach plant filtrates, and paper machine white water (Figure 3-14). The industry is also subject to air emissions; estimated annual emissions include 800,000 tons of VOCs, 340,000 tons of sulfur, and 150,000 tons of other hazardous air pollutants. In addition, as part of its operating costs, the industry spent more than \$1.6 billion for pollution abatement in 1991, and invested more than \$1.2 billion in capital for pollution abatement equipment.

Moreover, the products the industry manufactures are often not recovered in full. In 1993, the industry attained a recovery rate of just over 40%. In 1993, recycled paper constituted 31% of fiber used at mills.

Recycling reduces the energy used for harvesting and transporting the timber, but is offset by the energy needed to collect, transport, and de-ink the waste paper. Recycling paper products also creates a wet sludge waste, which is currently inefficiently used. Depending on the paper product, the energy savings from using recycled paper have been estimated to be up to 57%. However, some

Figure 3-14

Major Waste Water Sources in the Paper Industry

paper products require more energy to produce with recycled feed-stock than if manufactured from virgin materials.

Mandates for increasing the recycled content of paper will require investing in recycling facilities in the near future because the federal government as well as some state, local, and foreign governments are increasing the recycled-fiber content required in paper products they purchase. Also, large corporations and many consumers are demanding recycled paper for their use.

THE OIT PULP AND PAPER PROGRAM

OIT's Pulp and Paper Program supports high-impact research and development to promote the development of a more efficient mill of the future. Historically, the OIT Pulp and Paper Program has focused heavily on pulping chemical recovery processes, which are complex and not well understood. Current activities in this area include the development and testing of new black liquor recovery and utilization technologies. The program also conducts research in the energy-intensive areas of pulping and papermaking.

Pulping Catalyst Development: Helping a Good Technology Reach a Wider Market

(National Renewable Energy Laboratory, Institute of Paper Science and Technology)

Although the kraft chemical pulping process is the world's dominant pulping method, the process has some severe shortcomings, one of which is its low yield of pulp from wood. Typical yields of pulp from southern pine, a tree commonly used in southern mills, fall in the range of 45% to 55%. Various pulping modifications have been proposed over the years to overcome this problem, but none has achieved wide commercial success. A more recent development that holds great promise is using the chemical anthraquinone (AQ) as an additive to the kraft process. AQ is a white powder that, when added to the wood chips during cooking, accelerates the kraft process dramatically and gives a 2% to 3% increase in yield. Already more than 100 mills worldwide are using AQ. Further use in the industry appears limited, however, because AQ's high production costs are passed on to the mills as high prices.

Research is being conducted to develop a cheaper method of developing AQ that would have the added advantage of using renewable resources instead of petroleum,

the current feedstock. Specifically, the new process would use a portion of the lignin byproduct of the kraft pulping process as the feedstock for producing chemicals that could subsequently be synthesized into AQ. The new process would produce AQ at a lower cost, making it economically feasible for more pulp and paper mills to use this additive to increase their pulp yields. AQ also allows pulping to take place at lower temperatures, resulting in an estimated energy savings of 7 trillion Btu each year if widely adopted. An environmental benefit of using AQ is reduced bleaching requirements, which means a decrease in harmful bleaching effluents. However, the biggest potential impact is that the development of cheaper AQ is expected to expand the use of sulfur-free pulping, an alternative pulping method that does not emit sulfur gases like the kraft process.

Black Liquor Gasification: Don't Just Burn It—Gasify It (*Manufacturing & Technology Conversion Intl.*)

Black liquor—the combination of dissolved wood waste and used pulping chemicals—is currently burned in recovery boilers to recover the chemicals for reuse and to use the embodied energy content of the wood waste to generate steam for use in the mill. Although quite efficient, the recovery boiler has limitations. Scientists are working on a black liquor gasification process that would increase the flexibility and safety of black liquor recovery while allowing even more energy to be recovered. In this new process, the liquid black liquor would be heated enough to convert it into a gas. The pulping chemicals are then separated out and recovered, leaving the remaining gas to perform double duty—as a heat source to generate steam in a boiler and subsequently as a fuel to be burned in an electricity-generating gas turbine. This dual use of a single fuel is known as cogeneration.

The benefits of using gasification are numerous and include improved safety, decreased environmental impact, higher energy efficiency, and lower operating costs. The smelt formed at the bottom of a conventional recovery furnace poses a small but deadly risk in the form of smelt-water explosions, one of the most

feared occurrences at a pulp mill. Smelt can't form in the gasifier, so the risk is eliminated. The gasifier process reduces emissions of particulates, SO₂ emissions, and NO_x emissions. The energy efficiency of the gasification process is higher than the recovery boiler because there is no smelt (a major source of heat loss) and

Table 3-14
Annual Benefits of Pulping Catalysts

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	1749	1676	73	7253
Total Cost (\$1000)	25,406	24,071	1335	133,506
Energy Cost (\$1000)	24,956	23,921	1035	103,506
Capital Cost (\$1000)	0	0	0	0
O&M Cost (\$1000)	450	150	300	30,000
Emissions (metric ton)				
CO ₂	305,801	293,118	12,683	1,268,300
NO _x	257	247	11	1068
SO _x	2310	2214	96	9579
Particulates	6043	5792	251	25,063
Solid Waste (1000 tons)	N/A	N/A	20	2000
Risk				
Technical		MEDIUM		
Market		MEDIUM		
Year of Maximum Market Share		2000		

Table 3-15
Annual Benefits of Black Liquor Gasification

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	2240	1867	373	84,000
Total Cost (\$1000)	6479	5243	1236	278,204
Energy Cost (\$1000)	5006	4172	834	187,740
Capital Cost (\$1000)	12	15	-3	-661
O&M Cost (\$1000)	1461	1056	405	91,125
Emissions (metric ton)				
CO ₂	165,222	137,685	27,537	6,195,820
NO _x	222	0.0	222	49,851
SO _x	689	399	290	65,250
Particulates	1565	1304	261	58,693
Solid Waste (1000 tons)	N/A	N/A	18	4000
Risk				
Technical		LOW		
Market		LOW		
Year of Maximum Market Share		2017		

because of the high energy conversion efficiency of the cogeneration process. Additional environmental benefits of the technology could be achieved if it is proven viable with biomass feedstocks such as paper mill sludge.

Development of Black Liquor Physical Properties:

Filling in the Knowledge Gaps (University of Florida)

Although the kraft pulping process is used extensively throughout the pulp and paper industry, many chemical engineering properties of the black liquor produced during kraft pulping are not fully understood. For more than a decade, DOE has sponsored research to study the physical properties of kraft black liquors. The ultimate goal of the research is to obtain careful and accurate data on viscosity and other important properties, and to use this information to develop predictive computer models that will help pulp mill engineers to improve the efficiency of their operations.

Careful control of the kraft chemical recovery process is critical to recovering the maximum energy content of the liquor and to maintain the efficient and environmentally acceptable operation of the recovery boiler. When completed, the black liquor computer model will allow recovery boilers to be operated with a more concentrated black liquor, a condition that has many associated advantages. Using a more concentrated liquor will raise the combustion efficiency in the boiler. On an industry-wide basis, the total potential energy savings of this increase in efficiency has been estimated at 44 trillion Btu each year. Combustion-related emissions of CO₂, particulates, and SO_x would be reduced significantly, and the furnace would be able to burn more black liquor in a given time, improving overall productivity.

Validated Recovery Boiler Model: Improved Understanding of Black Liquor Chemistry (Institute of Paper Science and Technology, University of British Columbia, Oregon State University, T.M. Grace)

The goal of this project is also to fill in some of the gaps in knowledge about the complex kraft chemical

recovery process. While the previously described effort examined the physical properties of the liquor itself, this effort is focusing more on the chemical reactions that take place in the boiler. These reactions must be carefully controlled for a number of reasons. First of all, they are critical to producing the desired pulping

Table 3-16

Annual Benefits of the Development of Black Liquor Physical Properties

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	9100	8699	402	44,162
Total Cost (\$1000)	20,339	19,441	897	98,701
Energy Cost (\$1000)	20,339	19,441	897	98,701
Capital Cost (\$1000)	0.0	0.0	0.0	0.0
O&M Cost (\$1000)	0.0	0.0	0.0	0.0
Emissions (metric ton)				
CO ₂	671,214	641,601	29,612	3,257,361
NO _x	900	860	40	4368
SO _x	2800	630	2170	238,700
Particulates	6358	6078	281	30,857
Solid Waste (1000 tons)	-	-	-	-
Risk				
Technical	MEDIUM			
Market	HIGH			
Year of Maximum Market Share	1998			

Table 3-17

Annual Benefits of the Validated Recovery Boiler Model

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	3360	2912	448	67,200
Total Cost (\$1000)	19,340	18,338	1001	150,192
Energy Cost (\$1000)	7510	6508	1001	150,192
Capital Cost (\$1000)	10,369	10,369	0.0	0.0
O&M Cost (\$1000)	1461	1,461	0.0	0.0
Emissions (metric ton)				
CO ₂	247,833	214,788	33,044	4,956,656
NO _x	N/A	N/A	15	2250
SO _x	N/A	N/A	75	11,250
Particulates	2348	2035	313	46,954
Solid Waste (1000 tons)	-	-	-	-
Risk				
Technical	LOW			
Market	LOW			
Year of Maximum Market Share	2007			

chemicals—not some unwanted byproduct—for recovery. The reactions also determine how efficiently and completely the wood waste in the liquor will be burned. Finally, they govern the amount of atmospheric emissions of undesirable gaseous byproducts. In this research effort, scientists are incorporating all available knowledge about the chemical reactions occurring in the recovery boiler, together with data on fluid flow in the boiler, to develop a computer model for designing and optimizing the chemical recovery process.

The advanced fluid flow and chemical reaction model can be used both as a process monitoring tool by pulp and paper mills and as a valuable design tool for recovery boiler manufacturers. It is anticipated that use of the model will enable recovery boiler efficiency to be increased from 65% to 75%, which equates to energy savings of 67 trillion Btu annually. In addition to reductions in combustion-related emissions, use of the model should result in reductions in sulfur emissions because of improved control of boiler reactions involving sulfur.

Impulse Drying: Using Steam and Compression for More Efficient Drying

(Institute of Paper Science and Technology, Beloit, Union Camp)

During papermaking, the newly formed paper is transferred from the main body of the paper machine to the dryer section, where it passes over steam-heated drying cylinders. This drying process is the single largest energy use in the papermaking process. The moisture content of the paper entering the dryer section is less than 50%. A new technology known as impulse drying is being developed to reduce the moisture content of paperboard (the type of paper used in boxes) during pressing, the last step before drying. Impulse drying uses a very hot roll to squeeze the paper; the combination of steam (formed at the hot roll surface) and compression expel water from the sheet, resulting in a moisture content of less than 40%. This greatly reduces the energy required in the drying section and allows the entire paper machine to run faster, thus increasing productivity.

On a national basis, adopting impulse drying on paperboard machines could result in energy savings of nearly 27 trillion Btu each year. This would reduce emissions of CO₂ by almost 2 million tons, NO_x by 2600 tons, volatile organic compounds (VOCs) by 120 tons, and particulates by 18,800 tons annually. Impulse drying also enables paperboard manufacturers to use a much higher percentage of recycled fiber—as much as 80%—than they are able to use with conventional technology. Increased use of recycled fiber means that less new pulp is needed, with a corresponding decrease in the use of pulping chemicals and in pulping-related pollution. Finally, paperboard made with impulse drying is stronger than its conventional counterpart and can meet product specifications at a lower weight, thereby reducing pulp requirements even further. Because pulp requirements are directly proportional to a mill's demand for wood, using impulse drying will also reduce the number of trees cut.

Table 3-18
Annual Benefits of Impulse Drying

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	2464	2,016	448	26,877
Total Cost (\$1000)	9647	9100	547	32,824
Energy Cost (\$1000)	5506	4505	1001	60,071
Capital Cost (\$1000)	2761	2235	526	31,554
O&M Cost (\$1000)	1380	2360	-980	-58,800
Emissions (metric ton)				
CO ₂	181,726	148,685	33,041	1,982,461
NO _x	244	199	44	2658
SO _x	758	620	138	8269
Particulates	1721	1408	313	18,780
Solid Waste (1000 short tons)	-	-	-	-
Risk				
Technical	MEDIUM			
Market	LOW			
Year of Maximum Market Share	2002			

The Steel Industry

REFURBISHING A CRITICAL COMPONENT OF OUR INDUSTRIAL INFRASTRUCTURE

Steel is vital to the United States for both national security and economic well-being, and is the most basic and widely used metal in an industrial society. Steel's widespread usage can be attributed to its great versatility, high strength-to-cost ratio, and the fact that iron ore—the raw material from which steel is made—is one of the most abundant metallic minerals in the earth's crust. Although there are acceptable substitutes for steel in many of its uses, in the short term practical alternatives on a large scale are few because of the higher cost, inadequate performance or insufficient availability of these alternative materials. Moreover, the industry that makes, shapes and ships steel products is a \$57 billion dollar-a-year industry employing more than 236,000 workers that—despite its recent vast restructuring—remains as critical a component of our nation's industrial infrastructure as ever.

The steel industry is divided into two principal segments: the generally large, integrated producers and the typically much smaller nonintegrated producers. Integrated steel producers smelt iron ores to liquid pig iron in blast furnaces and refine the iron with added scrap in basic oxygen furnaces. Nonintegrated steel producers, on the other hand, rely primarily on scrap for their raw materials. Broadly speaking there are two types of nonintegrated mills: minimills and specialty mills. Minimills melt scrap in electric furnaces, and utilize continuous casting and hot rolling mills to produce tonnage carbon steel products. Specialty mills, on the other hand, produce stainless, high-temperature and other alloy steels for a variety of mostly niche markets.

The New Look of the American Steel Industry

In response to the numerous and severe competitive pressures confronting it in the 1980s, the U.S. steel industry has undergone widespread and profound restructuring. It has invested heavily in continuous casting and other new technologies, adopted new management styles, closed several outmoded plants, and greatly improved its productivity and quality. The restructuring has altered considerably the industry's basic profile. For example, in 1982 the top eight firms produced 74% of the nation's crude steel; by 1992, the share of industry output accounted for by the eight largest producers had declined to 52%. The decrease in industry concentration reflects both the expanded role of minimills in the industry and substantial downsizing of the integrated producers. The changing industry structure—with a greater role for electric-furnace-based minimills—boosted U.S. output of electric arc steel to 33 million tons in 1993 or 38% of the U.S. total.

As with all such upheavals, the restructuring of the steel industry over the past decade has had its downside. Raw steel production in the U.S. dropped by nearly 30% between 1980 and 1992, and the permanent closure of several

major steel mills cut the U.S. share of world steel capacity to about 10%. But the human dimensions of the restructuring have been staggering. The shutdown of numerous steelmaking facilities and furnaces resulted in the layoff of tens of thousands of workers. By 1992, steel industry employment had shrunk 60% to about 236,000 workers.

Fortunately, however, the extensive changes that have taken place in the steel industry have had significant positive effects as well. For example, the downsizing of the workforce, increased use of continuous casting and automation, and workforce training have significantly enhanced

Table 3-19
*Steel Industry Profile**

Volume of Products (1993)	82 million tons
Value of Shipments	\$57 billion
Total Employment	236,000 jobs
Capital Expenditures	\$2.6 billion
Net Trade Balance	-\$4.5 billion
Energy Consumption	1.7 quads
Waste Generation	8 million tons of dust and sludge
Average Hourly Earnings	\$17.52

*Data for latest year available

Figure 3-15

Geographic Distribution of Iron and Steel Facilities, 1992

Total Facilities = 310

worker productivity. Productivity increased at nearly a 7% annual rate during the last decade and now equals that of Japan and exceeds that of any other major steel-producing country. Moreover, as labor productivity increased, so did worker compensation. In 1992, steelworkers earned an average of almost \$30/hour (including benefits), compared with \$24 per hour in 1987. Though minimill wages tend to be somewhat lower, in many cases these firms have introduced profit-sharing plans and productivity base pay. Ultimately, the far-reaching changes occurring in the U.S. steel industry enabled it to ship about 82 million tons of product in 1993. At the same time, import market penetration was at its lowest level since 1980 (Figures 3-16 and 3-17).

Continuing Challenges: Competition, Cost, Quality and Coke

Despite the improved physical performance of the steel industry, it has continued to struggle financially—especially the large, integrated firms. Between 1989 and 1992, weak demand in the United States and abroad kept prices low, and the industry sustained a cumulative operating deficit of \$3.5 billion. Moreover, many stresses continue to challenge the steel industry. Foreign and inter-material competition as well as competition between the integrated producers and minimills are forcing steelmakers to develop and invest in ever more efficient and quality-enhancing technologies.

At the same time, environmental legislation is challenging the industry to develop cleaner and more efficient steelmaking processes. Steelmaking generates many air pollutants, including carbon monoxide, nitrogen oxides, sulfur dioxide, and particulates. Clean Air Act provisions covering air toxics, permits, and enforcement will also significantly affect the industry—especially coke ovens. Even though coke oven emissions have fallen an average of 90% since 1970, increasingly

stringent environmental regulations make operations at existing coke plants more costly and are speeding up the closure of several coke ovens. Coke-making capacity decreased from approximately 42 million tons in 1980 to 24 million tons in 1992. Because environmental regulations concerning coke ovens will force the shutdown of

many facilities, the steel industry is actively developing and testing alternatives to the conventional coke oven/blast furnace method of making iron.

In the long term, the steel industry will likely continue to move towards more simplified and continuous primary stage technologies that reduce the capital costs for new mill

Figure 3-16
Trends in U.S. Steelmaking

Figure 3-17
Comparison of Production Costs

construction, allowing smaller mills to operate efficiently. The OIT steel program is responding to these evolving needs.

THE MANUFACTURING PROCESS: MULTIPLE STEPS AND PROCESSES

The ore-based steelmaking process for semifinished steel production has five principal steps: 1) pelletization, 2) cokemaking, 3) ironmaking, 4) steelmaking, and 5) casting. Scrap-based steelmaking essentially has only the last two processing steps that ore-based steelmaking has. Iron ore and coal—supplemented by scrap—are the major ingredients for ore-based production, while steel scrap is the feed material for scrap-based steel production (Figure 3-18).

Pelletization: Preparing Ore for the Furnace

Iron ore is prepared by being crushed, ground, and then agglomerated into marble-sized pieces that can be fed into a blast furnace. Most often, this occurs through pelletizing. In pelletizing, an unbaked ball or green pellet is formed with iron ore concentrate combined with a binder. Such pellets are then hardened by heat treatment in an oxidizing furnace. Pelletizing is almost always conducted near the mine site.

Cokemaking: Boiling Off the Volatiles

Coke, a form of carbon, is used to produce reducing gases and heat to reduce iron ore to metallic (pig) iron. Coke is produced by heating (baking) high-grade (metallurgical) coal for nearly 15 hours, which boils off volatile compounds and leaves behind 90% pure carbon product. The reactions are stopped by quenching the coke with water from overhead spray systems.

Ironmaking: Removing the Oxygen from Iron Ore

Blast furnaces are the most common technology used to convert the prepared iron ore into iron. The ore is fed into the top of the blast furnace together with coke and limestone and/or dolomite. Heated air is blown into the furnace from the bottom, which produces carbon monoxide from oxygen in the air and coke. The carbon monoxide reduces the ore by removing oxygen to produce molten pig iron and slag. The molten iron is then removed from the remaining slag of limestone and other impurities.

Steelmaking: Refining and Alloying the Iron and Scrap

Steelmaking refines the molten iron or scrap. The process removes impurities and adds alloying elements to provide the required properties.

Integrated: Primary steelmaking occurs in a basic oxygen furnace where pig iron and scrap are refined into steel. Oxygen is blown into the furnace and reacts with carbon in the molten iron to form carbon monoxide and carbon dioxide. These gases remove carbon from the melt and vigorously boil the melt to accelerate other refining reactions. Refining time for the process is less than 1 hour.

Minimills: These mills produce steel by melting scrap in an electric arc furnace, which is economical at smaller scales than basic oxygen furnaces. The graphite electrodes are lowered into the furnace and melt the scrap by radiation. This process generally takes between 1 and 2 hours.

Casting: Steel Takes Shape

Continuous casting is the predominant technique in which the liquid steel is poured directly into its semifinished shape. Continuous casting forms steel into semifinished shapes that are rolled into such products as bars, rods, plates, and strip. Afterwards, the steel is annealed and allowed to cool slowly to relieve internal stresses in the steel. In 1993, 86% of steel was continuously cast, which is a significant increase from 29% in 1982, resulting in a marked improvement in yield of finished products from liquid steel.

Energy: Less Coal and Coke, More Electricity

The steel industry is the fourth largest energy-consuming industry in the United States. In 1991, the industry consumed 1.7 quads of energy. Coal is the largest energy source, accounting

Figure 3-18
Simplified Steelmaking Flowchart and Major Energy Flows

for nearly half of energy use, while natural gas accounts for a quarter of energy use. Electricity is the largest energy component of scrap-based steelmaking. On average, about 21 million Btu are currently used to produce a ton of finished steel. The most energy-intensive steps are cokemaking (6 million Btu), iron-making (14 million Btu), and finishing (4.7 million Btu). The industry spent \$4.8 billion on purchased energy in 1991, or 8.7% of the value of shipments.

Metals Initiative

The Steel and Aluminum Energy Conservation and Technology Competitiveness Act of 1988, commonly referred to as the Metals Initiative, was signed into law on November 17, 1988. The Act has the following purposes: 1) to "increase the energy efficiency and enhance the competitiveness of American steel, aluminum, and copper industries...", and 2) to continue the R&D efforts begun under the DOE program known as the Steel Initiative.

The Metals Initiative represents a commitment on the part of the federal government to pursue and promote the continued economic strength, energy security, and environmental integrity of the United States. It also reflects a growing awareness in both the private and public sectors of the importance of maintaining our nation's competitiveness in the global business environment. Significant R&D efforts in steelmaking and other metals production are already underway in Japan and the European Community, and efforts such as the Metals Initiative will continue to be important to maintain our position in an increasingly competitive and dynamic marketplace. The successful development and implementation of the revolutionary technologies now evolving through Metals Initiative R&D will assist the U.S. metals industries in meeting the growing international challenge. It will also provide the means to further improve the productivity standards of the U.S. metals industries while significantly reducing energy consumption.

Environmental Profile

Primary steelmaking produces many air pollutants, including carbon monoxide, nitrogen oxides, sulfur dioxide, and particulates. Coke oven emissions are targeted for early control under the Clean Air Act Amendments of 1990. Production of coke has declined sharply from about 60 million tons in the early 1970s to 24 million tons in 1992.

The primary production of steel also requires a great deal of water. One estimate placed 75,000 gallons of water for each ton of steel produced. While most of this water is recycled and reused, the industry is likely to be substantially affected by restrictive water quality regulations.

Capital expenditures for pollution control were about \$287 million in 1992, while the operating costs for pollution control added an average of \$14 per ton of steel shipped—or \$1 billion total in 1991. Finally, steel is recycled to the extent possible when economical, but the permanent use of steel in many applications, such as in buildings, necessitates production of raw steel. Of all the steel produced, about 60% is from recycled scrap (Figure 3-19).

THE OIT STEEL PROGRAM

OIT's R&D activities for the steel industry are conducted under the Metals Initiative, mandated under the Steel and Aluminum Energy Conservation and Technology Competitiveness Act of 1988. The iron and steel industry uses some of the most energy-intensive processes found in the entire industrial sector. To increase the energy efficiency of these processes, OIT is working to combine or eliminate energy-intensive operations, improve the efficiency of existing processes, and reduce manufacturing costs to increase the industry's competitiveness in world markets.

Direct Steelmaking: Revolutionizing the Future of Steelmaking

(American Iron and Steel Institute)

Incremental improvements to existing iron and steelmaking processes can improve efficiency and productivity only so far; to achieve more dramatic results, totally new technologies must be developed. A case in point is the direct steelmaking process, in which the blast furnace and coke ovens are replaced by a coal-based smelter. In contrast to current steelmaking processes—which are largely open and produce molten iron in batches—

Photo courtesy of Timken Company

Continuous casting of steel reduces energy consumption, is highly productive, and costs less.

Figure 3-19
Major Waste Sources

the direct steelmaking is closed and produces a continuous stream of molten iron (molten steel, if the current phase of research is successful). In this new process, coal and pre-reduced iron ore pellets are fed into a smelter vessel already containing a bath of liquid iron. Oxygen is injected into the vessel, converting the iron ore into liquid pig iron. Further treatment with oxygen reduces the carbon content of the steel to the desired levels for the finished product.

Potential advantages of direct steelmaking over conventional steelmaking are numerous:

- **Reduced energy consumption.** The new technology will potentially yield a 20% reduction in the energy required to convert iron ore to liquid steel.
- **High productivity.** The new process may achieve up to five times the production rate of conventional processing.
- **Simplification of facilities.** Coke plants, which are costly to build and operate, will be eliminated.
- **Feedstock flexibility.** The process can use a wide variety of non-coking coals, which are cheaper than coking coals.
- **Lower costs.** In addition to avoided energy costs, lower O&M and capital costs could be achieved.

Table 3-20
Annual Benefits of Direct Ironmaking at 350,000 tons per year¹

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	6440	5215	1225	165,375
Total Cost (\$1000)	63,302	47,017	16,285	2,198,475
Energy Cost (\$1000) ²	12,600	4500	8100	1,093,500
Capital Cost (\$1000)	17,627	11,017	6610	892,350
O&M Cost (\$1000) ³	33,075	31,550	1525	205,875
Emissions (metric ton)				
CO ₂	879,821	761,338	118,483	15,995,205
NO _x	700	70	630	85,050
SO _x	860	55	805	108,675
Particulates	525	340	185	24,975
Solid Waste (1000 tons)	-	-	-	-
Risk				
Technical		LOW		
Market		MEDIUM		
Year of Maximum Market Share		2030		

¹ Benefits projected are based on greenfield installations.

² Energy costs shown are after off-gas energy credit.

³ Includes non-energy materials.

- **Reduced emissions/reduced pollution control requirements.** Coke ovens are a major source of SO_x, NO_x, and particulate emissions. Elimination of cokemaking will reduce the burden of steelmakers in controlling these emissions to meet Clean Air Act requirements.

The bottom line is an expected \$20/ton reduction in operating costs (typically \$175/ton for a modern plant) over current steelmaking processes, which will help U.S. steelmakers to compete better with international producers such as Brazil and South Korea. The widespread adoption of direct steelmaking will result in total U.S. energy savings of about 200 trillion Btu annually.

Steel Plant Dust and Sludge (Waste Oxide) Recycling:

Recovering the Iron in the Landfill (American Iron and Steel Institute)

Waste byproducts are generated at a number of sites within the steel mill, including the coke ovens, blast furnace, basic oxygen furnace (BOF), and hot rolling mill. Blast furnace ironmaking generates dust that is removed by a dust catcher and a wet

scrubber. The wet scrubber produces an effluent that, after treatment, produces a fine-particle, sometimes oily sludge that is often landfilled. Similarly, the BOF process usually has an emission control system that removes fine oxides (in the form of dust) from BOF off-gas. The dust is either landfilled or treated with a wet emission control system, which yields sludge that is itself often landfilled. An iron oxide sludge is produced in the hot rolling mill. This sludge must be removed in a wastewater treatment system. For years, these byproducts have been landfilled on-site with the hope that reclamation would become economically feasible at some point in the future.

That point looms much nearer with the initiation of a project to develop a process for recycling blast furnace and BOF dust and sludge, and rolling mill sludge. The new process uses a smelter, a completely enclosed melting vessel. The molten pig iron is processed in the BOF. It is anticipated that more than 3.5 million tons of sludge and dust will be recycled each year with the smelter process, greatly

reducing landfilling of these wastes. The annual benefits of this include up to 150 trillion Btu of energy savings, \$100 million savings in disposal costs, and more than \$50 per ton of cost savings for pig iron produced using the recovered iron oxide.

Electrochemical Removal of Zinc from Steel Scrap: Better Use of a Valuable Resource
(Argonne National Laboratory, Metal Recovery Industries, Inc.)

Galvanizing is a process in which steel parts—such as those used in auto bodies—are coated with zinc to prevent corrosion. The high quality of galvanized steel makes this scrap a valuable feedstock for both steel-making and foundry operations. Unfortunately, the zinc coating on galvanized steel scrap causes severe operating and environmental problems and has a deleterious effect on product quality. The electrochemical dezincing process being developed not only removes this zinc but recovers it for reuse, potentially reducing U.S. zinc imports while producing clean scrap.

Electrochemical dezincing takes place in a large tank. The scrap is then washed and shipped to a steel mill or foundry. Energy is saved because the energy required to dezinc scrap is about 20% of that for producing molten iron, the conventional steel-making furnace feedstock. By the year 2000, electrochemical dezincing could conserve nearly 7 trillion Btu, reduce raw material costs to the U.S. iron and steel industry, and reduce foreign imports of zinc. Environmental benefits of the process include elimination of both baghouse dust and zinc contamination in waste water associated with the melting of galvanized scrap. The consumption of galvanized steels has roughly doubled since 1980 and is expected to continue growing at a steady rate; the U.S. steel industry cannot afford to underutilize this valuable resource.

Advanced Process Control Research Program for the Steel Industry: Developing Better and Faster Steelmaking Control Techniques
(American Iron and Steel Institute)

A 5-year program has been initiated to develop new and improved methods of measuring steel processing parameters and properties from

production through casting and forming into finished products. Being able to more accurately measure properties such as temperature, composition, and strength can help steelmakers optimize their processes to yield the highest possible quality steel and steel products as efficiently and with the least environmental impact as

Table 3-21
Annual Benefits of Steel Plant Dust/Sludge Recycling

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	17,700	15,900	1800	14,400
Total Cost (\$1000)	215,119	153,818	61,301	490,407
Energy Cost (\$1000)	37,521	33,705	3816	30,526
Capital Cost (\$1000)	35,238	21,143	14,095	112,761
O&M Cost (\$1000)	142,360	98,970	43,390	347,120
Emissions (metric ton)				
CO ₂	1,607,312	1,443,857	163,456	1,307,644
NO _x	218	195	22	177
SO _x	1234	1108	125	1004
Particulates	487	438	49	396
Solid Waste (1000 metric tons)	N/A	N/A	454	3629
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		2015		

Table 3-22
Annual Benefits of Electrochemical Removal of Zinc from Steel Scrap

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	881	148	733	7330
Total Cost (\$1000)	7414	5581	1833	18,330
Energy Cost (\$1000)	1534	2112	-578	-5784
Capital Cost (\$1000)	1081	869	211	2114
O&M Cost (\$1000)	4800	2600	2200	22,000
Emissions (metric ton)				
CO ₂	81,146	26,593	54,553	545,534
NO _x	0.6	25	-24	-241
SO _x	63	199	-136	-1365
Particulates	26	512	-487	-4865
Solid Waste (1000 tons)	N/A	N/A	82	820
Risk				
Technical		LOW		
Market		LOW		
Year of Maximum Market Share		2002		

Table 3-23
Annual Benefits of Advanced Process Control

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	26,100	25,800	300	16,500
Total Cost (\$1000)	247,000	245,123	1877	103,225
Energy Cost (\$1000)	121,959	120,557	1402	77,100
Capital Cost (\$1000)	0.0	1100	-1100	-60,500
O&M Cost (\$1000)	125,041	125,466	1575	86,625
Emissions (metric ton)				
CO ₂	2,840,166	2,807,520	32,646	1,795,507
NO _x	2372	2136	236	12,973
SO _x	19,842	18,377	1465	80,581
Particulates	52,328	51,727	604	33,081
Solid Waste (1000 tons)	N/A	N/A	0.4	20
Risk				
Technical		MEDIUM		
Market		LOW		
Year of Maximum Market Share		2005		

possible. Each of the six tasks currently sponsored by the program represents a collaborative effort between one or more research organizations, a sponsoring steel company acting as technical advisor, and an equipment manufacturer to commercialize the proven equipment or system.

Optical Sensors and Controls for Improved BOF Operations

(Sandia National Laboratories, Insitac Measurement Systems, Bethlehem Steel)

In the absence of up-to-the-minute data on what's really happening inside the BOF during steelmaking, steelmakers tend to err on the side of caution, leaving the molten steel in the furnace longer than necessary and tapping at lower carbon levels. Two new optical sensors are being developed that could change this practice—one for real-time measurement of the composition and temperature of BOF off-gases, and one for measuring the temperature of the steel bath. Both of these sets of valuable process information will be used to develop a new BOF control strategy to allow the molten steel to be tapped (removed from the furnace) at a lower temperature and precise carbon levels, reducing processing time and increasing

furnace productivity. These sensors also have potential use in other high-temperature processes.

Improved Liquid Steel Feeding for Slab Casters

(Westinghouse, North American Refractories Co., U.S. Steel)

Certain aluminum-containing steel alloys are difficult to cast into final products because the aluminum, in the form of alumina, tends to clog the valves and other moving parts in the caster feeding system. Clogging causes quality problems in the steel products, wastes valuable time for repairs, and forces early replacement of clogged parts. To eliminate clogging, an electromagnetic valve system with no moving parts is being developed for use in a continuous casting mold. The new valve should save both time and money while increasing product quality. This technology should find wide application in other continuous casting operations as well, particularly with advanced casting techniques that require precise control of the flow and level of liquid metal.

Microstructure Engineering for Hot Strip Mills

(National Institute of Standards and Technology, University of British Columbia, Northwest Mettech Co., U.S. Steel)

Hot rolling is a process in which the semi-finished steel shapes produced during casting are reheated and rolled into strip and other final products. Some steel alloys are difficult to hot roll because the desired properties of the final product must be controlled within very tight specifications. These properties are dependent upon the exact design and operating conditions of the hot strip mill. A new computer model is being developed to help steelmakers predict the thermal and microstructural evolution of steel during hot rolling, as well as predict the final product properties, based on mill design and operating practices. Quantitatively linking the properties of hot rolled products to the process parameters of the mill will yield higher quality strip with far fewer rejects, thus increasing yield by half a percent and reducing production costs.

Online Mechanical Properties Measurements

(Industrial Materials Institute, National Institute of Standards and Technology, Ultra Optec, Data Measurement Co., LTV Steel, Weirton Steel)

After steel strip is produced during hot rolling, the strip is cold rolled to improve the metal's ductility. The strip is subsequently heat treated to correct the deformation that occurred during cold rolling. The most common form of heat treatment is annealing. Because critical steel properties (such as strength) of annealed products are currently measured only in the front and tail of the strip, the quality of annealed products sometimes suffers. New on-line sensors currently under development will soon change this, however. Two sensors—one magnetic and one laser-ultrasonic—are being investigated as a means of measuring mechanical properties of

interest throughout the strip, thus ensuring higher quality and less time spent reprocessing out-of-spec strip.

Phase Measurement of Galvanneal

(Data Measurement Co.,

Jet Propulsion Laboratory, Inland Steel)

Galvannealed steel sheets are steel sheets coated with a mixture of zinc and iron to improve their corrosion resistance, weldability and paintability, desirable characteristics for products such as auto body panels. A critical factor in making galvannealed sheet is the micro-structure of the zinc-iron coating, which currently can only be measured off-line in the laboratory. This means that any necessary adjustments to control the micro-structure cannot be made quickly enough to benefit all of the sheet being processed. Any sheet that does not meet the required specifications must be reprocessed—wasting time, materials, energy, and money. An online X-ray instrument for determining the micro-structure is being developed that will greatly reduce the time lag between measurement and corrective action. This will improve both the efficiency and the productivity of galvannealing operations.

Temperature Measurement of Galvanneal

(Oak Ridge National Laboratory,

University of Tennessee, National Steel)

In another effort aimed at improving galvannealing operations, a new non-contact method of measuring the temperature of the sheet as it exits the galvannealing furnace is being developed. This new technique is based on phosphor thermography, in which a phosphor compound is applied to the surface of the strip and illuminated with a laser or ultraviolet light. This on-line measurement will provide faster feedback on galvanneal product quality, thus reducing product variability and rejection rates. In the long term, it is hoped that this sensor, together with the micro-structure sensor described above, will allow galvannealing properties

to be measured in real time, with no time lag between taking the measurement and getting the result. Industry experts believe that temperature sensing will be applicable to other steel-making processes.

The Aluminum Industry

USEFUL PROPERTIES, LOW COST AND HIGHLY RECYCLABLE

Aluminum possesses numerous useful properties including its strength and light weight, corrosion resistance, electrical conductivity, recyclability, and the fact that it is nontoxic. In addition, its natural resources (mainly bauxite) are abundant on a worldwide basis, and the costs of producing the metal are relatively low contributing to several mass markets. The useful properties of aluminum find applications in a particularly broad range of products from beverage cans to motor vehicle parts, aircraft, power transmission cables, and construction applications such as siding and doors.

The United States is the world's largest producer and consumer of aluminum metal and products. Industry shipments in 1993 of an estimated 8.2 million metric tons of product (up from about 7.1 million tons in 1980) were valued at about \$21 billion. This U.S. industry is divided into several major segments: alumina refining, primary metal smelting, secondary (recycled) metal smelting, fabricated products, and foundries. The primary segment produces aluminum from bauxite/alumina raw materials, whereas the secondary segment recovers aluminum from post-consumer and industrial scrap.

Electrolytic reduction of metal is the core technology around which the primary industry is built, and aluminum reduction (smelting) is a very energy-intensive process. On average, energy accounts for about a third of industry production costs, and the U.S. aluminum industry annually consumes approximately one quad of primary energy. The industry employs about 134,000 workers in all phases of its operation including alumina plants, smelting, recycling, fabrication, and foundries. Wages of aluminum industry workers exceed those of their counterparts in most other industries

as their hourly wages are about 41% above the average for all domestic industries.

Secondary (scrap) aluminum recovery requires considerably less energy than primary (virgin) metal production, and energy costs can be reduced as much as 95%. Low energy costs for recycling, together with growing concerns over solid waste disposal, have contributed to substantial growth in aluminum recycling in the United States. In 1960, about 400,000 tons of aluminum were recycled; by 1992, the corresponding figure was 2.8 million tons (Figure 3-20). Currently there are about 68 secondary aluminum smelters in the United States, employing more than 3,500 workers. Secondary smelters are mostly located near major industrial and consumer centers such as Southern California and the Great Lakes region, which generate large quantities of waste and scrap.

Recent Restructuring

For three decades following World War II aluminum was the fastest-growing U.S. metals industry, aggressively replacing steel in uses such as beverage cans and autos, and copper in wire and cable. Its light weight and strength also contributed to major tonnage uses in the aircraft market.

As late as the mid-1960s, the U.S. accounted for 40% of world aluminum production. However, as oil prices increased sharply in the 1970s, growth of the energy-intensive aluminum industry slowed considerably. Simultaneously, just as rising costs and aluminum prices were tempering rapid growth in demand for the metal, the number of countries producing the metal grew quickly, foreshadowing increased global competition.

By the 1980s, changing business conditions and a highly competitive world market forced the U.S. aluminum industry into an aggressive restructuring. Between 1987 and

Table 3-24
*Aluminum Industry Profile**

Volume of Products	8.2 million metric tons
Value of Shipments	\$21 billion
Total Employment	134,000 jobs
Capital Expenditures	\$0.8 billion
Net Trade Balance	-\$0.3 billion
Energy Consumption	1.0 quad (including electricity losses and alumina)
Waste Generation	130,000 tons of polliner and red mud
Average Hourly Earnings	\$15.14

*Data for latest year available

Figure 3-20
Aluminum Smelting Capacity and Recycling in U.S.

Source: U.S. Bureau of Mines

1992, U.S. firms closed about 1.1 millions tons of high-cost U.S. smelting capacity (nearly 25% of the U.S. total) to lower their average domestic production costs to more competitive levels. U.S. smelter closures, combined with expanded capacity in other countries, meant that by 1992, the U.S. share of world aluminum capacity had declined to about 20%.

As domestic firms lowered their presence in the smelting end of the business at home, they invested in low-cost aluminum capacity overseas in such countries as Venezuela, Brazil, Australia and Canada that have access to relatively low-cost electric power. Simultaneously, they increased their investment in the fabrication end of the industry in the United States, and boosted substantially their recycling of used beverage cans as a way of further reducing their average costs of production. In addition, they aggressively pursued larger shares of the automobile and packaging markets through joint ventures and foreign investment.

Competitiveness Strategies

The principal driving forces for restructuring the world aluminum industry over the last two decades have been the price of aluminum and the cost of energy. The United States has almost 25% of the world's capacity for primary aluminum production, but remains one of the higher cost producers in the world at about 56 cents per pound. The other leading producers, Russia and Canada, have production costs of 48 cents and 50 cents per pound, respectively (Table 3-25).

Though demand for aluminum continues to increase worldwide, lower power costs in competing countries reduce considerably the likelihood that greenfield aluminum smelters will be built in the United States. Rather, the aluminum industry seems likely to continue its recent supply-side strategies of investing in

Table 3-25

Aluminum Smelter Capacity, Production, and Average Production Cost (1992)

Country	Capacity	Production	Production Costs
	Thousand Metric Tons		Cents Per Pound
Australia	1240	1216	45.3
Brazil	1156	1195	54.3
Canada	2283	1972	50.0
China	1315	950	N/A
France	472	417	51.9
Germany	713	600	64.3
Norway	851	861	56.3
Russia	3654	3115	47.6
United States	4163	4042	56.1
Venezuela	610	566	45.3

Source: Industry and Trade Summary, U.S. International Trade Commission

primary aluminum smelters in low-cost areas outside of the country. At home, the industry seems likely to continue to prefer retrofitting existing plants with incrementally improved technologies rather than constructing new smelters. Another continuing industry tendency is likely to be increased investment in fabrication and recycling facilities in the United States. These fundamental tendencies of the evolving aluminum industry of the future are reflected in OIT's aluminum research and technology portfolio discussed on pages 75-77.

THE MANUFACTURING PROCESS: SEPARATION, SHAPING AND SCRAP RECYCLING

Though aluminum can be recovered from many minerals, it is produced most economically from bauxite. Bauxite is refined into alumina, which in turn is smelted to produce 99+%-pure aluminum metal (Figure 3-21). The average mass ratio of the three products—bauxite, alumina, and aluminum metal—is very close to 4:2:1. The industry processes the raw aluminum (ingots) into sheet, plate, foil, and extruded products. The secondary aluminum industry recovers aluminum metal from old (discarded products) or new (industrial) scrap. Secondary aluminum is typically converted into beverage cans or shipped to aluminum foundries and cast into fairly intricate shapes.

Refining: Separating Alumina from Bauxite

The Bayer refining process produces pure alumina (Al_2O_3) from bauxite. Bauxite generally contains alumina, gangue (worthless rock and minerals), and water. The bauxite is crushed and ground, then digested in hot caustic soda solution. The alumina minerals in the ore react with the caustic and dissolve as sodium-aluminate. Most of the impurities in the ore, such as iron and silica, do not dissolve and are separated out. The solution is then seeded with starter crystals, cooled and agitated to crystallize out alumina hydrate. This material is then calcined (heated) to remove the water, resulting in pure alumina.

Smelting: Separating Aluminum from Oxygen in Alumina

The Hall-Heroult smelting process reduces the alumina to aluminum and is practiced in virtually all smelting operations. Alumina is dissolved in a molten cryolite bath contained in carbon-lined steel cells (pots). In each pot, a direct current is passed through the bath (between a carbon anode and the carbon bottom of the cell) to reduce the dissolved alumina into aluminum. The reaction creates aluminum and carbon dioxide. Molten aluminum collects at the bottom of the pots and is siphoned off into large crucibles. The aluminum is poured directly into molds to produce

foundry ingot or refined, by adding alloying agents, to make fabricating ingot; more modern plants empty crucibles directly into alloy furnaces before casting ingot for sheet or extrusion products. Scrap aluminum may be added to the melt at this stage if desired. The carbon anodes are consumed in the process, necessitating continual production of these anodes, and are produced at the smelter by baking petroleum coke and coal tar pitch.

Fabrication: Forming Ingots into Useful Shapes

Foundries melt the ingot and cast aluminum into products (see Foundries section on page 78). Ingot is also used to fabricate products through rolling, forging, drawing, and extruding. All of these processes occur with heated, but not molten, aluminum ingot. Rolling presses aluminum into sheet, foil, and plate. Forging hammers aluminum into products by using dies. Drawing pulls aluminum through progressively smaller holes into rod, wire, and bar. Extruding pushes aluminum into shapes and tubing, including beverage cans.

Recycling

Scrap aluminum is generally recycled. Old scrap, such as castings and aluminum cans, along with new scrap, such as solids and clippings from aluminum users, is used to produce secondary aluminum. The value of the scrap is directly related to the ease and efficiency with which it can be collected, sorted, and processed into a salable product. The production of secondary aluminum involves four steps: collection and sorting, pre-smelting preparation, smelting and refining in furnaces, and pouring into ingot. Most secondary aluminum goes to foundries or into beverage cans.

Energy: Electricity Intensive

The primary aluminum industry has one of the highest energy-intensities in any manufacturing process. Although the industry only

Figure 3-21
Primary Production Process and Energy Flows

consumes about 0.3 quad of end-use energy, energy accounts for nearly one-third of all production costs. Most of the energy consumed is electricity for smelting. The main sources of this electricity are hydroelectric, coal and oil. On average, it currently takes more than 7 kWh to produce one pound of aluminum. The average total energy used to make a ton of aluminum is nearly 180 million Btu—nearly 9 times as much energy as is required to make a ton of steel. Secondary aluminum requires as little as 5% as much energy to produce, which makes the economic attractiveness of recycling favorable. In 1991, the industry spent \$2.0 billion in energy costs, or about 8.6% of value of shipments. For primary production, the costs were \$1.55 billion, or about 22% of the value of shipments. Smelting operations account for 70% of energy use for primary aluminum, and refining accounts for 15% (Figure 3-22).

Environmental Profile

Although aluminum production is not as damaging to the environment as some other metals production, it still has several environmental concerns. Roughly 50 to 70 pounds of spent potliner, or insulating brick, are generated for each ton of aluminum produced. The spent potliner contains fluoride, sodium, and cyanide contaminants and is listed as a

Photo courtesy of Coors Brewing Company

Beverage cans are made from secondary aluminum.

hazardous waste. The production of aluminum also creates fluoride emissions, which must be controlled. The reaction in the electrolytic cell creates carbon dioxide. Emissions also come from the production of electricity and from producing carbon anodes. Finally, the extraction of alumina from bauxite produces 2 pounds of gangue per pound of alumina and wastewater during the calcination process.

THE OIT ALUMINUM PROGRAM

The Metals Initiative described earlier directs the U.S. Secretary of Energy to conduct R&D activities of aluminum technologies in addition to steel. Currently, one project is being sponsored in each of the three major process areas: refining, smelting, and fabrication.

Energy Efficient Calciner: Letting Pressure Help Temperature Do the Job (ALCOA)

Calcination—heating at a high temperature—is the last step in the production of alumina from bauxite ore. In the calcining step, water is removed from the alumina to prepare it for processing in the Hall-Heroult electrolytic cell. The current alumina

calcination process relies on high temperatures to force out the water; a new process is being developed, however, that relies on the combination of high pressure and temperature to dry the alumina. Because there are two driving forces instead of one in the new process, the calciner can be operated at a lower temperature, thus saving energy.

In addition to energy savings of 5–6 trillion Btu annually, the new calciner will produce alumina that has improved physical properties over alumina from a conventional calciner. The size of the alumina particles will be more uniform, and they will produce less dust and therefore require simpler environmental controls. The new calciner system is designed to enable steam from the process to be recovered for process use within the plant. Researchers estimate that the total benefits of using the energy-efficient calciner will amount to cost savings of more than \$12 million annually.

Inert Anode/Cathode System for Aluminum Smelting: Closing the Gap on Efficiency (*Reynolds Metals, Great Lakes Research, Kaiser, ELTECH*)

For the past 100 years, all primary aluminum in this country has been produced in Hall-Heroult electrolytic cells that pass an electric current through alumina to convert it to aluminum metal. Each electrolytic cell has an anode—typically made of carbon—and a cathode consisting of molten aluminum. These types of anodes and cathodes are far from ideal from an operating perspective, however. The carbon in the anodes is consumed during the conversion process, forcing them to be replaced about every 2 to 3 weeks. In addition, the undulating surface of the molten aluminum in the cell dictates a large gap between the anode and the cathode to prevent short-circuiting of the cell. Unfortunately, this gap makes the cell consume much more electricity than is actually needed to convert the alumina. The combination of an inert

(non-reacting) anode, which would not be consumed during the electrolytic process, and a cathode whose surface would remain stable (unlike the sloshing molten aluminum), would allow the cell to operate with a much narrower anode-cathode gap while reducing downtime for anode replacement.

The combined efforts of a number of research organizations have resulted in the development of inert titanium diboride and graphite (TiB₂-G) cathodes and inert anodes composed of a ceramic-metal composite material (see Figure 3-23). The anticipated benefits of retrofitting a Hall-Heroult cell with the new inert anode/cathode system include:

- Potential to conserve up to 20% of the total energy currently used in the cell itself and in the production of conventional carbon anodes;
- Anode life expectancy of 5 years instead of 2 to 3 weeks;
- Nearly 10% reduction in the cost of aluminum production;
- Up to 25% increase in productivity, allowing production to be increased using the same number of cells;

- Elimination of carbon dioxide emissions normally associated with aluminum production;
- Elimination of carbon dioxide and other emissions associated with the production of carbon anodes from petroleum coke and coal tar pitch.

On an industry-wide basis, adopting the inert anode/cathode system could save 9 trillion Btu of energy and reduce carbon dioxide emissions by more than a million tons each year.

Figure 3-22

Energy Use in Primary Aluminum Production

Source: Manufacturing Consumption of Energy 1991, EIA

Table 3-26

Annual Benefits of Energy Efficient Calciner

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	5500	4400	1100	5500
Total Cost (\$1000)	16,709	13,558	3151	15,755
Energy Cost (\$1000)	15,118	12,094	3024	15,118
Capital Cost (\$1000)	1591	1464	127	636
O&M Cost (\$1000)	N/A ¹	N/A	0	0
Emissions (metric ton)				
CO ₂	290,277	232,221	58,055	290,277
NO _x	349	279	70	349
SO _x	1.5	1.2	0.3	1
Particulates	7.3	5.8	1.5	7
Solid Waste (1000 metric tons)	N/A	N/A	3525	17,775
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		2020		

¹ O&M not available. OIT cost expected to be approximately equal to current technology.

Spray Forming of Aluminum:

Streamlining the Casting Process

(ALCOA, Air Products and Chemicals, Olin, Massachusetts Institute of Technology, Idaho National Engineering Laboratory, University of California-Irvine)

The production of aluminum sheet for use in cars, airplanes, and other

applications consists of a series of individual operations that are far from optimal from the standpoint of energy, productivity, and materials. The main culprit is ingot casting, in which molten aluminum is poured into molds, cooled until it hardens, and then removed from the molds and reheated for rolling or other

processing. Spray forming of aluminum is being developed as an exciting new alternative to this inefficient series of steps. In spray forming, the molten aluminum is converted into aluminum droplets, which are then sprayed continuously onto a base form that is conveyed through a controlled-atmosphere chamber. The rapidly cooling film is then rolled or otherwise processed just as an ingot would be. The new process has fewer steps, simplifying production and eliminating the wasteful reheating step required with ingot casting.

Spray-formed materials have been determined to be metallurgically superior to those made from ingots in terms of corrosion resistance, strength, and toughness. The new process enables the microstructure of the aluminum products to be more closely controlled, which will enhance the process's ability to use recycled aluminum without degrading new product properties. Other benefits include:

- Energy savings of as much as 15%;
- Cost savings of several percent;
- Reduction in NO_x, SO_x, and other emissions.

It is anticipated that spray forming will expand the use of aluminum parts in cars, airplanes, and other markets because of the high-quality alloys that it can produce.

Table 3-27

Annual Benefits of Inert Anode/Cathode Aluminum Smelting

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	15	14	1	8936
Total Cost (\$1000)	413	386	28	327,424
Energy Cost (\$1000)	209	198	11	127,524
Capital Cost (\$1000)	0	4.2	-4.2	-50,248
O&M Cost (\$1000)	204	183	21	250,148
Emissions (metric ton)				
CO ₂	2559	2428	131	1,562,603
NO _x	2.1	0.5	1.6	20,000
SO _x	19	13	7	78,216
Particulates	51	48	3	30,879
Solid Waste (1000 short tons)	-	-	-	-
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		2020		

Table 3-28

Annual Benefits of the Spray Forming of Aluminum

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	13,190	11,190	2000	6000
Total Cost (\$1000)	1,218,104	1,183,336	34,768	104,304
Energy Cost (\$1000)	188,224	159,684	28,540	85,621
Capital Cost (\$1000)	4880	2652	2228	6683
O&M Cost (\$1000)	1,025,000	1,021,000	4000	12,000
Emissions (metric ton)				
CO ₂	2,306,387	1,956,670	349,718	1,049,153
NO _x	1941	1647	294	883
SO _x	17,419	14,778	2641	7924
Particulates	45,576	38,666	6911	20,732
Solid Waste (1000 short tons)	-	-	-	-
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		2020		

Figure 3-23

Inert Anode/Cathode System

ESSENTIAL COMPLEMENT TO THE PRIMARY STEEL AND ALUMINUM INDUSTRIES

The foundry industry in the United States melts and casts mostly scrap metal into literally tens of thousands of intricately-shaped metal parts. Foundries employ metal casting—a process of pouring or injecting molten metal into a mold cavity, allowing it to cool and solidify, and then releasing it from the mold. In many respects, metal foundries complement their primary metal industry counterparts in the U.S. metal system. The steel, aluminum and copper industries typically produce a relatively limited number of common product forms (commodities) such as sheet, tubes, bar or wire from virgin materials. Foundries, on the other hand, produce from the scrap largely unusable by the primary metal industries the much more highly specialized metal parts required to keep American industry running smoothly. Whereas the capital-intensive, scale-economy primary metal industries tend to locate near their energy or raw material supplies, the foundries that produce a much more diverse line of highly specialized products tend to be more labor intensive and locate closer to their customers and markets.

It has been estimated that metal castings made in foundries are used in the assembly of more than 90% of all durable goods and in virtually 100% of machine tools, manufacturing machinery, and similar capital goods. The U.S. market for metal castings is estimated to total about \$19 billion. When machined, castings are used as components in products ranging from motor vehicles and aircraft to appliances and power tools. Most homes contain more than a ton of cast pipe, bathtubs, sinks, fixtures, hardware, and furnace and air conditioning parts. Moreover, to properly appreciate the role of foundries in our industrial infrastructure, it must

Figure 3-24
Major Markets for Cast Products

Source: *Issues and Opportunities of the U.S. Metal Casting Industry*, Draft October 1993, Energetics.

be recognized that foundries are major consumers of waste materials. Scrap iron and steel are the major source of raw materials for foundries, accounting for about 85% of all ferrous castings produced in the United States. Reclaimed copper, aluminum, lead, tin, zinc, and other metals are also extensively recycled in making nonferrous castings (Figure 3-24).

The U.S. foundry industry is comprised of more than 3,000 foundries employing close to 200,000 workers. An important demographic characteristic of the foundry industry that contributes to several of its problems in an increasingly global economy is the fact that about four-out-of-five foundries employ less than 100 workers, and fewer than 10% have more than 250 employees. Foundries are located throughout the United States, although there is a somewhat higher concentration in the Midwest. The states with the largest foundry populations include Ohio, California, Pennsylvania, Michigan, Illinois, Wisconsin, New York, Indiana, and Texas.

In 1991, estimated world production of castings was 54 million tons and U.S. foundry output was about 11 million tons, 20% of the world total. U.S. production of ferrous castings totaled 9.4 million tons

Table 3-29
Foundry Industry Profile*

Volume of Products	11 million tons
Value of Shipments	\$19 billion
Total Employment	197,000 jobs
Capital Expenditures	\$0.7 billion
Net Trade Balance	\$-10 million (1989)
Energy Consumption	0.25 quad (1988)
Waste Generation	8 million tons of sand waste
Average Hourly Earnings	\$12.77

*Data for latest year available

(86% of the total) valued at about \$11.6 billion while output of the higher-priced non-ferrous castings was 1.6 million tons (14%) worth \$7.4 billion. According to the best available data, the U.S. foundry industry consumed about 250 trillion Btu of energy in 1988 for such major foundry operations as melting, molding, and heat treating. Energy expenditures (primarily natural gas and electricity) totaled \$3.3 billion in 1992.

The Shrinking Industry: Less Mass, Higher Value Added

Despite its critical positioning within the industrial economy, the U.S. foundry industry has undergone a dramatic decline during the past decade. Since 1980, the number of operating foundries has decreased by about 25%. In 1991, the industry produced 11 million tons of castings, a decrease of 45% from the 20 million tons cast in 1972. U.S. foundry employment of about 200,000 workers was down over 10% in just 3 years from its level of 225,000 in 1989.

Several factors have contributed to the decline in U.S. foundry production including a reduction in the domestic demand for metal castings, increased competition from foreign producers, the growing cost of compliance with government regulations, and to some extent increased use of substitute materials such as plastics, ceramics, and composites. But

perhaps the largest reason for the decrease in shipments of foundry products is related to the fact that automobiles and other transportation equipment consume nearly a third of all castings produced. Hence, U.S. automakers' loss of domestic market share to imports has diminished domestic foundries' largest market. In addition, the foundry industry has also been impacted by the shift to more fuel-efficient, lighter-weight automobiles. Engine sizes have been reduced, requiring fewer cylinders. And aluminum components have been supplanting heavier ferrous castings in such auto applications as cylinder heads, pistons, and transmission cases. These undoubtedly were major factors behind the reduction in malleable iron and steel castings from 1.9 million tons in 1980 to less than 1.1 tons in 1990.

Foundry Competitiveness: On Balance, O.K. for Now But...

Despite the significant contraction in the size of the U.S. foundry industry over the last two decades, on balance the industry appears to remain reasonably competitive—at least for the time being. Imports and exports of castings are roughly the same and represent about 7% of the U.S. market. Quality is an important reason why American foundries have remained relatively competitive. Industry experts feel that many foreign foundries are not able to meet, on a continuing basis, the quality and delivery requirements of domestic customers. This is particularly true for high-value-added castings, such as high-alloy valves and pump castings, which tend to dominate U.S. foundry exports. On the other hand, U.S. foundries have difficulty competing with foundries such as those in Korea that produce low-value-added castings, and import penetration will likely remain an issue among producers of standardized, highly price-sensitive products such as municipal castings and many simple valves and fittings.

While on balance the U.S. foundry industry appears to be holding its own against its foreign competitors, ominous signs portend possible trouble down the road. The major casting customers are much more sophisticated than they were 20 years ago, and a number of large, aggressively innovative, world-class American foundries have managed to keep up. However, there are growing questions about whether or not the great critical mass of the U.S. foundry population will be able to follow suit. Older equipment was based on mechanical and electrical technologies, and today's machines frequently use sophisticated electronic technologies and computer controls. But nearly 80% of U.S. foundries employ less than 100 workers, and do not have the financial resources to extensively modernize, let alone retool equipment necessary to meet customer demands. In addition, foundries have suffered high attrition rates in their skilled labor and engineers in recent years just at a time when rapidly evolving technology is creating a greater than ever need for such personnel.

THE MANUFACTURING PROCESS: MELT SCRAP AND CAST

Foundries essentially take scrap metal from various sources, melt the scrap, and remove undesirable contaminants. The molten metal is then cast. Casting is the process of producing a metal object of a desired shape by using a ladle to pour molten metal through a passageway into a mold and allowing the metal to cool and solidify. After cooling, the passageway leading to the mold is removed, and final machining is performed on the casting to achieve the necessary dimensional tolerance.

Melting

Melting occurs in furnaces of several types, such as cupola, electric arc, induction, and gas-fired. Cupola furnaces preheat the metal as it descends into the furnace, and are generally used for iron castings. Electric arc

furnaces were described in the steel industry section and are also used primarily for ferrous castings. An induction furnace uses magnetic fields and electricity for heat to melt the scrap. There are more induction furnaces in use than any other type of casting furnace, and almost all types of metals are cast using these furnaces. Gas-fired furnaces are generally used only for non-ferrous castings. Recent estimates indicate that cupola furnaces melt about 59% of all foundry metal, electric arc furnaces melt 11%, and induction furnaces melt 27%.

Casting

Currently, six types of casting methods are primarily used and are described in detail below: sand, permanent mold, die, investment mold, shell mold, and centrifugal, plaster evaporative pattern.

Sand Casting: Sand casting is used in 60% of all castings, and is used in over 75% of ferrous castings. Patterns are made to conform with the exterior dimensions of the casting. Sand is packed around the pattern in a molding machine, and then the pattern is removed. The molten metal is poured into the sand mold and left to solidify. Sand molds may be used only once, as they are broken up to remove the casting. Then the sand is recycled to form another mold.

Table 3-30
Castings by Type of Metal

Metal	1990 Production (million tons)	Change in Production 1972-1990
Gray Iron	5.12	-62%
Ductile Iron	3.19	+74%
Malleable Iron	0.28	-71%
Steel	1.14	-29%
Aluminum	1.07	+15%
Copper	0.22	-43%
Zinc	0.21	-48%
Other	0.05	+2%

Source: Issues and Opportunities of the U.S. Metal Casting Industry.
Draft October 1993, Energetics

Photo courtesy of Gas Research Institute

Hot molten metal pours from a furnace.

Permanent Mold Casting: Permanent mold casting, used in 11% of all castings, involves molds to produce thousands of castings before they need to be replaced. The molds are filled with molten metal under atmospheric pressure and require suitable mold coatings. Castings in permanent molds have closer tolerances than sand molds. However, the production quantity needs to be large enough to justify the expense of the molds.

Die Casting: Die casting, used in 9% of all castings, is the fastest way to produce a metal casting, and accounts for about 60% of all non-ferrous castings. Die casting differs from the other casting processes in that the molten metal is forced into the permanent steel mold under pressure and at high velocities. Once the die is sealed, the molten metal is injected. The casting is left to solidify (usually less than one minute), then the die is opened and the casting(s) ejected. The die casting segment is the most affected by foreign competition.

Investment Mold Casting: Investment mold casting processes, used in 7% of all castings, use heat-disposable patterns: waxes, some types of plastics, and organic substances that can be consumed by heat. In this process, the

pattern is surrounded with investment material (a slurry material), which sets at room temperature. After the investment hardens, it is heated to burn off the pattern leaving the mold cavity. The cavity in the investment mold is then filled with molten metal and left to cool. Once the metal has solidified, the investment mold is broken away from the casting. This process is the most effective for creating highly precise castings. The mold, however, must be destroyed after each use.

Shell Mold Casting: Shell mold casting, used in 6% of all castings, involves heating a metal pattern and dumping a resin-coated sand onto the pattern. The hot pattern causes about a quarter-inch layer of the sand to bond, forming a shell. The two shell pieces are hardened and then glued together to form a mold cavity for pouring.

Centrifugal, Plaster Evaporative Pattern Casting: Centrifugal, plaster evaporative pattern casting is used in 7% of all castings. A rubber pattern is surrounded by a plaster slurry. Once the plaster sets, the pattern is removed and the plaster mold dried. The mold is rotated around a horizontal or vertical axis and the liquid metal is forced against the rotating mold wall during pouring.

Energy: Melting Furnaces Offer Greatest Opportunity for Improved Efficiency

The metals casting industry consumed just over 0.25 quad in 1988 while producing 12.4 million tons of product, yielding an average energy use of about 20 million Btu for each ton of product shipped. Natural gas and electricity account for virtually all energy use, with an estimated 66% from natural gas and 34% from electricity. Depending on the type of casting, energy can account for 25% of production costs. Melting furnaces account for about 55% of the energy consumption of the industry, yet many are generally only about 35% efficient. Molding and heating each account for 12% of energy use. Energy expenditures were estimated to be \$3.3 billion in 1992.

Environmental Profile

Sand casting produces more than 100 million tons of sand annually. This sand is recycled until it breaks down and can no longer be recycled, yielding about 8 million tons of spent sand each year. Currently, more than 80% of the spent sand is landfilled. This equates to about 850 pounds of spent sand for every ton of ferrous metal shipped from a foundry; the amount increases for copper and aluminum. Ferrous foundries also dispose about 350 pounds of slag per ton of casting, and more than 200 pounds of emission control dust per ton of casting. About 4% of the industry's waste is hazardous; examples include sand from brass foundries, dusts and sludges, and quench dropout containing toxic heavy metals. In addition, about 5% of all castings produced currently are recast because they are of poor quality.

Annual operating costs related to waste management are more than \$1.25 billion to comply with environmental regulations. Measures under the Clean Air Act Amendments of 1990 are anticipated to add another \$750 million to the annual costs. For smaller foundries, investment in

pollution control equipment represents about 30 to 40% of all capital expenditures. On the other hand, one benefit the industry does provide is that between 15 and 20 million tons of all grades of scrap metal are annually saved from disposal and given new life by the foundry industry.

THE OIT FOUNDRY PROGRAM

In recent years, foreign competition has severely threatened the competitiveness of the U.S. metal casting (foundry) industry, which produces cast parts for such basic goods as cars, construction equipment, and other heavy machinery. To meet this challenge, Congress passed the DOE Metal Casting Competitiveness Research Act of 1990. Consistent with this legislation, OIT conducts R&D activities to improve the competitiveness and energy efficiency of the different segments of the metal casting industry. Because a major competitiveness issue of all foundries is the cost associated with complying with increasingly stringent environmental regulations, R&D efforts aimed at reducing foundry wastes are also included in the program.

Sand Reclamation: Easing the Economic Pain of Environmental Compliance

(University of Northern Iowa)

U.S. metal casters must add the cost of complying with strict federal, state, and local environmental regulations to their prices, affecting their ability to compete on an even basis with many foreign competitors. The biggest culprit is spent foundry sand—the sand that is used in the casting molds. The majority of spent foundry sand is currently landfilled. The life cycle cost of the sand, including its purchase, transport, and disposal, averages \$65 per ton. Instead of disposing of this sand, experts have long felt that developing an economical method of recycling it for reuse in the foundry would drastically reduce the negative effects of environmental compliance.

Just such a recycling method is now available, courtesy of research at one of DOE's Metal Casting Research Institutes. A mobile sand reclamation (recycling) unit has been developed that can be transported from place to place, enabling it to serve a group of foundries that on their own cannot afford to purchase an expensive, permanent reclamation unit. This mobile unit will cut in half the life cycle cost of sand to about \$32 per ton. Smaller foundries will now be able to reclaim and reuse spent sand, thereby reducing the need for new sand and its associated mining and transportation

energy requirements. On a national basis, more than 2 million of the 8 million tons of spent sand generated each year could be recovered.

Advanced Lost Foam Technology: Improving the Competitiveness of U.S. Metal Casters

(University of Alabama at Birmingham)

Lost foam casting is a form of investment casting, where each mold can only be used a single time. For many years, foundry industry experts have felt that technological advancements in lost foam casting could have significant benefits to the industry. Lost

Table 3-31

Annual Benefits of Sand Reclamation—Mobile Recycling Unit

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	103.1	87.0	16.1	821
Total Cost (\$1000)	424.7	414.6	10.2	518.8
Energy Cost (\$1000)	424.7	358.4	66.3	3382.7
Capital Cost (\$1000)	0.0	36.2	-36.2	-1843.9
O&M Cost (\$1000)	0.0	20.0	-20.0	-1020.0
Emissions (metric ton)				
CO ₂	8107	6841	1266	64,563
NO _x	17.30	14.60	2.70	138
SO _x	14.68	12.39	2.29	117
Particulates	3.13	2.64	0.49	25
Solid Waste (1000 short tons)	—	—	43.20	2203
Risk				
Technical		HIGH		
Market		HIGH		
Year of Maximum Market Share		2000		

Metal Casting Competitiveness Act of 1990

In response to the U.S. metal casting industry's urgent need to enhance its competitiveness, the Congress enacted Public Law 101-425, the "Department of Energy Metal Casting Competitiveness Act of 1990." As stipulated in the law, the Department of Energy established the Metal Casting Competitiveness Research Program for the purpose of performing and promoting research and development on issues related to the technology, competitiveness and energy efficiency of the U.S. metal casting industry.

In fiscal year 1992, DOE awarded \$1.833 million to the Universities of Alabama and Northern Iowa to establish a National Metal Casting Research Institute at each university. Guidance for the research activities of the institutes is provided by DOE Headquarters, the DOE Idaho Field Office, the Metal Casting Industrial Advisory Board, industry experts, and the technical societies serving the metal casting industry. In addition, the Metal Casting Industrial Advisory Board has developed working groups with the automotive industry, the heavy equipment and machinery industry, and the aerospace industry.

foam casting is a simple, cost-efficient process that offers exceptional design flexibility and can easily be automated to improve its productivity. This type of casting is particularly useful for producing complex castings of 30 pounds or less, such as those required by the electronics, defense, and aerospace industries.

Research is being conducted to refine and improve advanced lost foam casting, as well as other investment casting methods. This research includes using computer models and experimental data to improve existing casting technologies, as well as developing and demonstrating new ones. This project is using results from a previous OIT

project conducted by the American Foundrymen's Society. Results of the current project are expected to advance the state-of-the-art in lost foam casting—leading to reduced costs, increased design freedom, minimum post-casting machining requirements, reduced energy consumption, and minimum generation of emissions compared to sand casting, the most frequently used casting method. The project will also emphasize transferring advanced technologies to the foundry industry.

Table 3-32
Annual Benefits of Advanced Lost Foam Technology

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	0.57	0.56	0.01	0.28
Total Cost (\$1000)	2508.2	2308.0	200.2	4004.0
Energy Cost (\$1000)	8.2	8.0	0.2	4.0
Capital Cost (\$1000)	0.0	0.0	0.0	0.0
O&M Cost (\$1000)	2500.0	2300.0	200.0	4000.0
Emissions (metric ton)				
CO ₂	100	98	2	49
NO _x	0.08	0.08	0	0
SO _x	0.76	0.74	0.02	0.4
Particulates	1.98	1.94	0.05	1
Solid Waste (1000 short tons)	—	—	32	635
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		1998		

Table 3-33
Annual Benefits of Cupola Furnace Process Model

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	6990	6030	960	4800
Total Cost (\$1000)	12167.9	10496.8	1671.1	8355.7
Energy Cost (\$1000)	12167.4	10496.8	1671.1	8355.3
Capital Cost (\$1000)	0.0	0.0	0.0	0.0
O&M Cost (\$1000)	0.5	0.4	0.1	0.4
Emissions (metric ton)				
CO ₂	643,826	555,403	88,422	442,112
NO _x	5	4	1	3
SO _x	500	431	69	343
Particulates	203	176	28	140
Solid Waste (1000 short tons)	—	—	—	—
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		1999		

Development of a Cupola Furnace Process Model: Taking the Guesswork Out of Furnace Operation

(American Foundrymen's Society)

Cupola furnaces are used throughout the foundry industry to melt ferrous metals prior to casting. Furnace operators must rely heavily on their experience and expert judgement to control the furnace. This raises several issues. Operating the furnace is based more on rules of thumb rather than hard scientific facts, and is thus hard to optimize in terms of efficiency, productivity, and product quality. In addition, the industry is faced with the retirement of many of its more experienced workers, leaving less skilled employees to do the job. The time has come to develop a scientific base of knowledge on cupola furnace operation that can be used to tighten up current operating practices.

An OIT-sponsored research project is developing just such a knowledge base and is planning to use it to generate an expert system to help furnace operators improve the control of cupola furnaces. An expert system is a computer model that contains all available knowledge on a particular subject—in this case, cupola furnace operation—and can use this extensive knowledge to make recommendations on actions that should be taken based on a set of specific input conditions. The cupola furnace expert system will incorporate models of the heat transfer activities and fluid flows, as well as other thermal and chemical

phenomena, taking place in the furnace. These models are being verified with operating data from actual furnaces. The expert system would enable the furnace to meet the desired product quality with optimum energy efficiency, increased melting rates, reduced scrap, and more uniform and predictable iron compositions. The system would also allow off-line studies to be made for determining the process and cost impacts of intended changes in process inputs.

Table 3-34
Selected Other OIT Foundry Projects

Project (Developer)	Description	Benefits
Development of Lead-Free Copper Alloy-Graphite Castings (University of Wisconsin at Milwaukee)	This project is developing copper castings with graphite particles being substituted for lead, in order to alleviate health and environmental concerns associated with lead-containing materials.	<i>Environmental:</i> reduces hazardous waste <i>Energy:</i> reduces energy use for environmental compliance <i>Other:</i> maintains machinability and lubricating properties
Development of Clean Ferrous Casting Technology (University of Alabama at Tuscaloosa)	This project is developing techniques to improve casting quality by removing or minimizing non-metallic inclusions, oxide defects, and reaction products within and on the surface of coatings.	<i>Environmental:</i> reduces energy-related emissions <i>Energy:</i> reduces remelting and rework energy use <i>Other:</i> reduces production costs and produces higher integrity castings
Clean Metal Processing—Aluminum (Worcester Polytechnic Institute)	This project is investigating and developing melt cleanliness tools, melt contamination avoidance techniques, and melt treatment technologies.	<i>Environmental:</i> reduces energy-related emissions <i>Energy:</i> reduces energy use due to defect production <i>Other:</i> reduces defects
Casting Dimensional Control and Fatigue Life Prediction for Permanent Mold Casting Dies (Pennsylvania State University)	This project is evaluating process variables to assist in the development of new mold materials and improved mold design, in order to increase mold life and reduce machining requirements.	<i>Environmental:</i> reduces energy-related emissions <i>Energy:</i> reduces machining energy use <i>Other:</i> improves mold life and reduces machining which significantly reduces costs.

The Glass Industry

COMMODITIES MORE COMPETITIVE, SPECIALTIES MORE GROWTH

Glass is a strong, inert, noncrystalline ceramic material that possesses the additional and highly useful property of transparency. These unique qualities of glass contribute to a lengthy list of applications especially in the auto, construction, and container industry. The industry that supplies glass to the \$21 billion/year domestic market is large and diverse, energy-intensive and internationally competitive.

Though the raw materials—principally sand, limestone and soda ash—and upstream melting and refining processes of the glass industry are quite similar, its downstream shaping and value-adding processes and products vary considerably. This contributes to an industry structure possessing four distinctive segments: (1) flat glass used largely for windows; (2) glass containers such as bottles and jars; (3) fiberglass for insulation and structural applications; and (4) specialty glass such as optical fibers, flat panel displays and metallic glasses.

The physical quantity of glass produced in the United States has fluctuated around 20 million tons annually for the past decade. However, the value of glass shipments grew from \$14.9 billion in 1982 to \$21.3 billion in 1992. Gradually, the domestic glass industry is changing from a low-value-added, commodity business to an increasingly high-value-added, specialty business. For example, container glass—which accounts for just over half of glass industry production but which also includes products that are among the lowest-valued in the industry—accounted for about 35% of industry shipments in 1982; by 1992, however, container glass accounted for only 23%. On the other hand, more specialized glass products such as windshields, safety glass, and some industrial

glassware accounted for 33% of industry shipments in 1992, up from 20% in 1982.

The varying rates of growth of the glass industry's principal segments reflect its changing nature. For example, container and flat glass have been replaced by substitute materials such as aluminum and plastics in such applications as bottles, windows, and cans. On the other hand, the fiberglass industry is still a relatively young industry that continues to find new applications and compete favorably with more established materials such as steel and aluminum. But specialty glass remains the most dynamic industry segment as its cutting edge applications continue to explore and exploit numerous new market niches.

Recycling: Opportunities for Improvement

Glass recycling exceeds that of plastics, but is less than that of most common metals suggesting room for further improvement. Typically, recycled glass is crushed into small pieces known as cullet and used in conjunction with raw materials during glass production. An important factor limiting the recycling of glass is the relatively low cost of raw materials from

which glass is made. This depresses the price of scrap glass and deters widespread collection efforts. The lack of an efficient scrap glass collection infrastructure, especially outside major urban areas, further limits glass recycling. An effective but economical technology capable of sorting scrap glass by its principal colors—white, green and amber—would enhance glass recycling. Because of special circumstances, fiberglass is generally not recycled.

Though various economic, technological and other factors tend to limit international trade in certain types of glass products—especially container glass, a bulky, heavy product with relatively low value—overall the

Table 3-35
*Glass Industry Profile**

Volume of Products	21 million tons
Value of Shipments	\$21 billion
Total Employment	153,000 jobs
Capital Expenditures	\$1.1 billion
Net Trade Balance	\$0.1 billion (estimate)
Energy Consumption	0.3 quad
Waste Generation	N/A
Average Hourly Earnings	\$13.33

*Data for latest year available

Photo courtesy of Lewis Stewart, PG&E

Glass containers are one segment of the glass industry structure.

U.S. glass industry is quite competitive and accounts for about 25% of the world's flat glass capacity. The 1980s were a time of restructuring and consolidation in the glass industry with an increased global emphasis. The industry modernized extensively during this period contributing to a recent dramatic increase in exports of flat glass while imports have roughly stayed the same. The United States pioneered the fiberglass segment of the industry more than 50 years ago and maintains a strong competitive advantage and trade balance in fiberglass products. Similarly, U.S. firms retain a healthy export balance in the high growth, high-value-added specialty glass segment of the industry.

THE MANUFACTURING PROCESS: MELT AND REFINE, SHAPE AND TAILOR

Glass is produced by melting silica (from sand), limestone, and soda ash, along with other minor ingredients, in a furnace and allowing them to cool to an amorphous (non-crystalline) state. Other elements may be added to alter the color or other properties. While still molten, the glass is formed into a variety of products, including windows, mirrors, bottles, tableware, and fiberglass. The principal processing steps are: batch preparation, melting and refining, and forming and postforming (Figure 3-25).

Melting and Refining

After the raw materials are weighed and mixed, and recycled material (cullet) added if desired, the materials are batch charged or continuously charged to the melting furnace, where they are heated. After melting, the glass passes to the refining section of the furnace where it stays long enough for bubbles to escape from the molten glass. In regenerative furnaces, the charge is melted by a flame that plays over the glass surface. Fuel and preheated air are fired at one end of the furnace and hot combustion exhaust gases pass out the other end. This flow is reversed about every

Figure 3-25

Conventional Glassmaking

15 minutes. Most furnaces are fired by gas, but electricity is becoming more widely used in certain applications. Regenerative furnaces account for approximately 90% of capacity.

Forming and Postforming

Once refined, the molten glass flows to the forehearth section of the furnace where it is homogenized and heat conditioned to establish and maintain temperature uniformity. Overall, the melt is cooled to the proper working temperature, where its viscosity is suitable for shearing and gob formation (about halfway between that of cheddar cheese and molasses). Molten glass is drawn from the forehearth when it is ready to be formed. The forming stage differs greatly depending on the product being produced, using techniques such as floating, blowing, suction, pressing, or drawing. Postforming operations are used to adjust the strength and other properties of the formed product through a variety of operations, including annealing, quenching, coating, and polishing.

Energy

The glass industry consumed approximately 300 trillion Btu in 1991, including electricity losses. On average, it takes around 14 million Btu to make a ton of glass, but depending on the type of glass product, it can vary from about 8 to 20 million Btu per ton of glass. Not including losses, container

Figure 3-26

Estimated Glassmaking Energy Use

glass consumes the least amount of energy per ton of product, followed by flat glass, pressed/blown glass, and fiberglass, which consumes the most energy per ton of product. The melting and refining step is the largest energy consumer; it typically accounts for 50% to 68% of the total energy use in glassmaking (see Figure 3-26). Forming typically accounts for 12% to 33% of energy use, while postforming accounts for 11% to 18%. Total energy expenditures approach \$1 billion annually for the industry, with natural gas accounting for about 80% of end-use energy consumption and electricity accounting for about 16%.

Environmental Profile

Air emissions are the major concern of the glass industry, as the energy-intensive melters emit NO_x and other emissions. The Clean Air Act

Amendments of 1990 will require significant expenditures for equipment and monitoring, and permitting. Pollution abatement expenditures included \$43 million in capital costs and \$187 million in operating costs in 1991. There is also some concern over the health effects of fibers used during the production of fiberglass.

THE OIT GLASS PROGRAM

The OIT Glass Program concentrates on the glass melting and refining steps, which together account for more than half of all of the energy

used to manufacture glass. Developing new melting/refining processes could have widespread impact because of their applicability throughout all segments of the glass industry.

Rapid Glass Refiner/Melter: Reducing Processing Time from Hours to Minutes (Vortec)

The rapid glass refiner/melter is an advanced furnace system that reduces melting and refining time for fiberglass from more than a day to about one hour using equipment one-tenth the size of conventional equipment.

This huge reduction in processing time means that the new furnace uses only about half of the energy of a conventional melting/refining furnace. The new system was also designed to almost totally eliminate emissions of sulfur and NO_x. Because it is compact and eliminates the need for costly pollution controls, the rapid glass refiner/melter costs significantly less than a conventional furnace system of the same capacity. The combined effect of a shorter processing time and reduced capital costs is an estimated 10% reduction in the value added to fiberglass through manufacturing. This should improve the competitive position of U.S. fiberglass manufacturers in both global and domestic markets (Figure 3-27).

Table 3-36
Annual Benefits of Rapid Glass Refiner/Melter

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	441	180	261	89,514
Total Cost (\$1000)	3991	1539	2453	841,194
Energy Cost (\$1000)	1744	497	1248	428,246
Capital Cost (\$1000)	1247	843	404	138,548
O&M Cost (\$1000)	1000	200	800	274,400
Emissions (metric ton)				
CO ₂	28,880	9516	19,364	6,641,779
NO _x	35	14	24	8153
SO _x	26	0	26	8886
Particulates	61	0.2	61	20,804
Solid Waste (1000 short tons)	—	—	1	475
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		2020		

The rapid glass refiner/melter can be used in new fiberglass plants and to replace aging furnaces at existing plants. With expected energy savings of approximately 0.26 trillion Btu/year for a medium-sized (130 ton/day) furnace, total U.S. savings of nearly 90 trillion Btu could be achieved annually by the year 2020. The system also has the capability to recycle waste fiberglass, one-fourth of which currently ends up in landfills. The cost of feedstock materials used to produce glass could be reduced by 10% as a result of using waste fiberglass, further improving competitiveness while decreasing landfilling of consumer waste glass.

Figure 3-27
Rapid Glass Refining/Melting

Many industrial technologies are employed across numerous industry boundaries. Electric motor systems, cogeneration, new materials, and heat exchangers are just a few examples of these crosscutting technologies. Improvements in these widely used technologies offer the opportunity to improve efficiency, productivity, competitiveness, and the environmental profile of an especially broad range of firms.

OIT's R&D portfolio includes a range of crosscutting materials and energy technologies. OIT's advanced materials programs—including its intermetallic materials, continuous fiber ceramic composites and other new materials—are targeted largely at industrial applications where their high-temperature resistance, strength and durability are often greatly valued.

Two other important crosscutting technology programs in OIT are electric motor and combustion systems. These systems consume large quantities of energy in all the materials and process industries; consequently, small efficiency improvements in these technologies could be leveraged into very large gains when multiplied by the number of motors, boilers, furnaces, and similar units in use throughout so many industries.

Other crosscutting OIT technologies attempt to make better use of the huge quantities of waste heat generated in the large-scale processes found throughout the materials and process industries. Improved cogeneration, heat exchangers and heat pumps all recycle the heat content of Btu released in industrial processes back to more productive uses thereby reducing costs and industrial requirements for new energy.

Finally, OIT's industrial waste and municipal solid waste programs address technologies that can reduce the amounts of waste generated or improve the use of wastes that cannot be eliminated. These programs help prevent pollution, lower the costs of environmental regulations, and reduce the need for landfill space. They also help temper demand for nonrenewable and frequently imported raw materials and energy.

Advanced Industrial Materials

ENABLING MATERIALS FOR ENERGY EFFICIENCY, EMISSIONS REDUCTIONS, AND MANUFACTURING COMPETITIVENESS

During the past three decades unprecedented progress has been made in the development of advanced materials—including advanced ceramics, polymers, metals and composites of these materials. Typically, these materials possess properties that are far superior to those of conventional materials such as steel, aluminum, glass or plastics. As shown in Figure 4-1, advanced materials are often far stronger than conventional materials. In addition, they are frequently tougher, more wear-, corrosion- or heat-resistant, lighter, or are more efficient conductors of photons or electrons than conventional materials. The use of advanced materials in industry can improve process efficiency and productivity through reduced life-cycle energy use, higher processing temperatures, increased component and system life times, and reduced downtime.

Advanced materials are not supplied by a single industry; hence, the advanced materials industry does not consist of the relatively homogeneous group of firms that is typical of most other industries. Advanced materials are manufactured by firms in the chemical (polymer, composite, ceramic), metal (alloys, composites, intermetallics), and traditional ceramics and glass industries. Moreover, unlike other materials industries in which scale economies dictate that large firms predominate, many

advanced materials companies are small enterprises that were established to develop and sell one or a handful of highly specialized materials with superior properties.

Though the conventional materials industries are generally mature, cutting edge technology in each of the major classes of materials is highly dynamic. For example and as indicated in Table 4-1, advanced polymers are finding applications as nonlinear optical devices, permeable

membranes, thermal and electrical insulation, fuel cells, ceramic precursors, and sensors. Advanced ceramics and composites can be used in wear parts, cutting tools, heat exchangers, refractories, gas turbines, pump seals, substrates, and machine components for industrial processing. Metals, alloys, and metal matrix composites include ductile, high-strength materials and electrical conductors with uses that vary from structural materials, magnets, and processing equipment

to motors and engines. Because of the exceptional growth potential of advanced materials, the traditional materials industries—especially the chemicals, ceramics, aluminum, and specialty metals industries—have shown strong interest in the development and manufacture of these high-value-added materials.

Material Needs and Opportunities in Traditional Manufacturing Industries

Despite U.S. leadership in the development of new materials, these materials have not been widely applied in manufacturing. A recent report from the National Research Council concluded that—although the United States leads in materials science—a serious shortcoming in synthesis and processing knowhow impedes the transfer of advanced materials technology to the marketplace. Consequently, while the United States develops many new materials, other nations are better at doing the applied research needed to commercialize these materials and reap their economic benefits.

High cost is the main barrier to increased use of advanced materials. On a dollar-per-pound basis, advanced materials are often several times more expensive than conventional materials. Lower-cost processing methods are perhaps the most important need if advanced materials are to find wider use in industry and fulfill their potential. Standardization, liability concerns, and user familiarity are among the many other barriers that impede the diffusion of advanced materials.

Using advanced materials in industry has been inhibited further because opportunities to apply these materials in many traditional manufacturing processes have not been adequately assessed. In addition, potential users are not sufficiently aware of the performance benefits of advanced materials—let alone how or where to use them. Hence, an important initial step in accelerating the movement of advanced materials into industrial

Figure 4-1
Strength Comparison of Traditional and Advanced Materials

Table 4-1
Characteristics and Applications of Advanced Materials

	Examples	Characteristics	Selected Applications
Ceramics and Ceramic Matrix Composites	alumina, silicon carbide, silicon nitride, molybdenum disilicide, zirconia, fiber or particulate reinforced ceramic matrix composites	light weight, high strength, toughness, wear resistant, heat resistant, and corrosion resistant	wear parts, cutting tools, heat exchangers, refractories, gas turbines, pump seals, substrates, and machine components for industrial processing
Metals, Alloys, and Metal Matrix Composites	nickel aluminide, titanium aluminide, iron aluminide, aluminum alloys, titanium alloys, and fiber or particulate reinforced metal matrix composites	light weight, wear resistant, corrosion resistant, heat resistant, and ductile	structural materials, cutting tools, magnets, processing equipment, motors, and engines
Polymers and Polymer Matrix Composites	liquid crystal polymers, conducting polymers, nonlinear optical polymers, fiber or particulate reinforced polymer matrix composites	light weight, corrosion resistant, high strength and stiffness	nonlinear optical devices, permeable membranes, thermal and electrical insulation, fuel cells, ceramic precursors, and sensors

usage is to conduct detailed analyses of material needs on an industry-by-industry basis.

OIT's Advanced Industrial Materials program has taken the initiative in this area and has inventoried the material needs of the pulp and paper and glass industries. Satisfying these needs could have a significant impact on improving energy efficiency, productivity and environmental compliance in these industries. In pulp and paper, wear and corrosion—including abrasive and erosive wear, cavitation wear, sliding wear, and impact wear—are important issues because nearly every form of wear may be encountered during various processes. Replacing wear-critical components with more durable parts, inserts or surface treatments is needed. Corrosion issues are encountered throughout all pulping and papermaking processes and remain among the most visible and costly materials issues. Opportunities in the paper industry include:

1. Improved materials to provide impact-resistant edges for chipper blades, saws and knives;
2. Refiner materials suitable for higher rotation rates with lower mass and higher fracture toughness for high-speed bearings;
3. Boiler tube materials and surface coatings with improved resistance to hydrogen sulfide and stress-assisted waterside corrosion; and
4. Polymer-based structural materials for vessels, piping, and valves.

Table 4-2 summarizes the material needs and opportunities of the pulp and paper industry.

Several material needs and opportunities have been identified in the glass industry also (Table 4-3). Although many of the material needs in this industry are dependent on the specific end-uses, overall the problems of wear, corrosion, and erosion are major concerns in the glass industry. Material opportunities in the glass industry include:

Table 4-2
Material Needs and Opportunities in Pulp and Paper Industry Processes

Process	Materials Needs	Opportunities
Wood Preparation ■ Debarking ■ Chipping	<ul style="list-style-type: none"> ■ improve the abrasion and wear resistance of transport chutes, belts, saws, knives and debarking equipment ■ reduce the effect of impact damage to cutting and saw blades from rocks and hardwood 	<ul style="list-style-type: none"> ■ improved metals, ceramics, and/or surface treatments or coatings with improved abrasion and impact resistance
Pulp Preparation ■ Mechanical Pulping ■ Chemical Pulping	<ul style="list-style-type: none"> ■ improve the corrosion resistance of materials associated with presteaming, condensates containing sulfur-bearing acids and chlorides in mechanical pulping ■ improve the wear and pitting resistance of materials ■ improve the filters used for extracting liquids ■ improve the corrosion resistance and wear resistance of materials used in recovery boilers for chemical pulping 	<ul style="list-style-type: none"> ■ improved ceramics for rotating grindstones ■ improved materials for refiner plates providing extended bar life and resistance to contact damage ■ liner materials with improved corrosion resistance ■ refiner materials suitable for higher rotation rates with lower mass and high fracture toughness for high speed bearings ■ materials providing improved corrosion/erosion resistance for digester blow plates
Bleaching	<ul style="list-style-type: none"> ■ improve the corrosion resistance of materials throughout the bleaching process ■ cleanable filters and membranes to separate the bleach and pulp 	<ul style="list-style-type: none"> ■ abrasion resistant materials for pump slurries ■ optimized alloy systems for bleaching environments ■ corrosion resistant weld-filler materials and welding practices
Papermaking	<ul style="list-style-type: none"> ■ improve the abrasion resistance of materials used in doctor blades, slitters and drums ■ improve the wear and corrosion resistance of press rolls ■ replacement for cast iron dryer rolls 	<ul style="list-style-type: none"> ■ cost-effective and durable alloys with pitting resistance ■ new surface treatments to ameliorate residual stresses and improve corrosion fatigue properties ■ improved manufacturing processes including casting, joining, and machining

1. Developing new refractory materials using mullite or ceramic fibers;
2. Developing new coatings and deposition technologies for glass materials;
3. Modeling metals and ceramics to analyze their survivability in corrosive atmospheres; and
4. Developing intermetallics and ceramic fiber coverings for glass contact applications.

The application of advanced materials in areas of these industries where opportunities have been identified could help them increase product quality, satisfy emissions requirements, and improve energy efficiency. Improved materials could also lead to less downtime, more efficient manufacturing operations, and reduced operating costs. This would improve

the competitiveness of U.S. glass and paper producers, increase their exports, benefit employees in these industries and have a number of other positive impacts on the U.S. economy.

THE OIT ADVANCED INDUSTRIAL MATERIALS PROGRAM

OIT's Advanced Industrial Materials (AIM) Program works in partnership with private industry to commercialize new and improved materials and material processing methods for application in several major industrial sectors. The Program's strategy is to assemble teams of experts from the national laboratories, manufacturing companies, and the university community to identify advanced materials application opportunities in the industries of interest. Within each industry, four major materials categories are considered:

Photo courtesy of Coors Ceramics

Ceramics provide a unique combination of mechanical strength, thermal stability, and ease of assembly for application in several major industrial sectors.

Table 4-3
Material Needs and Opportunities in the Glass Industry

Process	Materials Needs	Opportunities
Raw Materials Processing	<ul style="list-style-type: none"> ■ elimination of contaminants including ceramics, metals, organics and alloys 	<ul style="list-style-type: none"> ■ sensors and removal systems ■ improved transport and conveyance mechanisms
Glass Melting	<ul style="list-style-type: none"> ■ improve the life, thermal shock resistance, creep resistance, glass compatibility, removal/disposal characteristics of refractories ■ replace chrome-containing refractories ■ replace water-cooled hardware ■ model flow patterns, thermal distribution, and compositional gradients in glass melt ■ replacement material for bubbler materials, plunger materials, and thermocouple sheaths to reduce precious metal use ■ replace furnace hardware such as electrodes, needles, and flow orifices that suffer from wear and corrosion 	<ul style="list-style-type: none"> ■ improved refractory materials ■ sensors to detect refractory wear ■ new coating and deposition technologies for increased furnace life ■ modeling shells to analyze the survivability of materials in corrosive environments
Glass Forming	<ul style="list-style-type: none"> ■ improve the wear and corrosion resistance of materials for nozzles, vanes, and other forming equipment ■ replace platinum/rhodium glass contact materials ■ develop non-contacting diagnostics ■ develop an inspection technology for immediate feedback 	<ul style="list-style-type: none"> ■ intermetallic materials for corrosion and wear resistant forming applications ■ ceramic and metallic coatings or coverings for glass contact applications
<ul style="list-style-type: none"> ■ Float Processing ■ Fiber Processing ■ Container Processing 		

- Advanced metals and composites
- Advanced ceramics and composites
- Polymers and bio-based materials
- New materials and processes.

Advanced Metals and Composites: New Components for High-Temperature Applications

(Oak Ridge National Laboratory, Los Alamos National Laboratory, Bethlehem Steel Corporation, General Motors, Metallamics, Sandusky International, Alloy Engineering, Advanced Refractories Technologies, Owens Corning Fiberglas, Air Products and Chemicals)

The technical limitations of conventional materials such as steel alloys often restrict the performance of furnaces, turbines, and other high-temperature industrial equipment. New materials that can withstand higher temperatures are needed to increase the efficiency of current industrial processes, as well as pave the way for the development of new technologies. To address these material needs, researchers are developing new alloys—known as aluminides—that combine aluminum with nickel, iron, or titanium. One nickel-aluminum alloy in particular, nickel aluminide, or Ni_3Al , has already been successfully demonstrated for applications in the heat treating and metal processing industries.

New Ni_3Al components have successfully been applied in the mechanism used to support and convey moving parts through walking beam furnaces, where metal parts such as gears and coils are heated to achieve the desired strength, toughness, and metallurgical properties. The new components have also been used in other heat-treating furnace applications and as transfer rolls in steel reheat furnaces in the steel fabrication industry. The Ni_3Al components have longer lifetimes—which reduce furnace downtime—have better wear-resistance and strength, permit higher furnace operating temperatures, and increase furnace productivity. Energy savings result from

the improved productivity as well as from the elimination of cooling water requirements. It has been estimated that natural gas savings of a furnace equipped with Ni₃Al components will approach 50%, and that the extended range of potential furnace operating temperatures will allow new products to be developed and processed. Overall, it is anticipated that the introduction of aluminides into the market will cut industrial energy use by 50 trillion Btu annually.

In other work in this area, researchers are developing and designing inter-metallic composite materials that resist fracture at high temperatures. Efforts have been focused on a material known as molybdenum disilicide (MoSi₂), which exhibits superior properties at elevated temperatures. These properties could be particularly useful in such applications as burner nozzles, gas turbine components, and heating elements for industrial furnaces. Using MoSi₂ parts will enable such equipment to operate at higher temperatures with higher thermal efficiencies, translating directly into reduced energy requirements. Currently, several manufacturers are

attempting to commercialize the technology as advanced heating elements, structural materials, and components in glassmaking furnaces.

Advanced Ceramics and Composites: If We Can Make Them, Industry Will Reap the Benefits

(Oak Ridge National Laboratory)

For at least three decades, titanium diboride (TiB₂) has been known to be suitable to use as the cathode in the Hall-Heroult electrolytic cells used to convert molten alumina to aluminum metal. OIT has sponsored a variety of research efforts to develop TiB₂ ceramic cathodes, the most recent of which is described under "The OIT Aluminum Program" presented in Chapter 3. As part of the development of any new material, researchers must determine the most efficient processing method for manufacturing that material. This means applying or adapting existing materials processing methods or coming up with entirely new methods. As part of OIT's cathode research, scientists have been investigating the use of chemical vapor infiltration to fabricate high-purity TiB₂ without damaging the ceramic fibers themselves. The success of this

effort could lead to energy savings of as much as 18% of the electricity used in the electrolytic cell, or as much as 100 trillion Btu per year industry-wide.

Like the TiB₂ fabrication effort above, OIT's other research efforts in advanced ceramics also seek to exploit the advantageous properties of ceramics—their resistance to high temperatures and corrosion—while limiting or overcoming their disadvantages—brittleness, quality control, and limitations in fabrication techniques. For example, researchers are investigating a process known as reactive metal infiltration to produce near-net-shape (meaning that minimal additional grinding or finishing is required) ceramic composites for light-weight structural and wear applications. In reactive metal infiltration, the brittle ceramic is reacted with a molten metal and is converted into a tough metal-ceramic composite.

Table 4-4
AIM Program Advanced Metals and Composites Research

Material or Processing Technology	Industrial Application	Benefits
■ Nickel Aluminide	furnace components used in the metal processing and heat treating industries	improved life cycles, increased wear resistance and strength, and heat resistant
■ Molybdenum Disilicide	gas burner nozzles, and heating elements used in the glass industry	superior oxidation resistance, low temperature toughness, and improved creep resistance at high temperatures

Table 4-5
AIM Program Advanced Ceramics and Composites Research

Material or Processing Technology	Industrial Application	Benefits
■ Fiber Reinforced Titanium Diboride	Hall-Heroult cell cathode for aluminum smelting in the aluminum industry	improved wettability, longer life, increased strength, higher strain-to-failure, and reduced processing cost
■ Reactive Metal Infiltration	processing metal and ceramic composites for materials producers	near-net-shape production of ceramic and metal matrix composites and reduced energy consumption

Advanced Material Benefit Estimates Not Yet Available

Benefit tables similar to those provided for other OIT-supported technologies have not been furnished for its advanced materials projects, including OIT's ceramic composites program. This is because it is very difficult to forecast all the expected applications, market size, and potential benefits of these widely used, enabling technologies. Materials developed for a specific application typically have properties that are found to be useful in many other applications that were originally unforeseen.

To help deal with this, OIT is working with the Materials Systems Laboratory of the Massachusetts Institute of Technology (MIT). MIT is conducting a market assessment and developing a Multi-Attribute Utility Analysis technique. This technique will enable more consistent estimation of the total economic, environmental and energy-related benefits associated with OIT-supported advanced materials in specific applications. Results of this study are expected to be available in September 1995.

Table 4-6
AIM Polymer and Bio-Based Materials Research

Material or Processing Technology	Industrial Application	Benefits
■ Waste Plastic Recycling	waste recycling for the plastics and other consumer industries	reduced costs for raw materials, reduced energy consumption, reduced waste, and environmentally safe
■ Conducting Polymers	electrochemical capacitors, gas separation, and metallization of insulators for the chemical industry and other processing industries	high selectivity, and low processing costs

Table 4-7
AIM Program New Materials and Processes Research

Material or Processing Technology	Industrial Application	Benefits
■ Microwave Processing	joining silicon carbide parts for materials producers, and used in heat exchangers and processing systems	leak-tight joints, and reduced energy consumption

Other research efforts are investigating the production of low-cost, inter-metallic-bonded ceramic composites for applications where the operating conditions are severe in terms of friction and wear rather than temperature, and the production of composite aerogel materials (lightweight, porous materials that contain more than 90% of air by volume) that improve the thermal resistance of a component by more than 50%. All of these technologies combined could reduce industrial energy consumption by as much as 100 trillion Btu each year, with a corresponding reduction in carbon dioxide emissions of about 10 million tons each year. Additional benefits of the near-net-shape ceramic parts produced using reactive metal infiltration include reduced wastes from grinding and other finishing operations.

Polymers and Bio-Based Materials: The Future Is (Recycled) Plastics *(National Renewable Energy Laboratory, Los Alamos National Laboratory)*

About 30 billion pounds of plastics end up in U.S. landfills each year. Currently, only about 2% of this waste is recycled because of the difficulties of working with different types of plastics mixed together. OIT is sponsoring

a number of efforts to recover high-value chemicals from mixed waste plastics using pyrolysis, a process whereby the wastes are heated in the absence of oxygen in a closed chamber. The most successful effort to date has been the recovery of the chemical caprolactam from waste carpeting. The pyrolysis process also has the potential to recover chemicals from mixed plastic beverage bottles.

OIT is also sponsoring a variety of other polymer research, including the development of polymers that conduct electricity. These types of polymers have a wide range of applications in such things as electric utility equipment, electric vehicles, separation of gases during chemical processing, printed circuit boards, and automobile parts. Conducting polymers can be used as a low-cost means of storing electricity in power back-up systems and in electric vehicles. They can be used to adapt membrane systems to separate specific combinations of gases, with the potential to yield annual energy savings of up to 300 trillion Btu. As a coating material, conducting polymers can reduce both the cost and the pollution associated with plating operations used for metallized printed circuit

boards, structural components for cars, and coated plastic parts. Finally, the Polymers and Bio-Based Materials Program is investigating novel processing methods, based on the use of magnetic fields, to make specific types of advanced polymers to use in separating chemicals and also making lightweight parts for cars.

New Materials and Processes: Cooking with Microwave Energy *(FM Technologies, George Mason University, Los Alamos National Laboratory)*

Silicon carbide (SiC) is a ceramic material that can safely and reliably withstand operating temperatures many hundreds of degrees higher than metals and metal alloys. In particular, SiC is desirable for use in high-temperature heat exchangers, recuperators (used to recover waste heat), and burners used in the metals, glass, and other industries. Limitations in fabrication techniques for ceramic components have been obstacles to using these beneficial materials, however. SiC is generally difficult to produce in the lengths and shapes typically required for many industrial applications. Ceramic heat exchanger tubes are also extremely difficult to join together to make a workable heat exchanger. These problems combine to make fabricating large ceramic tube assemblies prohibitively expensive. Recent research has been investigating the use of microwave energy to advance the manufacture of ceramic components in a cost-effective manner.

In one such effort, researchers are using fabrication techniques based on microwave energy to join one SiC component to another. Microwave processing is of great interest to materials researchers because its ability to heat material from the inside out has many technical benefits. The goal is to develop and optimize a practical joining method that can be applied to large-scale production of ceramic components such as high-temperature heat exchangers and burners. The method could also be used to make economical on-site repairs at a plant.

Microwave joining could save as much as 100 trillion Btu per year and could strengthen and expand the \$100 million/year radiant tube and heat exchanger markets.

In another effort, researchers are exploring other new applications for microwave processing using a new variable frequency microwave furnace. The variable microwave process will permit more energy-efficient processing of materials by virtue of its ability to operate at optimum frequency or at variable frequencies as the material is heated. It also generates a more uniform microwave field that allows for even heating of single and multiple parts in the furnace. Applications of this technology include producing multilayer ceramic capacitors (energy-storing devices) and processing certain plastics. The variable microwave process requires only a fraction of the energy of current processing methods and is several times faster, thereby improving productivity.

Continuous Fiber Ceramic Composite Materials

TOUGHENING UP THE FEET OF CLAY

Many opportunities for improving the productivity, energy efficiency, and waste utilization of industry are not pursued because of a shortage of materials capable of handling the severe operating conditions often present in industry. Yet materials that are lighter, stronger, more corrosion resistant, and able to perform at higher temperatures could improve productivity in many industries by allowing higher process temperatures, extending component and system life times, and reducing downtime for maintenance and repair. While a number of advanced materials have been developed in recent years with varying potential to meet these demanding requirements, ceramics offer the greatest potential where a combination of reduced weight, high-temperature performance, and ability to withstand corrosive environments is needed.

Ceramic products have been produced and used for thousands of years. Such ceramic products as bricks, pottery, and cement have been used for so long because their raw materials are abundant and cheap and their unique molecular structures give rise to many outstanding and highly useful properties. Typically, ceramics are as strong as or even stronger than metals yet they are also lighter. They possess exceptional heat, chemical and abrasion resistance and provide excellent electrical insulation.

Such properties could contribute to substantial productivity improvements in industrial systems successfully employing ceramic components compared to those using metals. Unfortunately, however, ceramics also possess a critical vulnerability that severely limits their practical use:

their brittleness and propensity for catastrophic failure. While metals bend, ceramics break.

Fiber Reinforcement Helps Ceramic Materials Achieve Their Full Potential

Ceramic composites help overcome this serious limitation. They are not only strong; they are also tough. By incorporating long, strong glass or ceramic fibers in a ceramic matrix, the toughness of ceramics can be improved substantially and their tendency to fail in high-stress environments can be reduced considerably. These fibers reinforce the ceramic to create a composite which is several times tougher (less brittle), and significantly less sensitive to strength-limiting flaws than the ceramic material alone. Fibers help maintain the productivity-enhancing properties of ceramics while controlling or eliminating their deficiency. Because of these enhanced properties, continuous fiber ceramic composites (CFCCs)

How Fibers Improve The Toughness of Ceramics

In continuous fiber ceramic composites (CFCCs), the ceramic matrix contributes chemical and thermal stability while the fiber contributes strength and toughness. The fibers provide toughness by arresting and bridging cracks through a phenomenon known as pull out. When a crack reaches a fiber, it must divert around the fiber—a process that consumes more energy than linear crack growth. Typically, there is not enough energy for the crack to change direction and bypass the fiber. Crack growth is thus arrested.

If there is sufficient energy to deflect around the fiber, the fiber can bridge the crack and thus hold the matrix together. Even if the matrix fails, the fibers must be pulled out before the composite can separate. Fibers give rise to a non-catastrophic failure mode similar to that of metals. The arresting and bridging of cracks and fiber pull-out are the principal mechanisms responsible for the increased toughness of continuous fiber ceramic composites.

offer the potential to satisfy materials needs across a broad spectrum of industrial applications.

Successful deployment of CFCC components in industrial applications would help improve energy efficiency, increase productivity, and reduce environmental impacts. For example, using CFCCs in the demanding environments of incineration systems could help ameliorate the waste disposal problem, decrease the toxicity of airborne pollution, and displace fuel consumption through enhanced waste energy recovery. Using CFCC components could enable gas turbines to operate at higher temperatures thereby increasing energy efficiency by as much as 4% which would help reduce fuel use by up to 13%. Other potential productivity- and performance-enhancing industrial applications of CFCCs include:

1. Industrial burners and combustors ranging from small-scale space-heating units to large-scale industrial systems;
2. Process equipment such as reformers, reactors and high pressure heat exchangers for use in industries such as chemicals and petroleum refining;
3. Filters, separation and sewage treatment systems;
4. High-temperature industrial heating, melting and heat-treating equipment such as furnace linings, crucibles, racks and kiln furniture;
5. Structural components such as beams, panels, decking and containers.

The CFCC Research and Development Agenda

The potential energy, economic and environmental benefits of CFCCs in so many applications provide strong incentive for government and industry to jointly pursue aggressive development and deployment of these highly useful materials. The CFCC

Figure 4-2
Potential U.S. Markets for CFCCs, 2010

Source: CFCCs for Low Cost Energy and a Cleaner Environment, RMCI

R&D agenda is driven by cost competitiveness and product reliability which remain the overwhelming concerns of potential users and suppliers.

To produce CFCCs that are consistent in composition and reliable in performance, processing techniques are required that allow the matrix to be uniform throughout the entire volume of the preformed fiber component or part. In addition, the processing techniques must accommodate not only the matrix and fiber, but must produce the required fiber-matrix interface which is critical to the desired toughness and performance of the composite. A variety of traditional and new fabrication techniques have been used to produce CFCCs with varying success, but none has emerged as clearly superior in its ability to produce desired properties at minimum costs.

Efforts that focus on developing cost-effective processing technology for industrial applications are needed. Advanced composite designs, standardization of test procedures, joining techniques, and prototype demon-

strations are also necessary to ensure that this promising material reaches its market potential. Specific technical needs for CFCC development and commercialization include the following:

- **Fiber development:** Providing more environmentally stable (oxidation and corrosion resistant), higher-temperature (greater than 1000°C) fibers at greatly reduced costs (less than \$200/lb).
- **Fabrication/processing improvements:** Developing cost-effective, reliable fabrication techniques compatible with commercial/industrial needs and operations. Areas of focus include:
 - High yield to achieve lower production costs;
 - Near-net-shape fabrication to minimize finishing steps;
 - Fabrication of complex shapes including 3-D fiber architectures;
 - Scale-up to production part size and rates.

- **CFCC materials characterization:** Establishing the materials database on properties, performance, and life necessary to understand and apply CFCC materials.
- **Composite design:** Establishing a better understanding of crack propagation and failure. Developing design models for predicting performance and properties and their relationship to processing. Developing better fiber coatings and fiber-matrix interfaces.
- **Standardization of test procedures and data:** Developing comprehensive standardized procedures for design, evaluation, qualification, and testing to encourage the use of CFCCs by the engineering community.
- **Joining:** Developing the joining/fastening techniques necessary to integrate CFCCs into systems where attachment to other parts and materials is required.
- **Prototype demonstrations:** Establish a successful performance and reliability history for CFCC applications in industrial settings.

THE OIT CFCC PROGRAM

OIT's CFCC Program is involved in developing advanced composite materials targeted to meet the needs of a variety of industrial applications. The program seeks to develop and demonstrate, at pilot scale, efficient and economical methods of processing CFCC components that are representative of the geometries and properties required by users. The program also develops the necessary supporting technologies for fabricating and testing CFCC materials and components, and provides components and related technologies for incorporation into applied R&D programs. The development of a specific fiber is not part of the OIT CFCC Program, which instead relies on ongoing efforts at the Department of Defense and National Aeronautics and Space Administration (NASA) for

developing advanced fibers. Materials must be cost-effective and capable of operating at higher temperatures than conventional materials; and processing technologies must be capable of meeting demanding economic targets and high production rates.

CFCC Components for Land-Based Gas Turbines: Operational Improvements Lead to Higher Efficiency and Lower Emissions
(General Electric, Textron Specialty Materials)

Current gas turbines used in power generation applications (excluding marine and aircraft applications) have large cooling requirements, typically requiring 30% to 40% of their discharge air for component cooling. This lowers the energy efficiency of the turbine, thus increasing its fuel requirements. Replacing metal alloy components with CFCC components could substantially increase this energy efficiency by allowing the turbine to operate at higher temperatures. The problem to date has been developing a CFCC and a corresponding fabrication method that could be used to make the components in the required shapes.

A new material called Toughened Silcomp has been developed for just such applications by an industrial team under OIT's CFCC Program. Toughened Silcomp consists of a continuous network of silicon carbide fibers within a silicon-silicon carbide matrix. This material and its fabrication technique—known as melt infiltration—can be used to produce a variety of fully dense, complex-shaped parts. The material's density gives the composite good oxidation resistance, high thermal conductivity, low thermal expansion, and good strength, all desirable characteristics for gas turbine applications. Using the CFCC components, gas turbines will be capable of operating at higher temperatures, reducing cooling requirements and allowing the turbine to operate more efficiently. Because of operational improvements, emissions of

Photo courtesy of Coors Ceramics

Advanced ceramic products are used for insulator products including electrostatic precipitator applications.

CO, NO_x, and unburned hydrocarbons will be reduced. It has been estimated that using the CFCC components would yield fuel savings of nearly \$1 million per year for a 100-megawatt gas turbine.

Ceramic Fiber Radiant Burner: Ushering in the Next Generation of Efficient Burners

(Alzeta, Southern California Gas, 3M)
Ceramic fiber (not composite) radiant burners are already in use in residential warm-air furnaces, commercial deep-fat fryers, dryers for the plastics industry, commercial greenhouses, residential and commercial water heaters, industrial boilers, and paper dryers. These ceramic burners have higher thermal efficiency, provide more uniform and controllable heat transfer, and reduce emissions of NO_x and CO compared with conventional radiant burners. Now, with OIT assistance, the manufacturer of these burners is taking the next technological step in the evolution of advanced burners—incorporating CFCC components into existing ceramic fiber burners.

Two design concepts have already been identified and are being tested. First, a CFCC screen is used as a protective outer sheath for the burner or as a reverberatory screen. Experiments have shown that the radiant output of the ceramic fiber burner can be increased by as much as 100% by using reverberatory screens, and that burner life will be at least double that of a conventional ceramic radiant burner at elevated temperature. The second design concept uses a CFCC pad, or mat, that presents a uniform face to the heated surface. The combined effect of the design changes is an increase in the thermal efficiency of the burner by between 2% and 10%, and a reduction in the formation of NO_x. In direct-fired industrial heating and drying applications, the efficiency improvements could be even greater, reducing fuel usage by as much as 35%. Assuming 10% of all industrial radiant burners are replaced with the improved burner, more than 50 billion cubic feet of natural gas could be saved and NO_x emissions could be reduced by 35,000 tons each year.

Ceramic Composite Radiant Tubes: Converting a Composite Concept Into Cost Savings

(Textron Specialty Materials,
Nova Industrial Ceramics, Stone &
Webster Engineering, Hauck Burner
Company, Materials Science Corporation)

For years, the concept of using CFCC tubes in waste heat recovery and power generation applications has existed, but no existing CFCC fit the requirements. Now, with DOE support, the dream has a good chance of being realized. An industrial team is developing and demonstrating a novel method for fabricating CFCC materials that can be used to manufacture low-cost tubes. The processing approach is to use various reinforcing fibers in a nitride-bonded silicon carbide matrix. Tubes made from this material will subsequently be impregnated and coated using the unique Textron Rapid Densification (RD™) process to enhance their durability.

The new CFCC tubes are targeted for a variety of applications, including steam/methane reformers used in the chemicals industry; and pyrolysis furnaces, immersion heaters, industrial

burners, and preheaters used primarily in the metals processing industries. One specific application being investigated is the recovery of waste heat from melting used beverage cans and other aluminum scrap in the aluminum recycling industry. In this case, fuel consumption for aluminum recycling could be reduced by one-half to two-thirds. On a national basis, this would result in a total energy savings for aluminum recycling facilities of about 0.3 quads per year. Using the new CFCC tubes in steam/methane reformers could result in a 20% reduction in requirements for natural gas feedstock. In general, an improvement of as much as 25% in operating efficiency is projected for many of the applications.

CFCC Applications for Diesel Engine Valve Guides: No Lubricants Required

(AlliedSignal, Caterpillar,
Quinn Engineering Systems)

The diesel engines currently used in some industrial and agricultural applications present a significant opportunity for energy savings and emissions reductions using CFCC components.

The cast iron valve guides used in current engines cannot operate at temperatures above 300°C because the cast iron has insufficient strength, resulting in valve deformation and eventual failure. These valves also require regular lubrication with commercial petroleum-based lubricants to maintain proper operation. Even if a valve could operate at higher temperatures, available lubricants develop deposits that would cause the valve to stick or wear excessively. However, the energy efficiency of the diesel engine increases with elevated operating temperature.

A unique solution to this dilemma—a self-lubricating, CFCC diesel engine valve guide—is being investigated by OIT and an industrial team. The material being used is a continuous-carbon-fiber-reinforced silicon nitride, which will be fabricated into components by one of several novel processing methods under consideration. The valve guide will provide the required friction and wear properties along with the structural integrity to operate under extreme temperature conditions. These new guides are expected to cut particulate emissions by 25% by reducing flows of lubricants into the combustion chamber. Other benefits include improved fuel economy and increased engine reliability. The CFCC valve guide technology has the potential for cost-effective use in high-load-factor industrial and agricultural applications, where operating costs are driven by engine fuel costs, and in alternative-fueled engines. It is also possible that the technology will be used in a substantial number of future diesel engines, and may eventually apply to internal combustion engines in general.

Supporting Technologies:

**Assisting in the Design, Fabrication,
Characterization, and Qualification
of CFCCs and CFCC Components**
(Oak Ridge National Laboratory)

Oak Ridge National Laboratory is leading a team of national laboratory, industry, and academic partners in

Table 4-8
Other OIT CFCC Projects

Project (Developer)	Description	Potential Areas of Use
Chemical Vapor Infiltration of Ceramic Matrices (Amercom, Solar Turbines, Surface Combustion, Detroit Diesel, ABB/Combustion Engineering, MSNW, Materials Sciences, University of Virginia)	Develop chemical vapor infiltration processing technology for preforms of continuous, multifilament ceramic fibers.	Piston rings for diesel engines, high pressure heat exchanger systems, hot gas filters, and burners and combustors.
Sol-Gel Impregnation Processing (Babcock & Wilcox, Virginia Tech, Fiber Materials, Ohio State University)	Develop liquid-to-solid-based processing method, sol-gel impregnation to produce oxide/oxide ceramic composite materials.	Boiler components, turbine combustors, heat exchangers, and hot gas filter components. Near term emphasis will be on hot gas filters intended for use in advanced fossil energy systems.
Chemical Vapor Infiltration of Silicon Carbide (DuPont Lanxide Composites, Foster Wheeler, Westinghouse, GE Power Generation, Alzeta)	Fabricate and test CFCC materials manufactured from silicon carbide through chemical vapor infiltration.	Gas turbine components, radiant surface components, reformers, heat exchangers, and hot gas filters.
Directed Metal Oxidation (DIMOX™) Processing of CFCCs (DuPont Lanxide Composites, Foster Wheeler, Solar Turbines, GE Power Generation, Westinghouse)	Examine Nicalon™ silicon carbide fiber-reinforced alumina matrix composites made from the DIMOX™ process.	Coal fired combined cycle power generation, heat exchanger tubes, turbine tip shrouds, and combustor liners.
Polymer Impregnation and Pyrolysis Processing of CFCCs (Dow Corning, Kaiser Aerotech, Solar Turbines, Sundstrand Fluid Handling, Synterials)	Fabricate and test materials manufactured from Sylramic® CFCCs using low temperature polymer impregnation and pyrolysis.	Gas turbine combustor liners, first stage turbine disks, and chemical pump components.

performing generic research of CFCC materials. Representative composite systems are being used to examine phenomena applicable to a broad range of materials, processing techniques, and service environments. The team's fundamental studies of materials, material interactions, and performance under use will provide the scientific foundation for industrial development and scale-up of reliable CFCC materials and components.

Specific tasks within this effort are focusing on composite design, materials characterization, test methods, and life prediction and database development. In the composite design task, researchers are developing micro- and macro-mechanical models that predict the properties and behavior of various CFCC components. Materials characterization research is aimed at determining the effects of typical processing and service environments on CFCCs. In the area of test methods, scientists are working to ensure quality control in characterizing, processing, and qualifying CFCC materials. Finally, research is underway to understand the time-dependent behavior, environmental stresses, and damage accumulation that can limit the life of CFCCs. A database to collect and summarize data for all of the tasks is being compiled.

Electric Motor Systems—Motor Challenge

THE WORKHORSE OF INDUSTRY

Electric motors and the systems they power perform vital roles in just about every niche of the U.S. economy. More than 1 billion electric motors currently are in use in industrial, commercial, residential, and utility power plant applications, consuming tremendous amounts of energy. The U.S. electric motor and drive industry accounts for roughly \$10 billion in annual sales, and the motor industry employs about 50,000 people.

Electric motor systems (EMS) are an integral part of industry. Motor-driven equipment accounted for approximately 70% of the electricity consumed in the industrial sector in 1990, and in some industries, represented 90% of electricity consumption. Roughly \$30 billion is spent on electricity to drive industrial motor systems. Industrial EMS account for more than 20% of total U.S. electricity consumption and nearly 40% of the electricity used in EMS in all sectors. According to the Electric Power Research Institute, manufacturing accounts for the vast share of electricity consumption by motors in the industrial sector, with mining, agriculture, and construction accounting for the remainder.

The widespread use of EMS throughout U.S. industry provides significant opportunities to capture broad-based benefits associated with more efficient EMS. Besides the potential for substantial energy savings, increases can be made in productivity. Reduced energy use and changes made in processes associated with the system can also result in lower emissions and reduced waste streams, thereby improving environmental quality while reducing costs associated with waste remediation. The bottom line is that using more efficient EMS can result in lower costs to industry and increased competitiveness.

Electric Motor Systems

Developed more than a century ago, the A/C induction electric motor remains remarkably similar to the motor of today. Materials and manufacturing methods have changed and improvements have increased the efficiency and ability to control motors, but the same basic principles still apply. The electric motor changes electric energy into mechanical power to perform work. In manufacturing, electric motors are the predominant means of providing drive power and motive force.

Electric motors are a core part of EMS, an integrated system of electrical and mechanical equipment. Electric motor systems include the motor, the electric supply system that provides electric energy to the motor, the motor starting control and drive system, the driven mechanical system such as fans, pumps, blowers and compressors, and the process application (Figure 4-4). Electric energy is the input to the system, and the output is the service or process application provided (for example, refrigeration, air flow, or material movement).

Electric Motor System Opportunities

Significant opportunities exist to improve the energy efficiency of electric motors and their connecting systems. It is insufficient to examine improvements that could be made to the motor alone, because energy use in other parts of the motor system could offset gains made by improving just the motor. In addition, the electric motor is only one of many factors

that contribute to the efficiency of an electric motor system. Other factors include the efficiency of other individual components of the electric motor system (such as the controlling devices, pumps, fans and compressors) and how the individual components are integrated into a complete system. Proper application of an efficient electric motor system requires the optimal integration of motors and drives with the power supply, as well as with the process application. In the industrial sector proper evaluation of the whole system is very important. Industrial EMS are often integrated into complex manufacturing operations in which productivity, quality, and energy factors need to be considered carefully.

There are four major opportunities to improve the efficiency of electric motor systems which together could

Figure 4-3

Total Net Electricity Demand by Manufacturing Industries, 1991

Note: Net electricity demand is defined as purchases, on-site generation, and net transfers of electricity, less quantities sold.

Source: EIA, Preliminary Manufacturing Energy Consumption Survey data, 1991

Figure 4-4

The Electric Motor System (EMS)

save 240 billion kilowatt hours annually by the year 2010. These include (1) improving the efficiency of the motor; (2) reducing losses associated with electricity distribution; (3) improving the match between the motor drive and the mechanical system; (4) and using equipment or processes that require less power (process optimization) (Figure 4-5). Efficient EMS on average use 20% less energy than a conventional system. Although initial capital costs are

higher for an efficient system, efficient EMS systems are expected to last 10% longer than conventional technology.

The materials and process industries account for over one-half of all electricity used in manufacturing motor systems. These industries, which include the chemical, petroleum, pulp and paper, metals, and food industries, offer major opportunities for improvement in the use of efficient motor systems. For example, in the pulp and paper industry, motors account for 95% of electricity consumed, with the potential to reduce electricity consumption by 11% to 49% through the use of energy efficient measures, according to the American Council for an Energy Efficient Economy (ACEEE).

Potential electricity savings in the chemical industry are similar, ranging from 11% to 44%, and in the food processing industry, potential savings range from 16% to 50%. In addition to the industries already mentioned, other industries in which significant electricity savings are possible through energy efficient measures include primary metals, transportation equipment, rubber and plastics, and electrical equipment, according to ACEEE.

However, a number of barriers must be overcome to achieve more widespread adoption of efficient EMS. These barriers include:

- **The electric motor system market is a cost-dominated market.** Companies often do not look beyond the initial purchase cost in deciding which motor to purchase, even though long-term savings could be substantial.
- **The motor often accounts for a small portion of the total system cost.** Thus, the importance of the motor is often overlooked.
- **The efficiency of existing motors is often not known.** The efficiency rating of a motor can be reduced substantially through successive repairs. Likewise, users many times do not opt for the more efficient, newly purchased motor that offers better life-cycle cost than an existing motor in need of repair.
- **The structure of the electric motor system market is complex.** Fragmentation in the market makes it difficult for a user to obtain sufficient, reliable information on the markets and end-use applications of motor systems. In addition, because motors are often components of larger systems, equipment manufacturers—not end users—often determine motor specifications.
- **Many end-users lack technical expertise.** Because many users lack sufficient experience or expertise in EMS, they do not always make the best technology choices. This is exacerbated by misinformation in the marketplace concerning efficient EMS.

Figure 4-5
Potential Annual U.S. Energy Savings from EMS Improvements

Source: Office of Industrial Technologies estimates for year 2010.

Photo by Jeff Uhrhau

Matching a motor that requires less power to a process improves energy efficiency.

THE OIT ELECTRIC MOTOR SYSTEMS PROGRAM

OIT's Electric Motor Systems Program is designed to improve energy efficiency, enhance environmental performance, and increase productivity by increasing U.S. industry's use of efficient EMS. The EMS program

targets the many technical, economic and institutional barriers that impede the rapid and widespread adoption of efficient EMS. The program will accomplish these goals by mobilizing private and public resources to focus on EMS opportunities, catalyze new alliances between interested parties, and promote the understanding, development, and adoption of EMS.

Motor Challenge

Motor Challenge is the centerpiece of OIT's Electric Motor Systems program. Motor Challenge is a joint effort of DOE, industry, equipment manufacturers and distributors, and other interested parties to promote integrated systems of energy efficient motors, adjustable speed drives, and efficient motor-driven mechanical equipment and processes. As part of President Clinton's Climate Change Action Plan (CCAP), the Motor Challenge Program is recognized as representing a significant opportunity to enhance environmental performance and reduce energy consumption in U.S. industry.

The overall goal of the Motor Challenge initiative is to advance industry leadership and provide technical assistance and resources to industry so that firms will better understand, apply, and target energy efficient EMS from a systems perspective. In most cases the technology already exists to use efficient EMS. Motor Challenge was designed to act as a catalyst to foster broad-based industrial participation in the exchange of information and the deployment of technology. The Department of Energy has worked diligently with stakeholders to identify barriers and opportunities related to the adoption of more efficient EMS. The program works with partners to focus on deficiencies in the market that influence the choices of stakeholders in specifying, purchasing, and operating equipment, and impede the development and introduction of better products and services.

The major goals of Motor Challenge are as follows:

- Provide national leadership and help focus public and private capabilities to assist U.S. industrial motor system end-users in achieving greater cost-effective energy efficiency, productivity, and environmental performance more quickly than they otherwise would;
- Provide comprehensive, timely, and reliable information and technical knowledge to industrial end-users by drawing on the experiences of industrial leaders in EMS;
- Discover and recognize engineering excellence in the design and operation of EMS and encourage other companies to follow these examples;
- Educate and train practitioners and trainers in the latest best practices associated with efficient EMS;
- Assess EMS markets to improve the timeliness and reliability of data on such systems;
- Support the development and implementation of market transformation strategies that will encourage demand for better products and services; and
- Recognize companies that have implemented internal corporate management practices and policies for efficient motor-driven systems in an exemplary and high-quality manner.

The Motor Challenge initiative consists of five basic elements: (1) partnership activities with stakeholders; (2) showcase demonstrations; (3) an information clearinghouse; (4) an EMS database; and (5) market transformation strategies.

Partnership Activities

Working through a partnership ensures that the OIT program reflects the needs and opportunities of all aspects of EMS, including design, manufacture, selection, purchase,

operation, and maintenance. Numerous activities take place through the partnerships, including information exchange, conferences, seminars, and training. Partnership activities initially focused on the motor and drive elements of EMS, but focus is shifting to barriers and opportunities associated with pumps, fans, blowers, and compressors.

These partnership activities and related marketing and deployment initiatives are being coordinated with DOE regional support offices, users, suppliers, distributors, utilities, and various industry associations, as well as other organizations. Nearly 100 organizations joined as partners during fiscal year 1994, and have been participating in regional and national information exchange activities.

Showcase Demonstrations

Showcase Demonstrations are intended to show that the full energy efficiency potential of EMS can be achieved cost effectively. This, in turn, should encourage replication at other facilities. Industrial end-users will lead each demonstration team, which might also include motor and drive manufacturers, original equipment manufacturers, architect and engineering firms, utilities, state energy offices, research institutions, universities, distributors, consulting firms, and others. The teams will submit proposals to demonstrate existing or new applications of efficient EMS. OIT will provide technical assistance and tools to help the teams (1) develop better strategies in implementing the project, (2) validate costs and benefits, (3) establish enduring alliances, and (4) gain recognition for their efforts. DOE will select approximately 25 Showcase Demonstration teams by May 1995.

Information Clearinghouse

The Information Clearinghouse became operational in February 1994, and serves as a one-stop-shop to provide interested parties easy access

Table 4-9
OIT Motor Challenge Partners (as of February 6, 1995)

<ul style="list-style-type: none"> *3M Corporation A.I.M. Energy, Inc. *ABB Industrial Systems Inc. Aerovox Group Alexandria Sanitation Authority *Alliance to Save Energy Allied Electric Motor Service, Inc. Alternative Energy Systems Consulting Inc. *Amer. Coun. for Energy Efficient Economy American Iron and Steel Institute American Portland Cement Alliance *American Public Power Association Anker Energy Corporation Arizona State University (EADC) Associated Air Products of Palm Beach Atlanta Armature Works Automation Engineering *Baldor Electric Company Baskerville-Donovan, Inc. Bearings Inc. Bethlehem Steel Corporation BGK Inc. Brabazon Pump & Compressor Brook Hansen Inc. *California Energy Commission Caprock Industries Inc. CEP Sales Company Inc. Chemical Manufacturers Association Chevron U.S.A. Products Company Clow-Rodgers, Inc. *Consol Coal Group Consolidated Papers, Inc. Cooper Communications Cray Research Inc. Curwood, Inc. Demand Side Management, Inc. Dip-Proofing Technologies, Inc. Diversified Mechanical Sales, Inc. Dreisilker Electric Motors, Inc. Dunn's Electric Motor Service DYN Corporation Echelmeier Company EcoTech/RAM-Q *Edison Electric Institute EG&G Florida E.I. duPont de Nemours and Company Inc. Electric League of the Northwest 	<ul style="list-style-type: none"> *Electric Power Research Institute *Electrical Apparatus Service Association Electrical Equipment Company Inc. Emerson Electric Emerson Swan Energy Analysis and Management Engineered Software, Inc. *Enron Corporation Eugene Water & Electric Board EWS Corporation Exxon Corporation Facility Management Consulting Services Florida Power & Light Company FLOWCARE Engineering Inc. Fluor Daniel (NPOSRCUW), Inc. *Ford Motor Company Ford Motor Company - Van Dyke G-N Electric Company Inc. General Electric ASD-EMP *General Electric Company *General Motors Corporation Georgia-Pacific Corporation GIW Industries, Inc. Global Energy Solutions, Inc. Gould's Pump, Inc. Graham Company Great Lakes Controlled Energy Co. Green Technologies, Inc. Gundersen Clinic, Ltd. Halmar Robicon Drives Group Hoechst Celanese Corporation Holnam Inc. Holt Electric Motor Company Hugh J. Cullen Associates *Hydraulic Institute Hydro Power, Inc. *IBT, Inc. ICF Inc. *Indiana Dept. of Commerce/ Ener. Pol. Div. Industrial Electric Motor Service, Inc. Industrial Pump Sales & Service *Iowa Dept. of Nat. Resources/ Energy Bur. Iowa State University (EADC) ITOCHU International ITT Flygt AB Jemco Electric Motor Johnson & Johnson Joliet Equipment Company K.C. Electric Association, Inc. Kaman Industrial Technologies Kellogg - Memphis Plant Kenetech Energy Management, Inc. Kentucky Division of Energy LaCrosse Footwear Inc. 	<ul style="list-style-type: none"> Lamour, Inc. Lange Electric Company, Inc. Lehigh Portland Cement Company Liberty Technologies Inc. LTV Steel Company, Inc. Magna Force, Inc. *MagneTek, Inc. Manassas Electric Motor Company *Marathon Electric Manufacturing Corp. Martin Marietta Armament Systems Massachusetts Div. of Energy Resources McBroom Electric Company, Inc. Mellin Industries, Inc. Mercy Medical Center Merion Pump Company, Inc. Midwest Power Mirro Company Morgan Products Ltd Motion Industries Inc. Myriad Marketing Services Nalco Chemical Company National Association of Manufacturers *Nat'l. Assoc. of State Energy Officials National Center for Atmospheric Research *National Coal Association *National Electrical Manufacturers Assoc. National Lime Association New Horizons Enterprise *New York State Energy Office *Nor. Carolina Ener. Div., Dept. of Commerce *Northern States Power Company Notre Dame University (EADC) NRG Systems, Inc. Old Dominion University (EADC) Oregon State University Paco Pumps, Inc. *Peabody Holding Company Pennsylvania Energy Office Ponderosa Pulp Products Pope & Talbot, Inc. Power Conditioning Systems, Inc. POWERTEC Industrial Corporation Public Service Company of Colorado Pump Pro's, Inc. R.L. Yates Electric Company, Inc. RC Cement Company, Inc. RCS Sales Company *Reliance Electric Company Resource Dynamics Corporation Richmond Newspapers, Inc. River City Electronics Company Riverton Corporation Robert Wood Johnson Univ. Hospital Safronics, Inc. 	<ul style="list-style-type: none"> Sandman Electric Showell Farms, Inc. *Siemens Energy & Automation, Inc. Smith and Sun *Solar Turbines, Inc. South Dakota State University (EADC) Southeast Pump & Equipment, Inc. *Southern California Edison Company Spina Electric Company St. Francis Medical Center *Sterling Electric, Inc. Strategic Pkg. for Energy & Environment Sub-Zero Freezer Company System Planning Corporation Teco American, Inc. TENSA, Incorporated Texas A&M University (IAC) *The Boeing Company *The Business Council for a Sustainable Energy Future *The Dow Chemical Company *The Electrification Council The Energy Group *The Lincoln Electric Company The Louis Allis Company *The Louisiana Land & Exploration Co. The Refractories Institute The Spencer Turbine Company *Toshiba International Corporation Tower Sales Company, Inc. United Electric Motors *U.S. Electrical Motors U.S. Industrial Sales University of Arkansas (EADC) Utility Focus, Inc. Vallejo Electric Motor Shop Inc. Virginia Power Volland Electric Equipment Company Washington State Energy Office Waupaca Foundry, Inc. W. Va. Development Ofc., Energy Eff. Prog. *Western Fuels Association, Inc. *Westmoreland Coal Company Wisconsin Center for Demand-Side Research Wisconsin Demand-Side Demonstrations *Wisconsin Energy Bureau XENERGY Inc. Youth Center at Beloit
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* Indicates joined as Charter Partner; October 1993

to a variety of resources. The clearing-house disseminates information and decision-making tools, as well as education and training materials. It also provides technical assistance, manages an electronic bulletin board, and publicizes upcoming conferences and workshops.

National Electric Motor Systems Database

The database will contain reliable data on the performance of electric motor-driven systems in real-world applications. The database will facilitate the exchange of information and technical know-how and help accelerate the adoption of efficient systems. It will also provide the basis for recognition of the achievements of individual end-user companies.

Market Transformation Strategies

Market transformation strategies will promote the development and delivery of more efficient technologies and services by leveraging the substantial market position of large industrial motor end-users, states, and the federal government to create demand for efficient motor system equipment. A transformed market demanding higher performance motor system

equipment will create business opportunities and incentives for designers and manufacturers. Market transformation strategies will include (1) working with industry to develop voluntary testing and performance protocols; (2) training and certification to strengthen system-level design assistance; and (3) supporting public and private sector purchasing initiatives. The first step in designing and implementing market transformation strategies is scheduled to begin during the third quarter of fiscal year 1995 with a roundtable discussion involving stakeholders.

Market and Technology Assessments and R&D

EMS program activities are designed to improve the quality and quantity of information available to decision-makers. In so doing, DOE is working with industry to develop and define key EMS market and technology opportunities while coordinating its R&D activities with other motor-related technology initiatives.

A focus of OIT's R&D activities involves the development and demonstration of advanced instrumentation and diagnostic equipment techniques that will provide a low-cost, portable

means to field-test EMS performance characteristics. Currently there is no low-cost, portable, accurate, and simple-to-operate system to test motor efficiency, vibration, and other performance characteristics. Reliable and consistent testing methods that are cost-efficient and easy to perform would help identify opportunities for more efficient EMS.

Other areas of EMS R&D relate to adjustable speed drives (ASD) and materials used in motors. ASD systems precisely control the speed of AC motors, thereby reducing the amount of energy wasted from operating motors at unnecessarily high speeds. ASDs also can extend the life of motors and the machinery they drive by reducing high torque starting conditions and the wear that can occur as a result of motors operating at unnecessarily high speeds.

Opportunities exist to improve the efficiency of motors and motor systems through advances in magnetic and other materials. Some of these opportunities are the result of R&D conducted under other OIT programs. For example, OIT is developing an electrolytic process for the economic production of neodymium from an oxide feed. The goal of the work is to make the use of neodymium/iron/boron magnets in electric motors commercially attractive. Using such magnets could reduce the initial costs of high efficiency motors to a level competitive with less efficient motors. As a result, the capital cost barriers to use efficient motors could be eliminated in all applications.

Table 4-10
Annual Benefits of The Motor Challenge Program

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	0.10	0.08	0.02	411,092
Total Cost (\$1000)	1.48	1.18	0.29	5,481,885
Energy Cost (\$1000)	1.41	1.10	0.31	5,866,371
Capital Cost (\$1000)	0.07	0.09	-0.02	-384,486
O&M Cost (\$1000)	0.00	0.00	0.00	0
Emissions (metric ton)				
CO ₂	17.25	13.42	3.83	71,883,068
NO _x	0.01	0.01	0.00	60,504
SO _x	0.13	0.10	0.03	542,906
Particulates	0.34	0.27	0.08	1,420,478
Solid Waste (1000 short tons)	-	-	-	-
Risk				
Technical		LOW		
Market		LOW		
Year of Maximum Market Share		2010		

HELPING TO REDUCE THE COST OF NITROGEN OXIDE CLEANUP

Whether used to raise steam, power turbines and engines, melt metals and glass, or heat and dry finished products, all fuels used for heat and power in the industrial sector undergo combustion. Combustion is the rapid chemical combination of oxygen and a fuel that results in the release of heat and byproduct gases. Accurate control of the combustion process is a critical factor in determining energy efficiency, emissions, and product quality in the materials and process industries.

According to the Gas Research Institute, the total quantity of fuel burned in combustion equipment to generate industrial process heat and steam was 15 quads in 1990. Thus, even a small increase in combustion efficiency could have a major impact on the total quantity of fuel used nationally. Similarly, in that same year, U.S. industry generated 8.3 million tons of NO_x emissions, 6.1 million tons of SO₂ emissions, 9.1 million tons of VOC emissions, and 3.5 million tons of particulate emissions. Again, incremental improvements in the emissions characteristics of industrial burners

How Nitrogen Oxides Formed

Nitrogen oxides, or NO_x, refers to the combustion byproducts nitric oxide and nitrogen dioxide. NO_x is considered to be a precursor of ground-level ozone, a common pollutant in urban areas. NO_x is formed via three mechanisms:

- **Fuel NO_x:** When nitrogen bound in the fuel combines with oxygen in combustion air;
- **Prompt NO_x:** When fuel hydrocarbons break down and recombine with atmospheric nitrogen;
- **Thermal NO_x:** When intense heat causes atmospheric nitrogen and oxygen to combine.

The Clean Air Act Amendments of 1990 are the primary drivers in the trend toward reducing NO_x emissions from industrial combustion equipment. Local areas, especially Southern California and New England, are implementing these rules with stringent emissions limits. While the timing and application of new rules are still being determined in many localities, a set of consistent terms has been established to describe general levels of compliance that could be required. For each level of compliance, the determination of the emission control options that must be used is based on available data on technical feasibility, availability, and demonstration of actual NO_x reduction. The terms and their definitions are as follows:

and combustion systems could have an extremely positive effect on the nation's environment.

Reducing Nitrogen Oxide Emissions: The Key Combustion Technology Driver

While burner manufacturers and users have traditionally focused on improving combustion systems efficiency and control, recent attention has focused on reducing emissions from combustion processes to avoid costly and inefficient post-combustion controls.

The basis for most air pollution policies and regulations in the United States during the past two decades has been the Clean Air Act and its amendments. Federal environmental officials are focused on implementing requirements mandated by the 1990 Clean Air Act Amendments (CAAA) to achieve acceptable ambient levels of air pollutants, a reduction in emissions of hazardous air pollutants, and control of acid deposition. In addition, various states have issued their own regulations that are sometimes more stringent than federal regulations. The 1990 CAAA are expected to influence the direction of air pollution regulations for several decades.

RACT—Reasonably Available Control Technology. Applies to existing emission sources above a defined NO_x emission threshold in ozone/NO_x nonattainment areas. The cost of control options is considered.

LAER—Lowest Achievable Emission Rate. Applies to new emission sources above a defined NO_x emission threshold in ozone/NO_x nonattainment areas. Defined as the greatest reduction technically achievable regardless of cost.

BACT—Best Available Control Technology. Applies to new NO_x emission sources in attainment areas. A case-by-case evaluation usually based on a top-down evaluation of emission reduction relative to a cost-effectiveness threshold.

Of the many provisions of the 1990 CAAA, among the most significant for industry are those related to the attainment of National Ambient Air Quality Standards (NAAQS) and control of such air pollutants as ozone, CO, fine particulate matter, SO₂, NO_x, and lead. Perhaps the most difficult of these to achieve has been the standard for ground level ozone. This ozone is formed in the atmosphere through a photochemical reaction from reactive hydrocarbons (i.e., VOCs) and NO_x. Federal programs prior to 1990 focused on controlling VOCs, but the CAAA requires control of NO_x as well as VOCs in ozone nonattainment areas. Because NO_x is a byproduct of all combustion processes, this requirement will have a major effect on industry. Many processes that have little or no emissions of such pollutants as particulates or SO₂, may for the first time require emission controls.

Although the actual provisions of the CAAA are complicated, the general thrust of the NO_x or ozone provisions is as follows:

- Specific deadlines for nonattainment areas to clean up to attain the standards have been set. Dirtier areas are given longer time to comply with NAAQS.

- States are required to revise implementation plans to include the new controls mandated in the CAAA.
- More facilities—including many small businesses—will be under control requirements in state implementation plans than in the past.
- Control technologies and feasible controls will be reexamined in light of new technology and experience with that technology.
- Different levels of control are called for under different conditions (i.e., RACT, LAER, and BACT) as discussed in the accompanying box. For existing sources, the control requirements may be limited to relatively easy to implement combustion modifications such as low NO_x burners or flue gas recirculation. However, for new sources or sources in areas with more serious nonattainment problems, expensive post-combustion controls such as selective catalytic reduction or selective non-catalytic reduction may be required.

Control of combustion emissions, especially NO_x, promises to be costly to U.S. industry for the foreseeable future. Improved combustion systems that can meet stringent emission standards without the need for costly, inefficient post-combustion clean-up would allow industry to invest in productivity-enhancing technologies that would promote economic growth. The potential economic and environmental benefits of such combustion advances would affect a wide range of applications. Hence, government and industry have strong incentives to jointly pursue advanced combustion technology.

THE OIT COMBUSTION SYSTEMS PROGRAM

OIT's combustion activities consist of two complementary programs—the Industrial Combustion Technology Program and the Industrial Combustion Equipment

Program. The technology program focuses on the fundamental physical and chemical characteristics of combustion, identifying new concepts that have the potential to improve combustion efficiency and reduce emissions of pollutants. The equipment program is applications-oriented and sponsors the development and demonstration of high-efficiency, low-emission combustion equipment. Often, promising concepts developed in the technology program are passed along to the equipment program for further development into advanced combustion equipment for use in industry.

Approaches to Nitrogen Oxide Reduction

Very low levels of NO_x emissions can be obtained with cost-effective modifications. The following describes some of the approaches under investigation by DOE and industry:

- **Low Excess Air**—Reducing the amount of combustion air provided to the flame can lower peak temperatures and reduce thermal NO_x.
- **Staged Combustion**—Adding fuel and air in stages can also reduce peak flame temperatures leading to lower NO_x formation.
- **Flue Gas Recirculation**—Recirculating flue exhaust gases, which have less oxygen than air, can be used to keep the peak flame temperature down, reducing NO_x.
- **Oxygen/Fuel Combustion**—Using very pure oxygen in place of air for combustion can lower NO_x emissions because no nitrogen is available to form NO_x. Combustion products cool below the NO_x threshold before leaving the exhaust stack.
- **Surface-Stabilized Combustion**—When a gaseous fuel is burned in or near a porous ceramic or metallic surface, the surface absorbs the heat from the flame, lowering flame temperature and decreasing thermal NO_x production.

Industrial Combustion Technology

The Industrial Combustion Technology Program pursues fundamental combustion advances that will ultimately lead to improved energy efficiency, reduced emissions, increased productivity, and enhanced fuel flexibility across a wide range of industries. The program is aimed at understanding and controlling the physical and chemical processes of combustion, developing a knowledge base that can be applied by industry to meet specific needs. As part of the program, researchers develop sophisticated computer models to assist design engineers in visualizing the result of equipment design changes or changes in operating parameters. Program activities are currently focused on three end-use areas—industrial burners, petroleum refinery combustion, and pulp and paper industry combustion.

Burner Engineering Research Laboratory: State-of-the-Art Test Facility Is Available to U.S. Burner Manufacturers

(Sandia National Laboratories)

The Clean Air Act Amendments of 1990 require industry to reduce emissions of combustion byproducts into the atmosphere. The challenge to industry is to find a cost-effective way to comply with these regulations while at least maintaining—and preferably increasing—current levels of combustion efficiency. OIT is helping industry meet this challenge by jointly funding (with the Gas Research Institute) the Burner Engineering Research Laboratory (BERL), a national testbed for new gaseous fuel burner designs.

BERL is available for use by burner manufacturers and other researchers who can use its state-of-the-art diagnostic facilities to collect data on the performance of their burner designs. The laboratory provides the flexibility to test a large variety of burner configurations, providing technical information previously unobtainable. For example, a new high-performance, low-NO_x burner design was recently

under evaluation at BERL. The manufacturer gained insight that will facilitate the scale-up of the 2 million Btu/hour prototype burner to a 15 million Btu/hour burner suitable for steel reheat and aluminum melting applications. In many cases, the results of experiments conducted at BERL are used in conjunction with computer models to identify the reasons for pollutant formation in a variety of commonly used industrial burners. This information can then be used to modify burner designs and operating parameters to reduce emissions from such burners.

Industrial Combustion Equipment

The passage of stricter environmental regulations affecting industry has led the Industrial Combustion Equipment Program to focus on the development and demonstration of advanced, natural gas-fired combustion equipment capable of meeting stringent emission targets without the use of traditional post-combustion control systems. The new technologies are expected to be at least as efficient as today's highest efficiency systems, and far more efficient than post-combustion clean-up systems, which are typically expensive as well as inefficient. Projects undertaken in the program are intended to result in commercial combustion equipment. Targeted industries include petroleum refining, chemicals, metals, and glass, although new technologies will ideally be applicable to a broad variety of industrial users.

Advanced Porous Radiant Burner: Extending Radiant Burner Benefits to High-Temperature Applications (Alzeta Corporation)

Radiant burners are used in a variety of boilers, furnaces, dryers, and other industrial and commercial combustion equipment. Their ability to heat efficiently and uniformly without the potential for localized overheating as well as their relatively low emissions make them desirable in many applications. The development of low emission radiant burners enabling

heating process temperatures of as much as 1800°F could have significant impact in high-temperature industries such as metals processing and petrochemicals.

OIT is currently sponsoring the development of an advanced, gas-fired, porous radiant burner that will extend radiant burner benefits to high-temperature processes that require very high, controlled heat fluxes. These burners produce low emissions of NO_x and CO while maintaining their high combustion efficiency. A new high-temperature burner material has been identified and patented. Even before the full-scale test at the high temperature, the contractor is offering the new burner material for conventional, lower temperature application. Initial installation of these prototype burners is planned for a hydrogen/steam reforming process, in which hydrogen is produced from methane (natural gas).

Workpiece Temperature Analyzer: Non-Intrusive Process Control for Heat Treating Furnaces (Surface Combustion Inc., Textron Defense Systems, Babcock & Wilcox, Johns Hopkins University)

The traditional method of determining the temperature of a workpiece (such as a metal sheet, slab, plate, or part) in a heat treating furnace is to measure the temperature of its surface. Current surface temperature methods, however, are limited in their applications and accuracy. Furnace control based on the internal (bulk) temperature of the workpiece would be much more accurate and could result in major operating cost and energy savings through better process control and scrap minimization.

A project is currently underway to develop a non-contacting commercial system that can determine workpiece surface and/or bulk temperature using laser techniques. One laser is used to initiate sonic waves through the workpiece; another laser detects the arrival of the waves at a set location. The detection of the wave arrival is used to determine the speed of the wave through the given material, which is a function of its temperature

Table 4-11
Annual Benefits of Advanced Porous Radiant Burner

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	132.8	126.1	6.6	27,000
Total Cost (\$1000)	460.0	440.3	19.6	79,884
Energy Cost (\$1000)	456.0	433.2	22.8	92,725
Capital Cost (\$1000)	2.0	2.6	-0.7	-2673
O&M Cost (\$1000)	2.0	4.5	-2.5	-10,167
Emissions (metric ton)				
CO ₂	8724	8288	436	1,774,005
NO _x	15.4	14.6	0.8	3123
SO _x	9.5	9.0	0.5	1926
Particulates	2.1	2.0	0.1	427
Solid Waste (1000 short tons)	-	-	-	-
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		2006		

and/or metallurgical state. The non-contact nature of this measurement makes it useful in a variety of heat treating applications. The analyzer system is a rugged, simple, and low-cost instrument that can be operated by unskilled personnel in dirty, hot, and dusty industrial environments. The ability of the system to obtain real-time measurement data will permit better process control, improved product quality, and reduced manufacturing cost. It has been estimated that these benefits translate into as much as 20% improvement in production rate and 10% reduction in energy use in steel heat treating processes.

Very Low Emission Combustion Systems: Helping Industry Reduce Emissions of Airborne Pollutants
(Alzeta Corporation, Institute of Gas Technology, Praxair, Riley-Stoker)

Approximately 80% of U.S. industry is located in ozone non-attainment areas—parts of the country where the level of ozone exceeds the maximum set by the Clean Air Act. Emissions of NO_x contribute to the formation of this harmful ozone, not to be confused with the protective ozone layer found much higher. Although the transportation and electric utility sectors are responsible for the majority of NO_x emissions, emissions from industrial combustion are significant, representing about one-sixth of total U.S. NO_x emissions. New combustion technologies are needed to help industry reduce its levels of NO_x emissions to comply with existing regulations and even stricter regulations expected in the future.

In the most critical of these ozone non-attainment areas, industrial expansion can not occur without emissions offsets and industrial combustion systems that meet the tightest NO_x emission standards. Currently, these targets can be met only by using costly, energy inefficient post-combustion systems. The goal of the four low emissions combustion systems projects is to produce a new generation of combustion systems capable of

Table 4-12

Annual Benefits of Workpiece Temperature Analyzer¹

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	2	2	0.1	34
Total Cost (\$1000)	24	56	147	1303
Energy Cost (\$1000)	24	23	1	112
Capital Cost (\$1000)	0.0	33	-33	-1074
O&M Cost (\$1000)	N/A	N/A	179	2265
Emissions (metric ton)				
CO ₂	4046	3910	136	1987
NO _x	1	1	<0.1	2
SO _x	5	5	0.2	2
Particulates	2	2	0.1	6
Solid Waste (1000 short tons)	—	—	—	—
Risk				
Technical		MEDIUM		
Market		MEDIUM		
Year of Maximum Market Share		2000		

¹ Data reflects a 5% productivity increase in aluminum heat treating and a 1.5% productivity increase in steel strip processing.

meeting the most stringent emission standards without the use of post-combustion controls.

OIT is sponsoring a project to help several burner manufacturers develop and test low-NO_x burner systems for a variety of industrial applications. The burner systems will most likely be aimed at combustion processes in the petroleum refining, chemicals, steel, aluminum, metal casting, glass, and pulp and paper industries. The companies involved have already performed much of the necessary research; OIT's support is needed for system development and for testing and evaluation at industrial host sites in preparation for technology commercialization. All of the burner systems being developed have NO_x emission levels lower than 9 parts per million, significantly lower than current standard burner systems.

Solar Technologies For Industry

UNLIMITED, CLEAN, DOMESTIC ENERGY FOR A VARIETY OF INDUSTRIAL NEEDS

American industry uses huge amounts of energy. About 37% of all the energy consumed in the United States goes toward fueling industry; this is equivalent to about 5 billion barrels of oil annually. Fossil fuels—primarily coal, oil, and natural gas—supply the vast majority of the energy used in industry.

OIT's solar industrial program is researching and developing solar technologies that help reduce American industry's dependence on fossil fuels. These technologies are being developed specifically for industry, and a variety of industrial and public sector partners including chemical companies, electronics manufacturers, waste management firms, other government agencies, and solar equipment manufacturers are collaborating with OIT to bring these technologies out of the laboratory and into commercial use.

The increased use of solar technology will benefit both industrial users and American society in general. Solar energy is stable, predictable, and abundant. Solar energy costs do not fluctuate because they are not influenced by changes in the global geo-political order. After the money saved on the cost of energy pays back the capital costs of installing and maintaining the system, solar users get free energy. Because solar energy reduces the use of fossil fuels, it also helps lower the generation of greenhouse gas emissions and airborne particulates that accompany fossil fuel consumption.

Solar technologies also create jobs. Most solar technologies involve precisely engineered systems comprising support structures, optical materials, control systems, piping, and pumps. Highly trained engineers

and technicians design and build these systems. For example, the industry that manufactures solar water heating systems has the highest ratio of employment per million dollars expended of any energy industry. This is because the use of solar energy represents a change from an investment in resources that are taken from the ground and burned, to an investment in people who build technology that uses a naturally abundant resource.

Target Markets: Process Heat, Waste Detoxification, Advanced Materials Manufacturing

Solar process heat technologies produce hot water, steam, and hot air for use in industry, business, and government. The technology is versatile and modular, and potential markets exist wherever large quantities of low temperature process heat are required. Solar process heat systems have successfully penetrated niche markets in federal and state governments where facilities such as schools, military bases, office buildings, and prisons need hot water for bathing, cooking, laundry, and space heating. Companies that require large quantities of heated ventilation air for warehouses, large manufacturing plants, airplane maintenance hangars, and similar facilities are also employing solar heating systems.

Solar detoxification technologies are targeted at the environmental remediation and waste management industries. These technologies destroy hazardous organic compounds such as solvents, fuels, and pesticides. Solar detoxification (or detox) technologies are currently being demonstrated at sites where surface water, soils, and groundwater have been contaminated. Solar detox is also being employed as a waste management technique at manufacturing facilities to destroy organic compounds produced in the manufacturing process. The potential market for solar detox is large, given the number of hazardous waste sites

in the country and the large number of industrial processes now being regulated for water and air discharge.

The market for solar manufacturing technologies primarily lies in the advanced materials industries. As will be discussed in the sections that follow, highly concentrated sunlight has properties that are well suited to the nontraditional techniques used to manufacture many of today's high-tech composite materials. In conjunction with a number of industrial partners, solar industrial program researchers are determining the feasibility of using sunlight to metallize ceramics, clad low-value substrates with high-value materials, surface-harden steel alloys, and synthesize high value chemicals and ceramic powders.

Barriers: Low Fossil Fuel Prices, Negative Perceptions, High Initial Costs

Unfortunately, a number of barriers retard diffusion and commercialization of solar industrial technologies. The solar industrial program is attempting to help overcome the effect of some of these barriers through partnerships with industry and other government agencies. Alternative energy technologies such as solar are often overlooked because fossil energy—from oil, coal, and especially natural gas—is currently inexpensive. Although solar technologies are now cost competitive in certain markets, potential users are reluctant to use them if a traditional, widely accepted fuel alternative is available.

To some degree, potential users' reluctance to consider solar is also the result of the rapid growth in the number of solar heating companies in the 1970s. Early systems often had operating problems that soured many potential users on the technologies. Although the efficiency and reliability of the technology has improved dramatically since the 1970s, the solar industry must overcome lingering negative perceptions. Also, solar

technology installation costs are high, and the payback period is often 6 to 10 years. Many potential users are unwilling or unable to incur these high initial costs.

THE OIT SOLAR INDUSTRIAL PROGRAM

The OIT Solar Industrial Program is driven by two pressing issues—industry's need for stable sources of inexpensive energy, and society's growing concern with the environmental consequences of relying exclusively on fossil fuels for power. The program is aggressively addressing these issues by working cooperatively with such industrial partners as Texas Instruments, Coors, Brush Wellman and SEMATECH through cost-shared partnerships to bring solar-based processes to the point where they will be successfully commercialized. A key feature of the program's strategy is the use of multiple entry points, targeting early applications based on a good fit in terms of geography, industrial need, economics, and environmental issues. Efforts are focused in three broad areas: (1) solar process heat; (2) solar detoxification; and (3) advanced materials manufacturing.

Solar Process Heat: A Viable Option for Many Industrial and Institutional Applications

A large percentage of the industrial sector's total energy use—typically between 30% and 40%—goes for process heating applications. These applications range from hot water and steam for food processing plants to hot air for space heating of factories and warehouses. In addition to industrial uses, solar process heat systems have numerous applications in the institutional market, including hot water for schools, hospitals, and prisons. Many of these applications can be met with solar thermal energy systems. In fact, depending on the geographic location and the specific application, solar energy can supply as much as 70% of the heat required for many processes. This can be used

to supplement existing heating systems, thus reducing the need for fossil fuel.

For solar energy to reach its full potential, however, potential users need to become more familiar with solar energy's capabilities. OIT's Solar Industrial Program is working with public- and private-sector partners to establish projects that will provide data to convince potential users that solar process heat can meet their energy needs. The program does this by bringing together potential users of solar-based systems with solar equipment manufacturers to conduct feasibility studies. If the user selects the solar option, the program will sometimes share the cost of equipment purchase and installation. To maximize its impact, the program is collaborating with other government organizations, state energy offices, and electric utilities.

Collaboration with Federal Government Agencies—The Solar Industrial Program works with a number of government organizations as a means of leveraging its resources while increasing the likelihood of an early market. The importance of

federal facilities (including military facilities) as host sites for solar thermal energy systems lies in the opportunity to deploy solar facilities within the next several years, demonstrating the technology's widespread potential. Solar heating projects will provide hot water for showers at Luke Air Force Base; air preheating for an aircraft maintenance hanger at Fort Carson, and hot water for an indoor swimming pool at Fort Huachuca. The program is also working cooperatively with the Federal Energy Management Program (FEMP) to implement third-party-financed projects to help comply with FEMP's mandate to integrate renewable energy options into government facilities.

Collaboration with State Governments—The Solar Industrial Program also provides assistance to state governments that have initiated programs to increase the industrial use of solar energy. Cooperative programs were recently established with Virginia, Florida, and Hawaii to help them design, build, and operate solar water heating systems to demonstrate the technical and economic potential of solar energy. The program has also established collaborative activities

Table 4-13
Annual Benefits of Solar Process Heat

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	8.4	0	8.4	464,595
Total Cost (\$1000)	.47	66	-19	-1056
Energy Cost (\$1000)	41	0	41	2278
Capital Cost (\$1000)	5	64	-59	-3278
O&M Cost (\$1000)	1	3	-2	-111
Emissions (metric ton)				
CO ₂	407	0	407	22,634,492
NO _x	2.6	0	2.6	141,677
SO _x	.0022	0	.0022	127
Particulates	5	0	5	227,295
Solid Waste (1000 short tons)	—	—	—	—
Risk				
Technical		LOW		
Market		LOW		
Year of Maximum Market Share		2025		

with California, Colorado, and New Mexico, leading to cost-shared solar heating projects in these states. In 1994 alone, seven new heating projects and three system rehabilitation projects were undertaken through the OIT/state government collaborations.

Collaboration with Utility

Companies—The program also represents one side of a demand-side management triangle whose other sides are represented by businesses (customers) and electric utilities. In this capacity, the program works to identify promising solar heat projects for businesses within a given utility district, and then bring them to fruition by encouraging utility rebates to solar users, helping the businesses find low-interest loans, or sharing the project costs. The Sacramento Utility District, the City of Tallahassee Electric Department, and the Arizona Public Service Company are three utilities currently participating in this effort.

Reducing the Cost of Solar Heat—

During the last decade, improvements in the technology have resulted in significant cost reductions. Further reductions, however, are needed to broaden the industrial market for solar heat. During 1995, OIT will expand its assistance to the solar industry to help it reduce the cost of solar energy. This will take two forms: technology development and manufacturing improvements. Technology development will use new materials to improve the efficiency and lower the cost of the solar collector. Advanced manufacturing techniques will determine methods of reducing production costs. This is important for an industry that has not yet realized the economies of mass production.

Solar Detoxification: A Novel Approach to Cleaning Up Hazardous Wastes

The detoxification of water, air, and soil contaminated with chemical pollutants represents another group of

applications being investigated by OIT's Solar Industrial Program. There are many opportunities for solar water detoxification systems in the area of environmental remediation. Nationally, there are almost 20,000 sites requiring remediation, with an associated treatment volume of 7.5 trillion gallons annually. One-fourth of these sites are in high-solar-insolation regions of the country, where solar-based systems could eventually displace current energy-intensive detoxification technologies that use fossil fuels or electricity. In addition to remediation, solar water detoxification technology can be used for the treatment of industrial wastewaters from chemical plants, petroleum refineries, and textile mills.

Solar detoxification can also be used to remove hazardous, toxic, or noxious chemicals from the air. This technology has become more important

with the passage of the Clean Air Act Amendments of 1990, which prohibit many previously unregulated industrial processes. Solar soil detoxification has the potential to clean up some of the estimated 730 million tons of contaminated soil in the United States, much of which is located at Superfund sites. It has been estimated that more than one third of this soil requiring detoxification is in areas of high solar insolation, presenting an opportunity for significant energy savings with solar detoxification technology.

To make the process meet the needs of the industrial sector, many systems are designed to work using either lamps or the sun as its source of energy. This allows the process to operate 24 hours a day and is an important reason why the process is already nearing commercialization for some applications. Major industrial firms, environmental

OIT Solar Detoxification Technology Demonstration Projects

IT Corporation, one of the nation's largest environmental technology firms, signed a cooperative research and development agreement (CRADA) with OIT's Solar Industrial Program recently to develop a gas-phase photocatalytic oxidation reactor. Under this 2-year agreement, IT will design and build a demonstration-scale reactor, while solar industrial program researchers characterize the process chemistry of a variety of contaminants that will be treated by the system. The project will culminate with IT demonstrating this system at an industrial site in 1995.

SEMATECH, the research consortium of the nation's leading semiconductor manufacturers, is also working with OIT under a CRADA to develop the photocatalytic detox process. SEMATECH is interested in using detox systems to treat contaminant-containing air streams produced during the manufacture of semiconductors. SEMATECH is identifying specific contaminants to be treated, and solar industrial program researchers are designing a number of detox systems to treat both individual contaminant streams and combinations of streams. SEMATECH will

select, build, and demonstrate one of these systems at the conclusion of the research partnership.

Solar Kinetics Inc., (SKI) and OIT are working through a cost-shared partnership to demonstrate the detox process on contaminated water. SKI, a major solar equipment manufacturer, selected a contaminated groundwater site at Kelly Air Force Base in San Antonio, Texas, to construct and operate this demonstration system. Researchers from the solar industrial program are assisting SKI with technical and design issues. The system is scheduled to begin operating in 1995.

OIT is also working with SAIC Inc., the U.S. Army Environmental Center, and the Environmental Protection Agency to design, build, and operate a photocatalytic detox system at the Sierra Army Depot in California. Designated the Tri-Agency Project in recognition of the three cabinet-level departments involved, the project will decontaminate a large volume of solvent-containing soil at the depot. The system is scheduled to begin operating by early 1996.

companies, chemical companies, and solar equipment manufacturers are working with the program testifying to the confidence the private sector has in the near-term commercial success of the technology.

Solar Detoxification of Water and Air
(IT Corporation, SEMATECH, Solarchem Environmental, Solar Kinetics, Inc.)

The solar detoxification of water and air uses a photocatalyst that becomes highly reactive in the presence of ultraviolet sunlight. When this activated catalyst is exposed to polluted air or water, it breaks down the volatile organic compounds or other contaminants, converting them into water, carbon dioxide, and other benign or easily treated compounds. The entire process, known as photocatalytic oxidation (PCO), takes place near room temperature. Several solar water detoxification projects are currently underway, providing the opportunity to evaluate the systems in an actual industrial remediation environment. For example, a demonstration-scale reactor for detoxifying contaminated air is being built and tested at an industrial facility. In another effort, a research consortium of the nation's leading semiconductor manufacturers is working with the program to develop a system to treat contaminated air streams produced during the manufacture of semiconductors. The program is also sponsoring research on the photocatalyst used in these systems to work on a wider variety of chemicals—one new catalyst showed promise for being 50 times as effective as other catalysts for some applications—thereby reducing operating costs.

Solar Detoxification of Soil
(Science Applications International Corporation, Energy and Environmental Research Corporation, IT Corporation)

Unlike the PCO detoxification technique used for water and air, the soil detoxification technique—known as photolytic detoxification—relies solely on concentrated sunlight and does not need a catalyst. Using a number of precisely aligned mirrors, solar

Photo by Warren Gretz, NREL

Solar concentrators are used to detoxify soil.

Table 4-14
Annual Benefits of Solar Detoxification of Air and Water

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Total Cost (\$1000)	124	90	34	44,000
Energy Cost (\$1000)	12	9	3	3255
Capital Cost (\$1000)	42	45	-3	-3255
O&M Cost (\$1000)	70	36	34	44,000
Solar Detoxification of Air				28,382*
Solar Detoxification of Water				189*
Risk				
Technical	LOW			
Market	MEDIUM			
Year of Maximum Market Share	2016			

*Million cubic meters of air/water treated.

energy is concentrated to a single point, similar to the way a magnifying glass concentrates sunlight. Photolytic detoxification systems are capable of concentrating the sun to 2500 times its normal intensity at the surface of the earth. Chemical contaminants such as waste solvents exposed to this intense solar energy rapidly combust into simple, harmless molecules. To determine whether the process is technically feasible and economically competitive, the program is conducting a cooperative project with the Department of Defense (Army Environmental Center) and the Environmental Protection Agency to pool the resources of the three agencies and demonstrate the technology at the Sierra Army Depot. Results to date have been very encouraging, showing a clear benefit for using solar energy to eliminate hazardous organic chemicals.

Advanced Materials Manufacturing: Solar Energy Meets Surface Science

Industry relies increasingly on high-value, high-technology materials such as ceramic/metal composites and surface-hardened materials to resist wear and operate reliably in high temperatures and other harsh environments. The development of such advanced materials has been deemed crucial to U.S. competitiveness and economic and strategic strength. Unfortunately, current materials fabrication techniques are often complex and expensive; some materials cannot even be produced because of the lack of appropriate fabrication methods. Recent breakthroughs in solar technology have provided a tool that can assist in the development of these materials, permitting the use of very small quantities of high-value materials to create inexpensive parts with superior properties. Solar-processed materials can contribute significantly toward a revitalized and dominant U.S. presence in the world market for emerging technologies.

The High-Flux Solar Furnace—Now a National User Facility

Photo by Warren Grotz, NREL

The National Renewable Energy Laboratory's High-Flux Furnace creates a unique laboratory situation.

Most of the solar industry work in advanced processes is undertaken at the National Renewable Energy Laboratory's (NREL's) High-Flux Solar Furnace (HFSF) in Golden, Colorado. DOE designated the Solar Furnace a National User Facility in 1993. This designation gives qualified outside researchers easy access to this cutting-edge solar laboratory.

NREL's HFSF is a research tool in the vanguard of both advanced materials and solar energy research. The HFSF offers researchers laboratory conditions unavailable elsewhere. By taking advantage of the HFSF's user facility status, industry can save considerably on R&D costs.

Highly concentrated sunlight—referred to as high solar flux—has properties that are well suited to advanced materials manufacture. High solar flux is created by reflecting sunlight off of precisely designed curved mirrors. In this way, solar energy can be concentrated from a few hundred to 50,000 times the normal intensity of the sun at the Earth's surface. This intense energy creates and sustains extremely high temperatures, yet can heat a material's surface while the base or substrate remains relatively unaffected. This ability allows advanced surface processes such as ceramic metallization, chemical vapor deposition, and cladding to be performed using high solar flux. The OIT Solar Industrial Program is exploring various possibilities of advanced materials manufacturing through both basic research and demonstration projects.

Basic Research Efforts

(National Renewable Energy Laboratory)
The High-Flux Solar Furnace at the National Renewable Energy Laboratory is the basic research tool used in the development of solar-based advanced materials manufacturing. In one ongoing effort, researchers have synthesized Fullerene molecules (C₆₀) by vaporizing a graphite pellet with solar radiation. Fullerenes, newly discovered forms of carbon, have unique chemical properties that are being investigated by the research community for diverse applications such as optical devices, superconductors, polymers, pharmaceuticals, and fuels. Preliminary results indicate that the solar-based Fullerene synthesis method is more energy efficient and less expensive than the electric arc method typically used. An inexpensive method to produce Fullerenes may lead to many new commercial

products for domestic use and for export. In two projects being conducted with the U.S. Bureau of Mines, solar furnace technology is being explored as a method for expanding certain minerals used in insulation products and as a method of cladding mining/mineral processing equipment.

Demonstration Efforts

(National Renewable Energy Laboratory, Brush Wellman Inc., Coors Ceramics, Texas Instruments)

OIT is working cooperatively with several materials manufacturers to determine the feasibility of manufacturing specific advanced materials using high solar flux. In one effort, a leading electronics/ceramics manufacturer is determining the feasibility of bonding an ultra-thin layer of metal—such as copper, palladium, platinum, or gold—to ceramic substrates using high solar flux. Experiments have shown that the resulting metallized ceramic components have improved properties compared to those manufactured using traditional processes. These electronic components are playing an increasingly important role in the domestic auto, computer, and telecommunications industries. In another effort, the feasibility of using high solar flux is being investigated for use in fabricating silicon photovoltaic solar cells.

Advanced Turbine Systems And Cogeneration

THE HEAT ENGINE OF CHOICE IN THE COMPETITIVE POWER INDUSTRY

During the past 15 years, the structure of the U.S. electric power industry has begun to change in important ways. Stimulated in part by the Public Utilities Regulatory Policies Act of 1978 (PURPA), the traditional stability of the U.S. electric power industry has given way to a more highly competitive system. PURPA introduced the notion of open market competition to the U.S. electric power industry by mandating that public utilities purchase power from qualifying nonutility power generators (NUGs) based on avoided costs. Exemptions from public rate regulations for NUGs and various state tax credits further encouraged the growth in industrial cogeneration and nonutility power capacity. As a result, NUG capacity grew at an annual average rate of about 14% between 1985 and 1991. Cogenerators and other nonutility power generators operated more than 5000 facilities in the United States by the end of 1992, and accounted for 55 gigawatts (GW) or 7% of installed U.S. electric power capacity. More significantly, they accounted for more than half of all U.S. power capacity additions between 1988 and 1992, as shown in Figure 4-6. A classification of nonutility power capacity by type of facility and industry at the end of 1991 is provided in Figure 4-7.

Gas turbines, whether in simple or combined cycle configurations, have been the heat engine of choice in the rapidly growing nonutility power generation industry (or competitive power industry). Gas turbines range in size from 6 kilowatts (kW) to over 200 megawatts (MW). They operate on natural gas, distillate fuel oil, crude oil, residual fuel oil, or synthesis gas derived from coal or biomass. Turbine manufacturers have developed highly

efficient, reliable, clean and relatively inexpensive combustion turbines in various capacities for use in power generation facilities. Because of their relatively low first cost, high efficiency, short lead times, high reliability and superior environmental performance, gas turbine-based systems are playing an increasingly important role in new generating capacity.

Recent trends in industrial cogeneration illustrate the growing reliance on gas turbine systems. In 1985, just after PURPA began to have significant

effect on the non-utility generation market, the majority (62%) of capacity in industrial cogeneration applications was based on conventional boiler/steam turbine systems. Most of the remaining capacity (21%) was based on simple cycle gas turbine systems, and only 9% was based on combined cycle systems. By 1991, however, combined cycle systems accounted for over 19% of the generating capacity in industrial cogeneration, while the capacity of simple cycle gas turbines increased to 28%. In contrast,

Figure 4-6

Net Increases in Generating Capacity: Utilities and Nonutilities, 1988-1992

Source: EIA and Edison Electric Institute

Figure 4-7

Profile of Nonutility Power Capacity, 1991

Total Nonutility Capacity = 48 GW

Source: EIA

conventional boiler/steam turbine configurations provided less than half (49%) of the industrial cogeneration capacity on-line in 1991.

Gas turbines are used in both simple and combined cycle systems. In simple cycle gas turbine systems, hot exhaust gases from the turbine are either vented if the system is used for power only or, in cogeneration applications, the gases are used directly for process heating or drying or to generate process steam from heat recovery boilers. Combined cycle systems—that combine a steam turbine with a gas turbine—provide greater efficiency and flexibility than either gas or steam turbines alone. In this configuration, heat recovered from the gas turbine exhaust is used to produce steam that generates additional electricity in the steam turbine or process steam in cogeneration applications.

Gas Turbine Systems Expected to Dominate New Generating Capacity

EIA forecasts that a total of 172 GW of new generating capacity will be required by 2010 to meet the expected growth in electric power demand. Moreover, a significant portion of existing generating capacity is expected to require replacement or undergo repowering during this time period. In addition, other countries are beginning to follow the U.S. lead toward a more competitive, innovative power system in which cogenerators, industrial and other nonutility power suppliers play a bigger role. This is creating large export opportunities for systems and equipment suppliers to the competitive power industry. Such trends and developments portend a growing need for more efficient, cleaner advanced gas turbine and cogeneration systems.

The move toward a more competitive power generation market is likely to further increase the role of the nonutility segment of the industry, and enhance opportunities for cogeneration. Industrial users and nonutility power producers often

choose gas turbine systems because they are easier to site and quicker to develop than similar-sized alternatives. Gas turbine cogeneration systems produce high ratios of electrical output to thermal output, better matching energy requirements at many industrial and commercial facilities. In addition, emissions from natural gas-fired turbine systems are significantly lower than emissions from similarly sized coal or oil power plants. As shown in Figure 4-8, simple and combined cycle gas turbine systems are expected to be employed in almost 70% of the 61 GW of new capacity planned by the nonutility power industry through 2000.

The efficiency, flexibility, reliability and other benefits of simple/combined cycle gas turbine systems are prompting utilities to employ such systems as well. Though designed primarily to meet peak and intermediate load requirements, these systems are also able to meet baseload requirements if necessary. Because of such versatility, utilities intend to employ simple/combined cycle gas turbine systems in over half their planned new capacity through the end of the decade as also shown in Figure 4-8.

Cogeneration and Combined Cycle Generation

Cogeneration is the production of both electrical (or mechanical) and thermal energy from the same primary energy source. Combined cycle generation is similar to cogeneration except that the exhaust heat from a gas turbine is recovered and then fed back to a boiler and used by a steam turbine to provide a second electricity generating cycle. The principal advantage of cogeneration systems is their ability to improve the efficiency of fuel use and reduce overall emissions. In a topping system, electricity is produced first and the remaining thermal energy may be used for industrial processes. In a bottoming system, thermal energy is first used for very high temperature industrial processes such as steel or glass furnaces and the exhaust gases then fuel boilers that drive turbines to produce electricity.

Continuing Advancements in Gas Turbine Technology Will Be Needed

Gas turbines have continued to improve their ability to meet the needs of the power generation market since their initial introduction in the early 1960s. In response to intense competition and user demands, gas turbine manufacturers have increased efficiencies, improved reliability and maintainability, lowered emissions profiles, and achieved wider fuel flexibility for their equipment. Efficiency and emissions improvements have primarily come from incremental advancements in existing designs, and development efforts have focused on higher firing temperatures, better materials, and improved cooling techniques. Gas turbine manufacturers are now introducing an improved class of turbines with significant incremental advances in performance achieved by applying aircraft engine technology. The new class of turbines is also environmentally superior, featuring dry, low NO_x combustion systems. The critical emissions issue for gas turbine systems is reducing NO_x emissions at higher firing temperatures without a resulting increase in CO and unburned hydrocarbon (UHC) emissions. By using dry, low-NO_x combustion technology, NO_x emission levels of 25 ppm or less can presently be achieved in industrial turbines with use of natural gas as a fuel.

Although the performance of these new gas turbine systems is impressive, further improvements in efficiency and emissions will be needed. Power producers must meet increasingly stringent emissions requirements, new capacity needs, and increasing competitive pressure to improve efficiency and reduce dependence on conventional coal and oil consumption. Improved turbine systems are needed to ensure reliable and economic electricity supplies, to help meet national energy efficiency and environmental goals, and to maintain the world leadership position of U.S. turbine manufacturers. To achieve

Figure 4-8

Planned New Generating Capacity by Technology: 1990-2000

Source: Utility Data Institute

significant improvements, advanced turbines are needed that operate at higher firing temperatures, while maintaining low emissions levels. However, manufacturers are reaching the limit of traditional technology approaches. Future advances in turbine technology will require significant turbine design changes, development and application of new materials, and use of innovative power cycles.

Advancements are also needed to ensure that U.S. gas turbine manufacturers remain competitive in the growing world market as the global market for power generation equipment becomes increasingly important to U.S. manufacturers. Overseas sales of gas turbine systems by U.S. manufacturers between 1988 and 1994 were more than two and a half times greater than total U.S. sales by those same manufacturers, and this trend is expected to continue. To illustrate, the World Bank estimates that an additional \$1 trillion will be invested in new power generation capacity outside the United States between 1994 and 2000, and recent studies have estimated the overseas market for gas turbines to be more than three times the size of the U.S. market between now and 2020. While U.S. manufacturers have traditionally been strong in this overseas market (40% of all gas turbine sales between 1988 and 1994

were from U.S. manufacturers), foreign manufacturers are aggressively pursuing technology improvements to challenge this position. Continued technology advancements in terms of efficiency, reliability, and emissions will be critical for U.S. manufacturers to remain competitive in this important global market.

Although many of the turbine advancements for the private sector resulted from technology developed through military R&D programs, direct government funding for civilian turbine development has historically been minimal. However, the technical and economic risks involved in the next generation of advanced turbine systems will be much greater than in the past, and private industry is not expected to pursue these advances without risk-sharing in the form of a government/industry cost-sharing program.

THE OIT ADVANCED TURBINE SYSTEMS AND COGENERATION PROGRAM

The Advanced Turbine Systems and Cogeneration Program conducts extensive research, development, and demonstration to meet the technical and market challenges associated with enhancing industrial cogeneration and moderate-sized independent power production opportunities.

By the year 2015, the use of OIT-supported advanced technologies with improved efficiencies and higher electric-to-thermal ratios could save 900 trillion Btu and reduce greenhouse gas emissions by 65 million tons per year beyond what is predicted with currently available equipment. Current program thrusts include the development of high-efficiency, low-emission gas turbine systems; a high-performance steam system; and a ceramic retrofit gas turbine.

Advanced Turbine System: Clean Gas-Fired Technologies for Meeting U.S. Power Needs

(Solar Turbines, Allison, Santa Barbara Air Quality Management District)

OIT is cost-sharing the development of advanced turbine systems with DOE's Office of Fossil Energy, the Electric Power Research Institute, the Gas Research Institute, the Environmental Protection Agency, and others in response to the Energy Policy Act of 1992, Section 2112 ("Heat Engines"). The goal for advanced turbine system efficiency is a 15% improvement over today's best gas turbine systems, reduced emissions of NO_x, CO₂, CO, and UHC, and a 10% reduction in the cost of generating electricity for both utility and non-utility power generators by 2002. Initial advanced turbine systems will be natural-gas fired, using oil as a back-up fuel. Studies will be conducted to address the potential for converting the systems to enable them to burn gas from burning coal, biomass, or other solid fuels. Program efforts are being guided by a steering committee composed of representatives from the participating agencies and institutes, and fall into four categories:

- Innovative cycle development to identify high-efficiency systems that can meet program goals;
- Component development and prototype testing for utility systems;

- Component development and prototype testing for industrial systems; and
- Research, development, and demonstration of generic technology in support of the program.

The OIT program is targeting the development of a new industrial-application turbine with a power generating capacity of less than 20 megawatts (MW), much smaller than the 150+ MW turbines used by electric utility companies. The advanced turbine system will need to operate at sustained firing temperatures of more than 2600°F (compared with the current 2350°F) and at high

pressure ratios to achieve higher efficiency. Higher firing temperatures will require manufacturers to incorporate such features as ceramic components and better turbine blade cooling techniques, for example. Operating at these temperatures alone will not meet the desired efficiency goals, however; manufacturers will need to make innovative cycle changes using compressor cooling, heat recovery, turbine reheat, and moisture injection technologies. The advanced turbine system will use advanced low-NO_x burners, thereby eliminating the need for costly emissions control equipment. The turbine will be coupled with a

high-performance steam system, also under development, to provide even higher efficiency.

High Performance Steam System: Updating 1950s Technology to Meet 21st Century Needs

(Innovative Steam Technologies, Inco, Precision Castparts, CONTEX, Coen Co., AlliedSignal)

Steam turbine systems (a boiler to generate the steam and a turbine to convert it to electricity) are used as both stand-alone systems and with gas turbines in combined-cycle systems for industrial cogeneration. The efficiency of these systems has changed little since temperature and pressure limits were set in the 1950s. These limiting conditions are mostly a result of the corrosion and erosion problems that occur when conventional steam system components are operated at high temperatures. If these problems could be overcome, however, steam temperature and pressure could be raised, resulting in increased generating efficiency (and thus power output) for a given quantity of steam. To address these long-standing limitations, OIT is sponsoring the development of a high performance steam system (HPSS) for industrial cogeneration applications.

The HPSS technology is based on using two advanced steam-cycle components. One is a high-temperature boiler whose tubes are made from Inconel 617, an exceptionally strong nickel alloy that is capable of withstanding high temperatures without wearing out. The second component is an efficient, high-speed steam turbine that incorporates state-of-the-art turbine blade materials technology borrowed from gas turbines. A system based on HPSS technology can handle steam with a pressure of 1500 pounds per square inch and a temperature of 1500°F, compared with current maximum conditions of about 900 pounds per square inch and 1000°F. This translates into an increase in conversion efficiency of more than 50% and an increase in electricity generation of more than 20% using the same

Table 4-15
Annual Benefits of Advanced Turbine Systems

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	1296	864	432	323,891
Total Cost (\$1000)	4550	3223	1327	995,594
Energy Cost (\$1000)	3166	2110	1055	791,416
Capital Cost (\$1000)	1157	998	158	118,768
O&M Cost (\$1000)	228	114	114	85,410
Emissions (metric ton)				
CO ₂	83,476	55,651	27,825	20,869,078
NO _x	89	59	30	22,238
SO _x	286	190	95	71,381
Particulates	738	492	246	184,573
Solid Waste (1000 short tons)	—	—	—	—
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		2006		

Figure 4-9
Advanced Turbine System

Photo by Warren Gretz, NREL

OIT is sponsoring the development of a high-performance steam turbine system.

Table 4-16

Annual Benefits of High Performance Steam System

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	810	442	368	68,091
Total Cost (\$1000)	1764	1299	465	86,007
Energy Cost (\$1000)	911	497	414	76,609
Capital Cost (\$1000)	587	587	0	0
O&M Cost (\$1000)	266	215	51	9398
Emissions (metric ton)				
CO ₂	64,698	35,290	29,408	5,440,519
NO _x	54	30	25	4554
SO _x	441	241	200	37,087
Particulates	1165	635	530	97,971
Solid Waste (1000 short tons)	-	-	-	-
Risk				
Technical		LOW		
Market		LOW		
Year of Maximum Market Share		2006		

amount of steam. Compared to the typical industrial practice of operating with conditions as low as 600 pounds per square inch and 750°F, the HPSS will more than double both power output and turbine efficiency.

Ceramic Retrofit Gas Turbine: **Ceramic Parts to Boost the Efficiency of Existing Turbines** *(Solar Turbines)*

Gas turbine efficiency is presently limited by the performance of the materials used for construction of the turbine hot section. Much progress has been made in the development of ceramic components for various high-temperature environments; now, attention is focusing on integrating such components into stationary gas turbines such as those used by industrial cogenerators and electric utilities. Using ceramic components would allow higher turbine inlet temperatures, improving the thermal efficiency of gas turbines. In the long term, turbines incorporating ceramic components will have enhanced ability to use lower-grade fuels.

OIT is currently sponsoring a cooperative program with industry to develop selected ceramic components such as nozzles, blades, rotors, and combustor liners for gas turbines. In addition to operating at higher temperatures, ceramic components are more durable, lightweight, and cheaper than conventional components. When combined with advanced ceramic combustor designs, these advantages translate into a significant improvement in thermal efficiency, considerably lower NO_x emissions than the best domestic equipment currently available, a major reduction in emissions of CO and VOCs, and lower capital costs. The technology could be used to retrofit an existing 15,000 MW of capacity, as well as be used for new capacity additions. The program is attempting to help U.S. gas turbine manufacturers to become the first to commercialize this technology and capture a major share of the \$100+ billion worldwide market.

Table 4-17*Annual Benefits of Ceramic Retrofit Gas Turbine*

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	648	486	162	101,216
Total Cost (\$1000)	2366	1921	445	278,217
Energy Cost (\$1000)	1781	1335	445	278,217
Capital Cost (\$1000)	529	529	0.0	0.0
O&M Cost (\$1000)	57	57	0.0	0.0
Emissions (metric ton)				
CO ₂	34,188	25,641	8547	5,341,929
NO _x	41	31	10	6428
SO _x	0.2	0.1	0.1	28
Particulates	1	1	0.2	134
Solid Waste (1000 short tons)	-	-	-	-
Risk				
Technical		HIGH		
Market		LOW		
Year of Maximum Market Share		2010		

Table 4-18*Annual Benefits of Low NO_x Combustion Gas Turbine*

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	194	194	0.0	0.0
Total Cost (\$1000)	862	709	153	30,498
Energy Cost (\$1000)	534	534	0.0	0.0
Capital Cost (\$1000)	276	158	118	23,665
O&M Cost (\$1000)	51	17	34	6833
Emissions (metric ton)				
CO ₂	10,257	10,257	0	0
NO _x	12	1	11	2200
SO _x	0.0	0.0	0	0
Particulates	0.0	0.0	0	0
Solid Waste (1000 short tons)	-	-	-	-
Risk				
Technical		MEDIUM		
Market		LOW		
Year of Maximum Market Share		2007		

Heat Exchangers And Recuperators

ENABLING THE REUSE OF HEAT TO IMPROVE INDUSTRIAL ENERGY EFFICIENCY

A heat exchanger transfers heat from one fluid (a liquid or gas) to another fluid. Heat exchangers are designed to reuse the heat content of in-process or waste liquids or gases. About two-thirds of all industrial energy use (or approximately 15 quads) is for process heat or steam. After initial use, materials or fluids being processed typically still retain a great deal of their original heat. Heat exchangers take advantage of this unused heat by transferring it to another application where it can be reused. This reduces the costs and requirements for new energy.

Heat exchangers are used widely in industrial processes under diverse conditions, and vary greatly in size, appearance, materials of construction, and method of operation. They can be plate-like, spiral, or tubular, and be made of metal, plastic, glass, brick, or ceramic. In the most common type of heat exchanger, heat is transferred from one fluid to another through a solid—usually a high-conductivity metal—that prevents the fluids from mixing. Three major applications of heat exchangers are process heat exchange, power generation heat exchange, and industrial waste heat recovery.

Though shell-and-tube exchangers are by far the most common type, they are but one of many varieties used in industry. The design, materials, and size of heat exchangers can vary considerably depending on such factors as scale of the industrial process and the properties of the fluids involved in the heat transfer process. Heat exchangers can range from the simple tube-within-a-tube variety to complex surface exchangers with thousands of square feet of heat transfer space. They can possess a broad range of distinguishing features

Photo by Warren Gretz, NREL

Heat exchangers are used widely in industrial processes under diverse conditions.

such as shape, presence or absence of area-expanding fins, and the direction of fluid transfer through the heat exchanger (concurrent, countercurrent or cross flow). Indeed, the great assortment of types of heat exchangers to a certain extent mitigates against a generic R&D program. Hence, most opportunities for heat exchanger R&D target a limited niche of the entire market.

Heat exchangers that recover waste heat from process streams (such as flue gases) that would normally be vented to the atmosphere or otherwise lost are commonly known as recuperators. Recuperators are typically used in medium-to-high temperatures, and often in corrosive environments. In less corrosive environments, the use of metallic heat exchangers is widespread.

Major Markets: Chemicals, Petroleum Refining, Electric Power

About a third of all industrial heat exchangers are used in the chemical industry where they are commonly used to transfer heat between liquids or from liquid to vapor. Shell-and-tube designs account for about 75% of all heat exchangers used in the chemical industry and they are most frequently

Figure 4-10
Basic Concept of Cross-Flow Heat Exchanger

used in the petro/organic chemical and agricultural chemical segments of the industry. Most process heat exchangers in the chemical industry are used in the medium-to-low temperature ranges. However, many process streams are highly corrosive requiring that heat exchangers have protective coatings. Higher temperature, less conventional applications of heat exchangers in the chemical industry include chemical reaction processes, such as steam reforming and steam cracking.

The petroleum industry is another large market for heat exchangers—accounting for an estimated 20% of all U.S. sales. An average refinery may have between 400-500 heat exchangers each with an average surface area of 2000-3000 square feet. Most heat exchangers used in the petroleum industry are of the liquid-to-liquid, shell-and-tube type. Corrosion is less of a problem for heat exchangers in this industry and consequently about 75% use carbon steel tubes.

The electric power industry pioneered the use of heat exchangers on a large scale in recovering waste heat from boilers and stack gases. Currently, the power industry is the third largest market for heat exchangers for use primarily as feedwater heaters, surface condensers and air preheaters. Heat exchangers used in the power industry are notable for their huge size. In addition, the working fluid (typically air) can be under high pressure, requiring a heat exchanger that can withstand high pressure, high temperatures, and a corrosive environment.

Needed: Heat Exchangers that Can Better Withstand Adverse Operating Conditions

Current industrial heat exchangers cannot effectively capture the estimated 4 quads of thermal energy released in high-temperature, high-pressure, and corrosive exhaust streams, nor are the materials commercially available to build viable high temperature and high pressure reaction vessels. Often, such adverse operating conditions are found in such large energy-consuming industries as metals and pulp and paper where the use of heat exchangers is generally less extensive than in chemicals, petroleum refining and electric power.

Surface fouling—the undesirable accumulation of solid or liquid deposits on heat-exchanger surfaces—retards the ability of the surface to transfer heat. This is another problem area, that if successfully addressed, would afford opportunities to expand the usage of heat exchangers in industry. Recuperators are another prominent research target because existing technology is unsuitable or inadequate for the job, and many opportunities for recovering waste heat in the industrial sector are unmet. Other heat exchanger technology needs include expanding heat transfer surface into less volume and reducing capital cost to enable payback in less than 2 years.

THE OIT ADVANCED HEAT EXCHANGER PROGRAM

The objective of OIT's Advanced Heat Exchanger Program is to develop and test methods and technologies for designing, fabricating, and using advanced heat exchangers for industrial waste heat recovery and process heat exchange. A major focus of the program is on the development of advanced high pressure heat exchange systems (HiPHES) for applications in chemicals production and for recovering waste heat from hazardous waste streams to generate electricity. The total potential energy

benefits of these applications and others could approach two-thirds of a quad annually (Figure 4-11). The program is also sponsoring the development of an advanced composite ceramic heat exchanger system for use in recovering waste heat from corrosive waste streams.

Table 4-19

Annual Benefits of HiPHES for Steam/Methane Reforming^{1,2}

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	9622	9649	-27	-163
Total Cost (\$1000)	40,624	35,578	5046	30,273
Energy Cost (\$1000)	29,664	26,523	3140	18,842
Capital Cost (\$1000)	13,860	14,565	-705	-4229
O&M Cost (\$1000)	-2900	-5510	2610	15,660
Emissions (metric ton)				
CO ₂	1415	26,306	-24,891	-149,344
NO _x	11	28	-17	-101
SO _x	1.2	30	-29	-175
Particulates	28	72.4	-44	-267
Solid Waste (1000 short tons)	—	—	0	0
Risk				
Technical		HIGH		
Market		HIGH		
Year of Maximum Market Share		2020		

¹ Data are for new plants only.

² OIT data are for a reformer integrated with a gas turbine. O&M costs are decreased by credits for electricity production (OIT technology only) and steam production (both OIT and current technology).

Figure 4-11
Potential HiPHES Energy Savings (Quads)

Potential Total Energy Savings = 0.63 Quads

Source: Advanced Heat Exchanger Program Plan, OIT

HiPHES for Steam/Methane Reforming: A Cleaner and More Efficient Method of Making Methanol (Stone & Webster)

Steam/methane reforming is one of the process steps used to produce the chemical methanol. Methanol is used primarily as an industrial solvent or in the production of other chemicals; it

Figure 4-12
HiPHES for Steam/Methane Reforming

Researchers are developing a HiPHES system for steam/methane reforming that uses an advanced material—ceramics—as well as an advanced design to significantly increase this conversion efficiency. The ability of the ceramic tubes used in the HiPHES reformer to operate reliably at tube temperatures of 1900°F could increase conversion efficiency to 99% or more, meaning that a separate recycling process step could be eliminated. The HiPHES reformer has the potential to save as much as 30% of the energy requirement compared with conventional technology. The new system is also smaller and costs less than a conventional reformer for a given methanol production rate. The HiPHES is even more attractive when integrated with a gas-turbine power cycle to produce electricity that can be sold as a premium byproduct. A single 1000-ton/day methanol plant using a HiPHES reformer could reduce its CO₂ emissions by nearly 6000 tons per year. As tighter U.S. environmental regulations stimulate the production of methanol-fueled vehicles in the near future, the demand for methanol is expected to grow. By the year 2005, HiPHES reforming systems could be saving nearly 25 trillion Btu each year in methanol production alone.

The design of commercial heat recovery equipment generally reflects a balance between heat recovery effectiveness and the capital cost of

the recuperator (heat exchanger) used to recover the heat. Technical limitations, however, occur in three areas largely unrelated to system economics—high temperatures, high pressures, and highly corrosive gas streams. Despite awareness of the possibilities for improved performance using high-pressure, high-temperature heat exchangers, earlier

The diagram illustrates a gas turbine waste heat recovery system. The gas turbine engine consists of a Generator, an Exhaust, and a Gas turbine. The Exhaust is connected to a waste heat recovery boiler. The boiler has three sections: a high-temperature section (2300°F, 36.5 lbm/sec) with an outlet to a turbine (1600°F), a middle section (1266°F) with an outlet to an optional waste heat boiler (800°F), and a low-temperature section (933°F) with an inlet from the turbine compressor (600°F, 38.7 lbm/sec) and an outlet to a heat exchanger shell. The heat exchanger shell has an inlet from the heat exchanger and an outlet to the waste heat out (1300°F).

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	538	120	418	10,445
Total Cost (\$1000)	7680	2768	4912	122,791
Energy Cost (\$1000)	7680	1717	5962	149,055
Capital Cost (\$1000)	0	884	-884	-22,103
O&M Cost (\$1000)	0	116	-166	-4161
Emissions (metric ton)				
CO ₂	94,101	21,044	73,057	1,826,428
NO _x	79	18	61	1537
SO _x	711	159	552	13,794
Particulates	1860	416	1444	36,092
Solid Waste (1000 short tons)	N/A	N/A	0	0
Risk				
Technical		HIGH		
Market		HIGH		
Year of Maximum Market Share		2020		

²Energy use is for a current hazardous waste incinerator with and without the OIT waste heat recovery technology. Capital and O&M costs are those associated with the waste recovery system only.

research efforts were largely unsuccessful because of problems with development and fabrication of the needed ceramic components. DOE is currently participating in the development of a new generation of high-pressure heat exchange systems (HiPHES) for use in a number of applications. The application receiving the most attention is the generation of power (in the form of electricity) from the heat found in available but unused high-temperature, corrosive gas streams.

The HiPHES technology being developed in this effort is designed to handle low-pressure gas streams with temperatures in excess of 2300°F. The gas stream could be an existing one, such as the exhaust from a hazardous waste incinerator or industrial process, or it could be from combustion equipment specifically built to dispose of some byproduct or high-sulfur fuel such as high sulfur wood chips or low-grade coal. The heat recovered by the HiPHES is fed into an indirectly heated gas turbine cycle, a type of turbine that is insensitive to the quality of the fuel being used. The power produced by the gas turbine can be used for electric power generation or other industrial processes. In addition, the clean, hot turbine exhaust gas can be used as process heat within the industrial facility.

Industrial Heat Pumps

HELPING INDUSTRY PUT WASTE ENERGY TO MORE PRODUCTIVE USE

The industrial sector accounts for over a third of all primary energy used in the U.S. economy—or about 30 quads—at an annual cost of more than \$100 billion. After subtracting out the electricity used for motor drive and process electrolysis and the energy used as feedstocks, virtually all the remaining energy consumed in industry is used to fire boilers, furnaces and other process heating devices. On an annual basis, this currently amounts to about 15 quads of energy valued an estimated \$50 billion.

The enormous use of energy in industry to fuel process heating systems inevitably generates huge quantities of waste heat. This, in turn, creates many opportunities for waste heat recovery and reuse. Optimizing the efficiency of waste heat use typically involves improved integration of various components of the industrial heat network and supply systems including boilers, fired heaters, heat exchangers and cogeneration systems. Industrial heat pumps (IHPs) are another, largely underutilized component of this network. IHPs are especially effective for recovering waste heat in low temperature (less than 350°F) applications so as to avoid primary heat requirements.

The basic purpose of an industrial heat pump is to recycle heat between different heating streams in a system. An IHP removes waste heat from a process at one temperature, adds a small amount of energy to increase the temperature of the heat, and delivers that heat to a process at the higher temperature. Because they use energy that is normally discharged from processes as waste heat, heat pumps help reduce primary fuel consumption, energy costs and the emissions associated with supplying

process heat. The use of heat pumps can also eliminate the need for expensive new boilers and heaters when present equipment capacity has been reached.

Specialized heat pumps also provide industry with process cooling below ambient air temperature—heat pumps used for this purpose are typically called refrigeration systems or chillers. The cooling capability of heat pumps also enables them to condense volatile organic and other hazardous compounds to liquids so they can be recovered from exhaust air streams. For example, a specialized heat pump known as the Brayton solvent recovery heat pump is helping U.S. pharmaceutical and chemical companies recover solvents from waste streams.

Current and Potential Markets

Industrial heat pumps provide process heat in lumber drying kilns, petroleum refineries, food processing plants, chemical plants, and pulp and paper mills. The largest single use of IHPs in U.S. industry is in the lumber industry where they supply heat to dry lumber and cooling to remove water from the drying lumber (Figure 4-14). Many petroleum refineries and chemical plants use heat pumps known as mechanical vapor recompressors to recycle heat within distillation systems.

Estimates provided in the International Energy Agency's Implementing Agreement on Advanced Heat Pumps (Annex 21)

indicate that the use of IHPs in the U.S. market could result in energy savings approaching 350 trillion Btu annually by 2010 (Table 4-21). At current energy prices, this would also help reduce annual operating costs in industry by over \$1 billion. In addition, the increased use of industrial heat pumps would reduce overall industrial air emissions (CO₂, NO_x and SO_x) by an estimated 1%.

Another market study by RCG/Hagler, Bailly, Inc., investigated the heating potential of industrial heat pumps in 27 industrial processes. Three industries account for more than 80% of the potential market; these industries include chemicals (54%), food (15%) and pulp and paper (13%). This study concluded

Figure 4-14
IHPs in Use in U.S. Industry

Total number of IHPs installed: 1389

Source: RCG/Hagler, Bailly, Inc. IHP Efficiency, Productivity, Experience and Opportunities in Key Process Industries, for DOE, 1984, Table 1

Table 4-21

Estimates of Potential Energy Savings and Emissions Reductions From IHPs in the United States

Type of Savings	Average Case	Maximum Case
Projected Energy Savings 2010 (trillion Btu/year)	169	348
Projected Net Emissions Reductions (1,000 tons per year)		
SO _x	19.3	40.5
NO _x	22.1	45.6
CO ₂	12,025	24,782
CO	8.9	18.2
CH ₄	0.4	0.9
Particulates	0.9	1.8

Source: Annex 21

that heat pumps could reduce industrial energy use by about 400 trillion Btu per year. The study also estimated the potential size of the domestic industrial heat pump market to be \$10 billion for the period between 1995 and 2010 with an additional \$5 billion potentially available from export sales over the period.

Needed: Higher Lift and Delivery Temperatures

In the United States, IHPs most commonly use a compressor to increase the temperature of waste heat (Figure 4-15). Current technology limits the maximum temperature lift of an IHP to about 50°F to 100°F, with a maximum delivery temperature of 350°F. Heat pumps that could provide higher lift temperatures economically and that could deliver heat at higher temperatures (as much as 500°F) would have much wider usage in industry than those currently available.

One technology that is being explored to achieve these temperature characteristics is the chemical (absorption) heat pump. New technology being developed for chemical heat pumps allows higher lift and delivery temperatures. Another advantage of chemical heat pumps over conventional technology is that they use standard heat exchangers rather than motor-driven vapor compressors (Figure 4-16). A heat exchanger costs less and requires less energy than the compressor and motor used in conventional IHP technology. Though there are a few chemical heat pump (CHP) installations in Europe and Japan, the use of CHPs for process heating in the United States is virtually nonexistent.

Though the number of opportunities for use of IHPs far outweighs their actual application, the use of IHPs can be costly to industry because IHP systems must be individually designed for each application. In addition, for many applications, it is necessary to perform a process heat integration analysis prior to design that considers

Figure 4-15
Mechanical Vapor Recompression Heat Pump for Steam Recompression

Source: DOE/EPRI, *Industrial Process Integration*, April 1991

a variety of different heat recovery possibilities to determine if heat pump recovery will, in fact, save energy. This custom design and analysis significantly increases up-front costs. As a result, many companies are reluctant to make the initial investment for the analysis without knowing for certain whether heat pumps would be beneficial to them. Consequently, the complexities and costs of identifying heat pump opportunities limit the use of IHPs in industry.

THE OIT INDUSTRIAL HEAT PUMP PROGRAM

Through its Industrial Heat Pump Program, OIT is seeking to make industry aware of the potential benefits of IHPs and the opportunities that exist in specific industries for IHP implementation. The program promotes the deployment of existing technology as well as the development of advanced heat pump technologies. Specific goals of the program include improving the economics of IHPs, extending their applications by allowing for higher delivery temperatures and greater lifts, and developing process cooling options that do not require chlorofluorocarbons (CFCs) and process heating options that reduce emissions. The current focus of the program is on the development of chemical heat pumps.

Annex 21

As a result of a DOE proposal, the International Energy Agency (IEA) added an annex to its Implementing Agreement on Advanced Heat Pumps to investigate the possible applications and environmental benefits of IHPs. Entitled "Global Environmental Benefits of Industrial Heat Pumps," Annex 21 estimates the market potential for various types of IHPs and the potential global environmental benefits of IHPs resulting from energy savings and emissions reductions. Annex 21 also provides an information base for industry to help match heat pump technology to specific applications.

Chemical Heat Pumps: Expanding Industrial Heat Pump Applications
(Oak Ridge National Laboratory)

Chemical heat pumps use a non-CFC refrigerant and can be driven by high-pressure steam or waste heat. The use of a chemical heat pump reduces boiler steam consumption or eliminates the need for an additional boiler when expanding a process. This type of heat pump is ideal for applications in the petroleum refining, chemical processing, pulp and paper, and food processing industries because they generate large amounts of waste heat that could be used to drive the heat pump.

OIT is sponsoring research to advance the state-of-the-art in chemical heat pumps, focusing on the working media used by the pumps and on high-lift heat pump designs. The goal

Figure 4-16
Chemical Heat Pump Operation

A chemical absorption heat pump uses a series of heat exchangers (absorber, desorber, evaporator, condenser and liquid pump)—rather than a compressor and motor—to compress working fluid to lift heat. In the absorption cycle shown above, the absorption process releases heat and the desorption process requires heat, which can be provided by high-pressure steam or waste heat.

Source: DOE, *Industrial Heat Pump for Process Heating and Cooling*, 1993

of the research is to develop equipment that is cheaper, more energy efficient, and free of the corrosion problems experienced with earlier chemical heat pump designs. Researchers are looking at various working media—the chemicals in the heat pump that accept and release the heat—that can work at higher temperatures, resist corrosion, and offer high lift and a wide range of temperature applicability. The specific media being investigated are a liquid/vapor, where vapor is absorbed into a liquid, and solid/vapor, where vapor is absorbed into a solid.

Advanced heat pump technologies such as the chemical sorption heat pump can be used in applications beyond those considered in the Annex 21 and Hagler, Bailly market studies. In particular, the chemical heat pump is well-suited for use in process heat integration applications. Such versatility could enable the use of chemical heat pumps to save industry nearly 500 trillion Btu per year by 2010 as shown in Table 4-22.

Solid/Vapor Heat Pump Development
(Rocky Research, Standard Refrigeration)
An advanced solid/vapor heat pump that uses ammoniated complex salt compounds has been developed and is being field tested at an industrial

host site. In this heat pump, ammonia—acting as the refrigerant—is absorbed into salt compounds such as calcium chloride. These salt compounds are excellent media because they absorb large quantities of the refrigerant and are generally inexpensive and nontoxic. Other advantages of this new heat pump include the elimination of moving parts (such as pumps) that could require repair, the potential for temperature lifts of as much as 200°F, and the ability to operate at a wide range of delivery temperatures (-70°F to 300°F). The solid/vapor heat pump is feasible in many more process applications than conventional heat pumps, opening up new opportunities for saving energy. A prototype solid/vapor heat pump designed to provide process heat at 130°F, while at the same time providing refrigeration at 15°F, will be demonstrated at a Bilmar Foods turkey processing plant in Zeeland, Michigan.

Liquid/Vapor CHPs—
Alktrate™ Working Fluid
(Energy Concepts Company, Litwin Engineers & Constructors)
Another novel chemical heat pump working medium that has been developed under OIT sponsorship

is a liquid/vapor combination that uses a patented liquid called Alktrate™. Alktrate™ consists of a salt compound such as sodium nitrate dissolved in water. A chemical heat pump using this medium can be constructed from standard industrial materials at a moderate price. The most exciting feature of this heat pump, however, is its ability to withstand temperatures as high as 500°F without corroding, more than 150°F higher than its conventional counterparts. This means that process applications where using a heat pump was previously unfeasible may now be technically and economically attractive, leading to reduced primary fuel use. An Alktrate™ heat pump also has enhanced temperature lift capability. A prototype system is currently being field tested at a refinery in Ohio.

Brayton Solvent Recovery Heat Pump: A Novel Use of Heat Pump Technology to Improve the Environment
(3M, NUCON International)
Millions of tons of VOCs are released to the atmosphere each year from the hundreds of industrial processes that use solvents. These VOC emissions represent an economic loss to

Table 4-22
Annual Benefits of Chemical Heat Pumps

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	640	5	635	475,130
Total Cost (\$1000)	2968	518	2450	1,832,934
Energy Cost (\$1000)	2307	17	2290	1,712,787
Capital Cost (\$1000)	539	421	118	88,508
O&M Cost (\$1000)	122	80	42	31,639
Emissions (metric ton)				
CO ₂	45,226	339	44,887	33,575,475
NO _x	66	0.5	65.5	48,994
SO _x	95	1	94	70,268
Particulates	179	1	178	132,903
Solid Waste (1000 short tons)	—	—	—	—
Risk				
Technical		LOW		
Market		LOW		
Year of Maximum Market Share		2010		

figure 4-17
Brayton Solvent Recovery Heat Pump System

industry and contribute significantly to air pollution. Conventional VOC control strategies used by industry include incineration and carbon adsorption. Both processes are energy intensive; incineration also results in the loss of the solvents and their embodied energy. This energy content is substantial—as much as 30,000 Btu/lb of solvent, considering both the energy of the petroleum-based feedstock and processing energy requirements. Although carbon adsorption systems allow the solvents to be recovered, the capital and operating costs are sometimes prohibitive, especially for small firms.

As an alternative to these conventional technologies, OIT has sponsored the development of the Brayton solvent recovery heat pump (BSRHP). This heat pump system uses the same basic thermodynamic process (the Brayton Cycle) that is widely used to generate electricity using gas turbines, but in reverse. The reverse Brayton Cycle compresses, cools, and expands the solvent-laden air to allow the VOCs to condense and separate. The Brayton solvent recovery heat pump offers low energy costs and competitive capital and operation and maintenance costs compared to conventional solvent recovery technologies. Unlike incineration, the BSRHP recovers the solvent for reuse, thus lowering industrial demand for new solvents. A mobile system has also been developed that allows for multiple sites to

Photo courtesy of NUCON International

A Brayton-cycle solvent recovery heat pump was recently installed at a Pfizer Pharmaceuticals plant in Puerto Rico.

be serviced with a single system, particularly attractive for small solvent users who cannot justify the purchase of their own systems. The BSRHP technology has been successfully commercialized; the five operating systems are recovering a combined total of about 4650 tons of solvents annually. Cumulative energy savings of 770 billion Btu have been achieved through 1993, with savings of 400 billion Btu in that year alone.

Industrial Wastes

EXPLOITING OPPORTUNITIES TO CUT COSTS AND CREATE FEEDSTOCKS AND FUELS

The industrial sector generates about 14 billion tons of waste annually—of which the manufacturing sector accounts for about 9 billion tons or almost two-thirds (see Chapter 2). Outside of manufacturing, the principal sources of industrial waste include mining, oil and gas extraction and agriculture. Industrial wastes include airborne emissions of such pollutants as SO_x , NO_x , and VOCs as well as over one billion tons per year of CO_2 and other global warming gases. Each year the industrial sector also generates huge quantities of solid wastes and sludges as well as billions of tons of waste water. Other categories of industrial waste include hazardous and toxic wastes that—when compared to the total quantities of waste generated by the sector—account for a relatively small but potent, tightly regulated and highly expensive proportion of the full amount.

There is a strong relationship between energy use and waste generation in manufacturing. The materials and process industries that consume about 80% of all the energy used in manufacturing also generate an estimated 95% of all manufacturing waste. The materials and process industries are responsible for separating useful constituents from those that are unusable in the raw materials produced by the extractive industries. The potentially useful substances are then recombined (or synthesized) into consumable industrial materials, fuels or foodstuffs. Separation and synthesis are intrinsically energy- and waste-intensive processes.

The high levels of waste generated by the energy-intensive materials and process industries translates into large expenditures for pollution control in these industries. Preliminary estimates of the Department of Commerce indicate that manufacturers spent

Photo courtesy of Argonne National Laboratory

At Argonne National Laboratory, DOE has developed a flue gas cleanup unit designed to help industry comply with pollution control regulations.

roughly \$25 billion on pollution control equipment and operations in 1992—about 1% of the total value of all manufacturing shipments. However, pollution control costs do not fall evenly among industries. Five materials and process industries—petroleum refining, pulp and paper, chemicals, metals, and ceramics and glass—account for about 70% of all expenditures for pollution control in manufacturing. On the average these five industries spend about 15% of all their capital expenditures on pollution control. This amounts to about 2% of the value of all sales by these industries and is about three times greater than that spent by the rest of manufacturing.

Waste Reduction: Lowering Waste Generation within the Plant Boundaries

Pollution control costs are largely the cost of end-of-pipe clean up of regulated waste. A key strategy for cutting pollution control costs is to reduce the quantity of waste produced in the first place. This is the principal objective of a variety of waste reduction options, technologies and strategies.

When industry generates waste, materials as well as energy are not being used efficiently. The wasted energy is embodied in the unused or inefficiently used materials, in the energy content of waste streams, and in the energy required to manage and dispose of wastes. Because of the close

linkage between energy use and waste, waste reduction is an important mechanism for increasing energy efficiency in industry. Waste reduction in industry decreases the fuel use of industrial processes as well as the energy used to treat and dispose of wastes.

Another way of looking at waste reduction is through the concept of process yield improvement. Process yield is the proportion of useful product obtained after processing input raw materials—and the inverse of yield is the proportion of unused product (or byproduct waste) that is generated. Hence, improved yields contribute to less waste—the objective of waste reduction. Improved process yields result in greater throughput, improved productivity and competitiveness, and increased capacity as well as reduced waste.

Each of the materials and process industries has many opportunities to increase yield and reduce waste through improved and more efficient industrial processes. Unfortunately, there are often barriers that prevent the commercialization and adoption of higher yield and less waste-generating processes. One of the most important barriers is related to the concept of diminishing returns. In many industrial processes, the optimal yield that contributes to the lowest unit cost is often around 90%-95%. Almost inevitably there are expensive trade-offs that must be made to improve process yield to 100% or where zero waste is created. As a result, certain quantities of industrial waste are unavoidable from a practical standpoint—at least at the process, product, plant, firm or industry levels.

Waste Recycling and Use: Turning Unavoidable Waste into Feedstocks and Fuels

But at the broader level of industry as a whole, the unavoidable wastes of different processes and industries can be recycled and eventually reused as inputs by other processes or industries. Where waste reduction through process improvement or product

Strategies for Reducing Industrial Wastes

- Improve operational efficiency
- Recycle wastes within the process
- Redesign the production process
- Use alternative feedstocks
- Redesign the product for more effective use of materials

redesign is no longer practical, waste recycling and use processes can help convert this waste to materials or energy useful as inputs elsewhere in industry. The objective of waste recycling is to convert unavoidable industrial waste into feedstocks for other parts of the industrial infrastructure.

Organic waste such as plastic and paper is not as resilient as metals, glass and other inorganic materials. As it is recycled numerous times, organic waste degrades and loses its ability to reliably perform useful functions. But organic waste—unlike inorganic waste—possesses a high Btu value that when combusted yields considerable heat that can be converted to steam to generate electricity. The use of organic waste as fuels to generate electricity is preferable to waste treatment and disposal.

THE OIT INDUSTRIAL WASTE PROGRAM

The objective of the OIT industrial waste program is to increase industrial energy efficiency and productivity by reducing the generation and increasing the use of industrial wastes. On one hand, the waste reduction component of the program focuses largely on activities within the plant. On the other, its waste recycling and reuse component focuses mainly on activities that are outside the boundaries of a single plant. While OIT-supported projects typically target specific waste streams in individual industries, often these technologies may be adapted to meet the needs of other industries with only minor modifications. The program consists of five major

Strategies for Reusing Industrial Wastes

- Separation and recycling
- Conversion to reduce toxicity or prepare for recycling
- Remanufacture to reassemble discarded goods and new parts into new products
- Demanufacture to disassemble discarded products for further use
- Direct conversion of energy through combustion or catalytic conversion
- Remining or extracting to recover valuable materials from discards

elements: waste characterization, opportunities assessments, R&D, technology transfer, and institutional analysis. The majority of funding, however, is used in the R&D element.

VOC Control Strategies: Helping Small Industries Stay Compliant and Competitive

(Mechanical Technologies Inc., Chemsystems Software, Pajco Corporation)
Many industrial processes, including printing, chemicals production, metal cleaning, photographic development, and dry cleaning, rely on solvents to dissolve organic materials and contaminants from a product. In many of these processes, the solvent ends up as a vapor contaminant—a volatile organic compound, or VOC—in a warm air stream. Until recently, the majority of VOCs were unregulated and were often subject to uncontrolled release into the atmosphere. Now, however, the removal of VOCs from industrial waste streams is required for compliance with environmental regulations such as the Clean Air Act. For some small businesses and industrial facilities, the financial burden of complying with environmental regulations can be the difference between financial stability and insolvency. Cost-effective VOC minimization techniques and recovery technologies could help U.S. industries stay competitive while reducing their emissions.

Table 4-23
Selected Other NICE³ Projects*

Project Title (Developer)	Project Description	Affected Industries	Wastes Addressed
UV-Curable Coatings for Aluminum Can Production (Coors Brewing)	Demonstrate feasibility of utilizing ultraviolet curing for external surface printing and protective over-varnish during aluminum can production.	Aluminum can manufacturing	Volatile organic compounds; Glycol ether
Demonstration of Automated Dyebath Reuse in Carpet Manufacturing (Shaw Industries)	Demonstrate automation of reconstituting and reusing dyebaths in batch dyeing operations.	Textiles	Dyes; Chemicals; Water
Electrophotographic Screening (Thomson Consumer Electronics)	Develop electrophotographic screening process for the production of picture tubes.	Consumer electronics	Phosphor; Water
Hydrochloric Acid Recovery System (Beta Control Systems)	Develop hydrochloric acid recovery system for needs of galvanizers and small to medium sized steel manufacturers.	Steel	Hydrochloric acid
Direct Osmosis Concentration & Solar Evaporation: Food Industry (Osmotek)	Demonstrate direct osmosis concentration separation process in conjunction with solar evaporation for the production of tomato products.	Food processing	Air emissions (e.g., N ₂ O, NO ₂)

*The NICE³ Program is described in greater detail in Chapter 1.

Recognizing the lack of information available to industry on VOC minimization and control, OIT's NICE³ Program has sponsored the development of computer software that identifies optimal VOC control strategies for individual facilities. As part of this effort, technical personnel in government, industry, and the utility sector will be trained in the use of the software. A second goal of the project is the demonstration of an energy-efficient solvent condensing system for recycling VOCs. The prototype system is sized for small manufacturers who are presently emitting as much as 25 tons/year of VOCs. The new VOC recovery technology is more energy-efficient than conventional VOC treatment methods and, unlike incineration (a common method), recovers the solvents for reuse in the industrial process. Although the energy savings of individual applications will vary, the estimated national potential energy savings are 34 trillion Btu annually. There is also an estimated reduction in VOC emissions of nearly 140,000 tons/year that could be achieved through widespread adoption of the new recovery technology.

Development of Superior Asphalt Recycling Agents: Enabling More Road Building Waste to Be Recycled (Texas A&M University)

About 27 million tons of asphalt and nearly 20 times this much aggregate are consumed each year to build and maintain more than two million miles of roads in this country. During an average cycle of about 12 years, these roads must be resurfaced. Unfortunately, present recycling technology cannot be applied to millions of tons of used road-building material. The only significant impediment to wider adaptation of current asphalt recycling technology is the lack of adequate specifications for high-quality recycling agents that can rejuvenate most, if not all, of the hard, older material into a ductile, long-lasting material with new material properties.

To increase the recyclability of aggregate/asphalt road building waste, OIT is investigating how to produce high-quality asphalt recycling agents. This should lead to techniques that would allow about one-third of the road-building waste generated each year to be recycled. In addition to saving the embodied energy content of the asphalt (which is substantial because

asphalt is made from petroleum), the asphalt recycling technology will reduce the fuel consumption associated with hauling new material to the roads under construction and old materials away. This combined energy savings has been estimated to be 236 trillion Btu annually. In addition, the disposal of aggregate/asphalt road waste will be reduced by more than 100 million tons each year.

Electroplating Waste Minimization: Reduced Landfilling of Toxic Sludge (Boeing, Los Alamos National Laboratory)

In metal plating operations, parts made of one metal or alloy are treated in large baths to plate the part with another metal to achieve specific material properties. The plating industry, along with numerous DOE industrial facilities, generate large quantities of toxic metal wastes containing such pollutants as zinc cyanide. The standard treatment method is to convert the waste to sludge and send it to a landfill for disposal. This method wastes valuable metals and energy, and costs millions of dollars each year. In addition, the eventual burial of metal sludges does not adequately protect the environment from toxic metal leaks. The Environmental Protection Agency has established regulations that restrict the form and quantity of metals sent for disposal, thus making the need for metal recovery technologies more acute.

To address this need, OIT is developing and evaluating technologies to reduce plating wastes. The goal is to separate and purify the metals to allow them to be reused in the plating bath. This will reduce raw materials requirements, transportation of raw materials and sludges, and sludge processing requirements. Plating waste minimization technologies could save 26 trillion Btu per year by 2015. Reducing plating wastes will decrease environmental pollution from toxic metals and is expected to slow the increasing inventory of stored metal sludges. It has been estimated that total heavy

metal sludge production could be reduced by 226,000 tons per year, resulting in a decrease of more than 700,000 drums of hazardous waste that must be disposed of each year.

Collection of Vapor-Liquid Equilibrium Data for Acid Gas-Mixed Amine Systems: Improving the Efficiency of the Natural Gas Purification Process

(Texas A&M University)

Before natural gas is used as a fuel to produce heat and power, or as a feedstock for chemicals production, it is commonly purified to remove acid gases, especially sulfur-containing gases. The standard purification process is to contact the contaminated gas stream, known as sour gas, with chemical compounds that absorb the acid gases. Heat is subsequently added to the absorbing compounds to strip away the acid gases for disposal. The energy efficiency of the process depends on accurate predictions of the vapor-liquid equilibrium (VLE) behavior of the mixtures—that is, how the chemical reactions occur as a function of factors such as temperature, pressure, and exact chemical composition of the mixtures involved. Because the VLE behavior of these mixtures is not well known, natural gas purification systems are often operated too conservatively, wasting significant amounts of energy for excessive pumping and reboiling (Figure 4-18).

OIT is presently sponsoring the development of an analytical technique to improve the measurement of VLE data for natural gas purification systems. The new technique is based on a form of infrared spectroscopy, which can determine the exact composition of the mixtures. With reliable VLE data, existing purification systems could be operated much more efficiently—as much as 50% more efficiently than current systems—and new systems could be designed that would have lower operating and capital costs. The reduction in energy consumption by optimization of existing systems or construction of improved

systems will result in a corresponding reduction in the waste gas associated with the on-site burning of natural gas for purification process energy. A substantial portion of these benefits could be realized very rapidly, because the recommended operational changes could be applied to existing systems with very little capital investment.

Low-Temperature Catalytic Gasification of Industrial Waste Waters: How to Get the Energy Out of Food Processing Wastes (Pacific Northwest Laboratory, Onsite*Offsite)

It has been estimated that less than half of the 200 million tons of raw agricultural commodities harvested annually in the United States end up

Table 4-24

Annual Benefits of Superior Asphalt Recycling Agents

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	7	2	4	236,430
Total Cost (\$1000)	28	10	17	951,284
Energy Cost (\$1000)	27	9	18	974,034
Capital Cost (\$1000)	0.4	0.9	-0.4	-24,387
O&M Cost (\$1000)	0.1	0.1	0.0	1637
Emissions (metric ton)				
CO ₂	0.0	0.0	0.0	0.0
NO _x	0.0	0.0	0.0	0.0
SO _x	0.0	0.0	0.0	0.0
Particulates	0.0	0.0	0.0	0.0
Solid Waste (1000 metric tons)	N/A	N/A	2	106,991
Risk				
Technical		HIGH		
Market		HIGH		
Year of Maximum Market Share		2010		

Table 4-25

Annual Benefits of Electroplating Waste Minimization

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	10	1	9	26,973
Total Cost (\$1000)	1162	436	726	2,177,201
Energy Cost (\$1000)	48	5	43	130,624
Capital Cost (\$1000)	352	112	241	722,377
O&M Cost (\$1000)	761	320	441	1,324,200
Emissions (metric ton)				
CO ₂	1150	115	3108	9,322,958
NO _x	1	0.1	0.9	2669
SO _x	8	0.8	7.2	22,318
Particulates	22	2	20	58,388
Solid Waste (1000 metric tons)	N/A	N/A	0.1	226
Risk				
Technical		LOW		
Market		LOW		
Year of Maximum Market Share		2015		

as useable products. The rest is waste material, typically wet materials that have relatively little market value but possess significant energy content. For example, a typical large brewery produces about 28,500 tons/year of spent grain solids with a total energy content of 500 billion Btu. Other food processing industry waste streams with significant energy potential include cheese whey, potato waste, wet corn milling waste, meat packing waste, and even cattle feedlot manure. On an industry-wide basis, the food processing industry accounts for 20% of the total organic waste generated by all industries. A technology that could extract the energy content of these types of wastes, while at the same time reducing the amount of wastes that need to be disposed, could be extremely beneficial to the food processing industry.

With OIT funding, researchers are developing a unique catalytic gasification concept that converts wet food processing wastes, as well as other wet industrial wastes, to methane and carbon dioxide. The methane can be used as a fuel in industrial boilers for generating process steam; the carbon dioxide has applications in bottling, packaging, and other plant uses. Other benefits of the new system, called the Thermochemical Environmental Energy System, or TEES, include its potential to cogenerate electricity and its ability to reduce solid waste handling and waste water treatment requirements. TEES technology is distinctive in its ability to handle wet wastes; no other existing biological or thermal process exhibits the potential to provide the same overall impact. In addition to applications in the food processing industry, the TEES has tremendous potential for use in organic chemical manufacturing and possibly in the handling of hazardous waste water streams.

Figure 4-18
Natural Gas Purification

Table 4-26
Potential Applications of TEES Technology

Industry	Waste Production Rate (wet tons/year)	Energy Potential (trillion Btu/year)
Malt beverages (not including spent grain)	249 million	5.0
Cheese whey	7 million	3.5
Potato waste	132 million	1.2
Wet corn milling	37 million	1.7
Meat packing	465 million	5.6
Total	890 million	15.3

Waste Tire Utilization: Scrap Rubber Treatment Process Allows Tires to Be Converted to Valuable Products
(Composite Particles, Inc.)

Scrap tires represent both an energy resource that is largely unused and a serious waste disposal and environmental problem. Each year throughout the United States, 26 million scrap tires are used as fuel and another 28 million find other uses; 188 million tires, however—more than 3 times as many as are used—are dumped or landfilled. This equates to nearly 4 billion pounds of tire rubber every year, and adds to the existing inventory of 2 billion tires already landfilled. The development of economical recycling technologies would enable these valuable materials to be used.

A project within the Industrial Waste Program is developing a new technology to convert finely ground tire rubber to high-value material for use in products such as bicycle tires, shoe soles, automobile bumper covers, canal liners, caulks, molded epoxy resin pipe fittings, and epoxy adhesives. By treating the ground rubber with a chemical such as chlorine, the chemical bonding characteristics of the surface of the rubber particles can be modified, enabling it to replace and supplement virgin polymers. The treated scrap rubber is projected to be less costly than 80% of the plastic resins currently used. In addition, it requires far less energy to make—only 9000 Btu per pound—compared to resins requiring between 30,000 and 100,000 Btu per pound.

Biological Conversion of Waste Gases to Acetic Acid: Designer Microorganisms Do the Job
(Bioengineering Resources)

About 10 billion pounds of waste gases (including CO₂ and CO) are discharged into our environment each year as byproducts of the manufacture of carbon black, a material used to make rubber products, printing inks, and pigments. These waste gases represent lost energy and chemical feedstocks, as well as contribute to depletion of the ozone layer and to global warming. Unfortunately, conventional methods of waste gas recovery and separation are expensive and impractical with current methods of carbon black production. A new biological process of converting these waste gases into usable chemicals has emerged as a viable method of not only controlling these emissions but putting the wastes to beneficial use.

Recent advances in biotechnology have led to the development of designer microorganisms capable of promoting chemical reactions for a variety of applications. In a cooperative project with OIT, researchers are developing and testing a process for converting waste gases from carbon black manufacture into acetic acid. The technology should also be applicable to waste gases from the production of coke, which is used to make steel. Acetic acid is a relatively high-value, large-volume petrochemical—more than 3 billion pounds are produced annually—that is mainly used in the production of plastics. The price of biologically produced acetic acid is expected to be substantially less than the cost of acetic acid made from petrochemicals because it uses industrial waste as the feedstock and requires much less energy to produce.

Automobile Shredder Residue Recycling: Recovering the Plastics in Junked Cars
(Argonne National Laboratory)

Obsolete automobiles are the most recycled high-volume consumer product in the United States. Currently, 92% of ferrous auto scrap

is recovered for use as feedstock for the steel industry. The availability of low-cost scrap metals has played a significant role in the development of the electric arc furnace steel industry in this country, which today enjoys one of the lowest costs of production in the industrialized world. However, for each ton of steel that is recovered,

between 500 and 700 pounds of automobile shredder residue (ASR) are produced. ASR contains plastics, rubber, wood, paper, fabrics, glass, sand, dirt, metal pieces, and possibly automotive fluids and refrigerants; the current disposal technology is landfilling. Unfortunately, when ASR is landfilled, a lot of high-priced

Table 4-27
Annual Benefits of Waste Tire Utilization

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	1000	180	820	246,000
Total Cost (\$1000)	15,580	5826	9754	2,926,428
Energy Cost (\$1000)	3571	643	2928	878,553
Capital Cost (\$1000)	1409	1183	226	67,875
O&M Cost (\$1000)	10,600	4000	6600	1,980,000
Emissions (metric ton)				
CO ₂	68,289	12,292	55,997	16,799,127
NO _x	126	23	103	31,020
SO _x	86	16	70	21,045
Particulates	19	4	15	4604
Solid Waste (1000 metric tons)	N/A	N/A	9	2727
Risk				
Technical		HIGH		
Market		MEDIUM		
Year of Maximum Market Share		2020		

Table 4-28
Annual Benefits of Biological Conversion of Waste Gases to Acetic Acid

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	4501	2200	2301	48,328
Total Cost (\$1000)	62,919	25,082	37,838	794,592
Energy Cost (\$1000)	37,522	18,338	19,183	402,846
Capital Cost (\$1000)	16,697	3743	12,955	272,045
O&M Cost (\$1000)	8700	3000	5700	119,700
Emissions (metric ton)				
CO ₂	584,368	285,606	298,763	6,274,016
NO _x	524	256	268	5622
SO _x	3561	1741	1821	38,237
Particulates	9358	4574	4784	100,474
Solid Waste (1000 short tons)	—	—	—	—
Risk				
Technical		LOW		
Market		LOW		
Year of Maximum Market Share		2010		

materials with significant embodied energy are lost. This loss, combined with the cost of landfilling, more stringent regulations, long-term viability concerns, and shrinking landfill space dictate that viable disposal alternatives be developed to maintain a healthy metals recycling industry.

With this in mind, OIT has been investigating a process for recycling many of the plastics found in ASR. These plastics have potential use in foam rebonding and in the production of plastic blends and plastic parts. Also recovered during the process are iron- and silica-rich fines, whose potential for use as a fuel in pulverized coal combustion systems is being evaluated. The recycling process will yield a net energy savings of about 52 trillion Btu/year in 2010. Because the process recovers virtually all of the constituents of the ASR waste stream, there is a large reduction in the amount of solid waste that would otherwise be landfilled. Recovering the recyclable plastics will provide a new source of low-cost raw materials for industry, reducing the need for imported petroleum feedstocks by millions of barrels of oil equivalent each year. The process will also directly reduce the import of as much as 100,000 tons/year of scrap industrial polyurethane foam, valued at \$60 million, for the domestic rebonding industry. Perhaps most importantly, the new ASR recycling process will allow the automobile shredding industry to continue to provide low-cost raw materials to the steel industry, which will enhance its overall competitiveness in the world market.

Table 4-29
Annual Benefits of Auto Shredder Residue Recycling

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	1096	419	677	52,114
Total Cost (\$1000)	18,175	5436	12,739	980,901
Energy Cost (\$1000)	3914	1497	2417	186,116
Capital Cost (\$1000)	1931	922	1009	77,684
O&M Cost (\$1000)	12,330	3017	9313	717,101
Emissions (metric ton)				
CO ₂	74,845	28,627	46,218	3,558,793
NO _x	138	53	85	6571
SO _x	94	36	58	4458
Particulates	21	8	13	975
Solid Waste (1000 metric tons)	N/A	N/A	74	5715
Risk				
Technical		MEDIUM		
Market		MEDIUM		
Year of Maximum Market Share		2010		

Municipal Solid Waste

SIGNIFICANT, BUT LARGELY UNTAPPED ENERGY AND MATERIAL RESOURCE

According to the EPA, the United States generated 196 million tons of municipal solid waste (MSW) in 1990—compared to 88 million tons in 1960. EPA's definition of MSW, however, excludes industrial wastes, and as a result, DOE estimates that roughly an additional 70 million tons of industrial wastes currently end up in municipal landfills. MSW generation is estimated to be increasing at a rate equal to or slightly greater than population growth in the United States. MSW generation is expected to be just more than 220 million tons in 2000 (Figure 4-19).

In 1990, about 67% of MSW was landfilled, compared to about 62% in 1960. This percentage peaked in the early 1980s at just more than 80%. Also in 1990, about 16% of MSW was composted; virtually all of this occurred to recover energy. Incineration accounted for nearly 30% of MSW use in 1960—mostly without any energy recovery or air pollution controls. Recovery accounted for the remaining MSW use in 1990 (about 17%), with recycling representing the vast majority of this category and composting accounting for a very small fraction of MSW use. This is significantly higher than 8% in 1960 (Figure 4-20).

MSW management includes collecting waste, transporting the waste to a landfill or a processing facility (a combustor or a materials recovery facility), and possibly transporting the residue from processing to a landfill. The energy resource potential of MSW is significant; the current MSW stream contains over 2 quads of energy.

Municipal solid waste contains durable goods, such as furniture and tires; nondurable goods, such as clothing and newspapers; containers and packaging, such as boxes and cans; food wastes, such as corn cobs and

vegetable peelings; yard wastes, such as grass clippings and leaves; and other, miscellaneous inorganic wastes. The estimated composition, by weight, of MSW in the United States in 1990 is illustrated in Figure 4-21.

Landfill Disposal

Open landfills have been used as a waste management option for centuries. Regulations for landfill

operation were established by the Resource Conservation and Recovery Act (RCRA) and have become increasingly stringent since the mid-1970s. Currently, less than 5,400 landfills are in operation, significantly fewer than about 30,000 landfills and open dumps operating in 1976. The 200 largest landfills receive more than 40% of all MSW disposed in the United States.

Figure 4-19
Trends in and Projections of MSW Generation

Source: *Characterization of Municipal Solid Waste in the United States: 1992 Update*, EPA

Figure 4-20
Disposition of MSW, 1960 and 1990

Source: EPA

Recent experience indicates a tendency to close smaller landfills and open or expand larger landfills.

The cost of disposing MSW in landfills, referred to as tipping fees, has escalated substantially. Average costs have roughly tripled from about \$10 in 1982 to about \$29 in 1992. This is in large part because of increased regulatory requirements. Generally, tipping fees are substantially higher in more densely populated areas, such as the Northeast and Mid-Atlantic states (Figure 4-22). In addition, many landfills are reaching their capacity limits, leading to increased concerns about future availability of landfill space in some locations.

Waste to Energy

Over time, the organic constituents of MSW—food, paper, yard waste—naturally degrade to landfill gases such as methane and CO₂. It is estimated that it takes 2 years to 20 years for landfills to release one-half of the full methane potential. The collection of between 30% and 85% of landfill gas generated can be facilitated by: (1) careful enclosure of MSW, by providing liners underneath it (which also helps control leachate and eliminate groundwater contamination), (2) installing gas collection systems, and

Figure 4-22

Average Landfill Tipping Fees for Selected States, 1992

Source: *Bicycle*, May 1993

(3) capping the landfill when it is filled. Energy recovery is more economically viable at very large landfill sites where the quantity of gas generated is sufficient to justify the expense of the collection equipment. Landfill gas is currently recovered for its energy content at more than 100 of the nation's larger landfills—producing about 40 trillion Btu of energy annually.

Electricity is also generated from the combustion (burning) of MSW at 130 operating MSW combustion units in the United States—saving about 0.26 quads of fossil energy use in 1990. The Clean Air Act Amendments of 1990 have made emissions requirements for MSW combustion more stringent. This will force many older facilities to update their pollution control equipment at great expense. In addition, the ash produced by MSW combustion has generated substantial controversy. Currently, it is not listed as a hazardous waste, but when RCRA is reauthorized, certain groups will petition for its inclusion as a hazardous waste—mainly because of the presence of trace amounts of lead and other metals that may leach from the ash.

Recycling

Recycling is a common MSW option for several wastes, such as aluminum cans, newspapers, and glass. The numerous benefits of recycling include: conservation of landfill capacity, conservation of natural resources, and reducing waste disposal costs. These benefits allowed recycling to reduce energy demand by 0.11 quads in 1990. For example, aluminum recycling saves considerable energy because aluminum smelting is very energy-intensive, and recycling technologies and markets are readily available.

However, recycling frequently requires large and sometimes risky investments in technologies for collecting, separating materials, and processing (materials recovery facilities). In addition, repackaging, resale, and disposal of processing wastes must be considered. These decisions are influenced by such factors as waste quantities and composition, as well as institutional factors.

Due to increasing concern for the environment, more than 5400 communities have set up recycling programs (many of these were mandated

Figure 4-21

MSW Composition by Weight, 1990

Total = 196 Million Tons

Source: EPA

by state governments)—well up from 1000 in 1988. However, the cost of community recycling programs is usually higher than competing disposal methods.

Other Viable Options

Other options for managing MSW streams include composting of yard and food wastes, cofiring refuse-derived fuel with coal, anaerobic digestion of MSW to produce methane, and gasification or pyrolysis of MSW to produce a fuel gas. Except for composting, data regarding these technologies are limited because they are rarely used at present. Additional development work is needed to demonstrate the practicality of these technologies as effective MSW management options.

THE OIT MSW PROGRAM

The OIT MSW program is focused on resolving issues that prevent integrated approaches to municipal waste disposal, including those that inhibit using waste disposal processes such as waste-to-energy and recycling. The program's multiple goals include minimizing landfill requirements and maximizing both energy and material recovery from post-consumer wastes. Also, significant opportunities exist for the development of new technologies, and adaptation of existing technologies, with improved economics and reduced emissions.

Anaerobic Digestion System: Turning Tuna Waste into Turbine Fuel
(National Renewable Energy Laboratory)
American Samoa, an island territory with two tuna canneries, is looking at ways to solve its tuna sludge disposal problems. The sludge (consisting of heads, skin, and other wastes) is currently dumped a few miles off shore, an action that is environmentally controversial as well as expensive. Compounding the island's waste problem is the MSW produced by the population. In addition, the volcanic island's topography is unsuitable for landfills and lacks soil for ground cover. Anaerobic digestion—decomposing in the absence of oxygen—

has been suggested as a possible method of simultaneously combating both of the island's major waste problems.

In anaerobic digestion, the organic materials (such as food wastes) in the MSW are separated from the inorganic materials and fed into a reactor vessel, where the waste is biologically converted to methane and CO₂. Anaerobic digestion essentially speeds up the natural degradation process from months to two to four weeks, reducing the volume of waste by more than 50%, and yielding a compost that can be used as a soil amender. Tuna sludge is an organic waste; experiments have shown that adding tuna sludge to MSW increases the yield of methane from the digestion process. The methane can be burned to gener-

ate electricity. A transportable pilot unit will be evaluated in California and then moved to American Samoa. This novel approach will reduce the amount of MSW that is landfilled while constructively using tuna sludge.

**Landfill Gas Recovery:
Gas from Decomposing Garbage
Can Replace Fossil Fuels**
(National Renewable Energy Laboratory,
Electric Power Research Institute,
Environmental Protection Agency)
The U.S. Environmental Protection Agency has proposed regulations requiring 500 to 700 of the largest landfills in the country to control gas emissions emanating from decomposing MSW. Methane, the main energy component of landfill gas, is a particularly potent greenhouse gas because of its ability to trap heat. It has been

Table 4-30
Recovery of MSW Wastes, 1990

Category	Million Tons Recovered	Percent Recovered
Paper and Paperboard	20.9	29
Glass	2.6	20
Ferrous Metals	1.9	15
Aluminum	1.0	38
Other Nonferrous Metals	0.8	68
Plastics	0.4	2

Photo courtesy of Recycle Seattle

Recycling wastes such as cans, glass, and newspapers conserves natural resources, reduces waste disposal costs, and saves land that would otherwise be used for landfills.

estimated that on a carbon equivalent basis methane accounts for about 18% of all greenhouse gas emissions, and that methane from landfills represents roughly 4% of the total U.S. contribution to greenhouse gases. Landfill gases also pose serious odor and safety problems; if trapped in pockets in landfills without gas collection systems, methane can explode and burn. There are two methods to control landfill gas—flaring, which burns the gas in open air without recovering its energy, and recovery, which collects the gas for uses such as boiler fuel.

As part of its program to increase the recovery of landfill gas, OIT will sponsor joint cooperative research, development, and demonstration projects between federal, state, and industry to remove technical and other barriers to enhanced landfill gas recovery. Recovery processes provide a valuable renewable fuel—methane—for generating heat and electricity, thereby reducing the demand for fossil fuels from non-renewable sources. Recovery could also contribute to reduced emissions of methane, and improve the safety of landfill operations. The fuel sold helps to offset

the cost of the gas collection equipment, and in some cases, may result in a net increase in revenues for the landfill.

Data Collection and Analysis: Filling in the Knowledge Gaps on MSW Management Options

(*National Renewable Energy Laboratory, Argonne National Laboratory, Environmental Protection Agency, APA, Solid Waste Association of North America*) Experts in the field of MSW acknowledge that the best management approach is one that integrates the available disposal options. However, it is impossible to integrate the available options—and get the most use from the waste—without knowing the facts. Unfortunately, data on the energy, economic, and environmental characteristics of municipal waste management options are incomplete, out-of-date, inaccurate, and often non-existent. Sometimes data are available but not in comparable formats, units, regions, or circumstances. Planning for effective waste management requires an abundance of good quality data to provide a basis for making short- and long-range decisions for waste management strategies and methods. Therefore, the collection

and analysis of comparative data on waste disposal options is of paramount importance.

Developing, analyzing, and communicating the needed information is a major focus of this OIT-sponsored program. Up-to-date energy, economic, and environmental data are being collected and compiled for each of the potential waste management options including as many different regions, community sizes, and individual situations in the United States as possible. In one study, researchers are filling the knowledge and data gaps on the energy, environmental, and economic effects of materials recovery facilities, which sort and separate recyclable constituents in MSW. In a joint effort with the Environmental Protection Agency, the different disposal options for specific waste streams including paper, food, yard waste, and glass are being analyzed. Case studies of six integrated waste management systems are also being performed to develop better data on the cost of the technology systems, as well as performance data from each. Because the information being developed will lead to better understanding of MSW management options, the program will ultimately contribute to energy savings, reduced landfill requirements and emissions, and improved economics of MSW management systems.

Table 4-31

Annual Benefits of Anaerobic Digestion System

Category	Current Technology	OIT Technology	Reduction	
			Unit	Industry
Energy Use (billion Btu)	330	0	330	33,032
Total Cost (\$1000)	2417	2261	155	15,539
Energy Cost (\$1000)	494	0	494	49,362
Capital Cost (\$1000)	1826	2261	-435	-43,504
O&M Cost (\$1000)	97	0	97	9681
Emissions (metric ton)				
• CO ₂	23,080	0	23,080	2,300,000
NO _x	20	0	20	1952
SO _x	168	0	168	16,283
Particulates	441	0	441	44,102
Solid Waste (1000 short tons)	N/A	N/A	166	16,566
Risk				
Technical	MEDIUM			
Market	MEDIUM			
Year of Maximum Market Share	2007			

Methodology for Calculating Potential Benefits of Technologies Supported by OIT

The following discussion describes the procedures used to calculate the potential benefits of OIT-supported technologies described in this report.

DATA COLLECTION

Technology and Commercialization Data

For each technology, data or estimates for each of the following categories of information were collected from OIT program managers, project managers, contractors, and other sources such as technology characterizations, project descriptions, and various publications:

- Identification of principal competing technology and its current energy use
- Year of commercialization of OIT technology
- Expected maximum market share of OIT technology
- Number of units of OIT technology in place at maximum market share
- Number of years to maximum market share
- Unit energy use, capital cost, non-fuel O&M cost, average efficiency, operating factor, equipment lifetime for OIT and competing technologies
- Solid waste, SO_x, NO_x reduction per unit

Technical and Commercial Risk

Technical and market risks were derived using the Gas Research Institute's Project Assessment Methodology¹. For this report, Technical Risk was defined as the likelihood that the project will attain its cost, technical and performance

goals. Market Risk was defined as the likelihood that the technology will be successfully accepted by manufacturers and end-users.

OIT program managers assigned technical risk scores to each OIT technology in the following categories:

- Proof of concept,
- Complexity, and
- Technology gaps and difficulties.

OIT program managers also rated the commercial risk of each technology in three categories:

- Commercializing agent commitment,
- Regulatory or code/standard requirements, and
- Market infrastructure.

BENEFIT CALCULATION

The benefits of the OIT-supported technologies were calculated for the year in which maximum market share was expected; the benefit calculations pertain to only that year—they are not cumulative. For example, if the expected year of commercialization for a particular OIT technology was 2000 and it was expected to take 15 years for this technology to achieve maximum market share, then the year for which benefits were calculated was 2015.

Annual Energy Use and Cost

Given the unit energy use values of the OIT [UEU(OIT)] and competing [UEU(PT)] technologies, reduction in energy use per unit (UEnSave) and for the entire industry or market (IndEnSave) were estimated based on the following equations:

$$\text{UEnSave} = \text{UEU(PT)} - \text{UEU(OIT)}$$
$$\text{IndEnSave} = \text{UEnSave}[\text{N(OIT)}],$$
where N(OIT) = Number of units in place at maximum market share

Note that the energy use estimates pertain to a delivered Btu basis.

Projected energy costs were based on 1995 industrial energy prices (1993\$/mmBtu) as published in the Energy Information Administration's 1995 Annual Energy Outlook.

Average energy price was calculated for each of the competing technologies based on their respective fuel consumption mixes. Annual energy cost was estimated by multiplying average energy use by average energy price. Annual energy cost reduction was the difference between the average energy cost of the OIT and competing technologies.

Other Annual Costs

The unit capital cost data that were collected include first and installation costs. The capital cost reported in the benefit tables were annualized based on equipment lifetime (ELife) and a discount rate (DR) assumed to be 10%. If the unit capital cost for the OIT technology was denoted as UCapCost(OIT), then the annualized unit value for OIT [UAnnCap(OIT)] was as follows:

$$\text{UAnnCap(OIT)} = [\text{UCapCost(OIT)}] [\text{CRF(OIT)}],$$
where CRF(OIT) = capital recovery factor =

$$\text{DR} \frac{(1 + \text{DR})^{\text{ELife(OIT)}}}{(1 + \text{DR})^{\text{ELife(OIT)}} - 1}$$

Similar equations were developed for competing technologies.

The difference between UAnnCap(OIT) and UAnnCap(PT) was the unit reduction of capital cost reported in the table. The industry-wide reduction was obtained by multiplying the unit reduction by the number of units in place.

Unit reduction in non-fuel operating and maintenance (O&M) cost was calculated as the difference between the unit non-fuel O&M cost for the OIT and competing technologies. The industry-wide reduction was calculated by multiplying the unit reduction by the number of units in place.

Total unit cost was the sum of the unit energy cost, annualized unit capital cost, and unit non-fuel O&M cost. In a few instances when the OIT technology and competing technologies had equal capital or non-fuel O&M costs, a value of NA (not available) was assigned to the particular cost for both technologies. Consequently, the value of the total cost for each of these technologies would not include that particular cost item.

Annual Emission and Solid Waste Reductions

The first step in calculating emissions benefits was to convert electricity to its primary energy. The second step was to estimate the fuel mix of the total primary energy use. Appropriate emissions factors (from EIA) were then applied to these energy values. If additional reductions were expected from the OIT technologies due to installed controls or improved combustion, then these reductions were also included in calculating the emissions benefits.

If an OIT technology was expected to have significant solid waste reduction benefits, then these were calculated based on the given unit solid waste reduction and the number of units in place.

Technical and Market Risk

Risk calculations were simply an arithmetic average of the estimated risk for each of the three commercial and technical risk categories.

¹ Gas Research Institute, *Results of Appraisal of GRI 1994-98 R&D Plans*, June 1993