ENERGY, ECONOMIC, AND ENVIRONMENTAL IMPACTS OF ADVANCED INDUSTRIAL PROCESS INNOVATIONS, 1976-1996

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DOE INDUSTRIAL TECHNOLOGIES PROGRAM

The mission of the Office of Industrial Technologies (OIT), within the Office of Energy Efficiency and Renewable Energy, is to develop and deploy advanced energy efficiency, renewable energy, and pollution-prevention technologies, through partnerships with industry, government, and non-governmental organizations. Since 1976, OIT has been helping industry develop and adopt new energy-efficient pollution-prevention technologies through a wide spectrum of programs -- from materials and components research, through product and process development, demonstration, and technology transfer. The Office supports technologies that are too risky for individual companies to undertake, are pre-competitive, have broad national application, and have potentially significant energy, economic and environmental benefits.

OIT's objectives have evolved and broadened over nearly two decades, continually responding to a changing energy situation and shifting national priorities. By the early 1990s, pollution prevention, improved resource use, industrial competitiveness, and jobs had taken their place alongside the basic objective of improving energy efficiency. Industry and government are more sophisticated than they were 20 years ago in understanding the interconnectedness of these objectives.

Today, the key focus of the OIT programs is the Industries of the Future approach. This strategy of close collaboration with industry catalyzes and facilitates technology development and transfer efforts in seven manufacturing industries that together account for over 80% of the energy used and over 80% of the wastes produced by the manufacturing sector. In this approach senior level industry groups develop a future vision of their industry and a technology roadmap to attain the vision. DOE helps facilitate this process and partners with industry to identify and pursue an advanced technology R&D portfolio. The seven industries are aluminum, chemicals, forest products, glass, metalcasting, petroleum refining, and steel. In managing all its activities, OIT draws upon program support provided primarily by National Laboratories, universities, and private-sector research organizations throughout the country that have the diverse and specialized expertise needed to develop advanced industrial technologies.

Approximately 78 industrial technologies developed with Office of Industrial Technology (OIT) support have successfully entered commercial markets. These technologies have saved a cumulative total of almost 900 trillion Btu, representing a net production cost savings of over $1.8 billion. These dollar savings represent the net total value of all energy saved by technologies developed with OIT support minus the net cost to industry of using the technologies (including capital costs, operating and maintenance costs, and any non-energy production cost savings). In 1996, two additional DOE programs were transferred to the Office of Industrial Technologies: the Energy-Related Inventions program and the Innovative Concepts program. About 30 technologies developed in these programs have seen application in the industrial sector and have had significant energy savings. OIT is currently planning to incorporate these technologies into its tracking system.

AN R&D IMPACT ANALYSIS SYSTEM

OIT has developed a system to monitor certain public returns on the investments made in its programs. From the time that OIT-sponsored technologies were beginning to demonstrate energy and cost savings, OIT has tracked energy data through a rigorous process of annual inquiry and data management. Non-energy impacts including pollution reductions, productivity improvements, and employment effects have been analyzed. Roll-up assessments have estimated the overall cost effectiveness of the OIT programs from a national viewpoint. Recently, commercial histories of selected technologies have been developed to reveal new insights into the industrial innovation process.

Technology Tracking Method

For over 15 years, the Office of Industrial Technologies (OIT) has been tracking and recording information on technologies developed through cost-shared R&D projects with industry. The active tracking process involves the collection of technical and market data on each commercially successful technology. Commercially successful technologies are defined as full-scale operational units involved in making products for the marketplace and which have the potential for continued use and replication. Information collected includes:

- Number of units sold, installed, and operating in the United States and abroad (including size and location)
- Units retired since the previous year
- Energy saved by the technology
- Environmental benefits
- Improvements in quality and productivity achieved through the use of the technology
- Impacts of the technology on employment
- Marketing issues and barriers

Information on technologies is gathered primarily through telephone interviews by the Pacific Northwest National Laboratory staff contacting either vendors or end-users of the technology. These contacts provide the primary data needed to calculate the unit energy savings associated with an individual technology, as well as the number of operating units. Technologies are tracked until the developers and/or users claim the technology is no longer commercially available or is retired, up to a maximum of ten years from the time of initial commercial introduction.

Unit energy savings are unique to each individual technology. Technology manufacturers or end-users usually provide unit energy savings, or at least enough data for a typical unit energy savings to be calculated. The total number of operating units is simply equal to the number of units installed minus the number of units retired in a given year, information usually determined from sales data or end-user input. Operating units and unit energy savings can then be used to calculate total annual energy savings for the technology. The cumulative energy savings represents the accumulated energy saved for all units for the total time the technology has been in operation (including previous savings from retired units).[4]

After cumulative energy savings have been determined, long-term impacts on the environment are calculated in terms of the associated reduction of air pollutants. This is a straightforward calculation based on the type of fuel saved and the pollutants typically associated with combustion of that fuel. For example, for every million Btu of coal combusted, approximately 2.5 pounds of sulfur oxides (known acid rain precursors) are emitted to the atmosphere. Thus, every million-Btu reduction in coal use results in the elimination of 2.5 pounds of polluting sulfur oxides. Air pollutant emission factors used for the analysis are shown in Table 1.

Table 1. Combustion Air Pollutant Emission Rates
(lbs/million Btu)

Fuel	Particulates	VOCs	SO_x	NO_x	CO_2
Distillate Oil	0.010	0.002	0.160	0.140	161.43
Residual Oil	0.080	0.009	1.700	0.370	173.72
Natural Gas	0.003	0.006	0.000	0.140	118.83
Propane	0.003	0.006	0.000	0.140	118.83
Gasoline	0.000	0.090	0.000	0.140	156.98
Coal	0.720	0.005	2.500	0.950	207.10
Electricity	0.400	0.004	1.450	0.550	200.90

Source: Particulates, SO_x, NO_x, VOCs - Reference 11.
CO_2 - Reference 12.

Technology Tracking Results

The results for annual and cumulative energy savings, as well as cumulative pollutant emission reductions for many actively tracked technologies, are shown in Table 2[1].

Table 2. OIT Selected Technology Program Impacts, 1995

Technologies Commercially Available	Cumulative Energy Savings (10^{12} Btu)	Annual Energy Savings (10^{12} Btu)	Cumulative Pollution Reductions (10^3 Tons)				
			Particulates	VOCs	SO_x	NO_x	CO_2
Arc Furnace Post-Combustion Lance	0.54	0.31	0.108	0.001	0.392	0.149	36.180
Biomass Grain Dryer	1.35	0.05	0.136	0.003	0.489	0.233	83.363
Catalytic Distillation	9.07	0.68	0.014	0.027	0.000	0.635	512.455
Cement Particle-Size Classifier	12.98	1.96	2.596	0.026	9.411	3.570	869.660
Chemical Separation by Fluid Extraction	0.01	0.00	0.000	0.000	0.000	0.000	0.000
Cogeneration - Coal-Fired Steam Turbine	234.92	31.42	84.571	0.587	293.650	111.587	24431.680
Computer-Controlled Oven	27.75	0.20	0.042	0.083	0.000	1.943	1567.875
Dual Cure Coatings	0.00	0.00	0.000	0.000	0.000	0.000	0.000
Electric Tundish	0.04	0.02	0.000	0.000	0.001	0.003	2.577
Energy-Efficient Canning	2.91	0.16	0.004	0.009	0.000	0.204	164.415
Exo-Melt Process	0.00	0.00	0.000	0.000	0.000	0.000	0.000
Forty Percent (40%) Recycled Paper	0.00	0.0	0.000	0.000	0.000	0.000	0.000
Glass Feedstock Purification - Optical Sorting	0.05	0.02	0.000	0.000	0.001	0.004	3.221
High-Efficiency Weld Unit	20.67	4.69	4.134	0.041	14.986	5.684	1384.890
Hydrochloric Acid Recovery System	0.10	0.05	0.000	0.000	0.006	0.007	7.563
Hyperfiltration - Food	5.39	1.10	1.078	0.011	3.908	1.482	361.130
Hyperfiltration - Textiles	0.92	0.00	0.331	0.002	1.150	0.437	95.680
Industrial Analysis Center Audits	83.46	8.93	5.687	0.165	22.171	11.430	5618.527
Improved Diesel Engines	238.43	72.15	1.192	0.238	19.074	16.690	19193.615
Irrigation Systems	48.60	0.65	3.312	0.096	12.911	6.656	3271.752
Membrane System for Purified Gas Production	0.00	0.00	0.000	0.000	0.000	0.000	0.000
Methanol Recovery Process	0.10	0.04	0.000	0.000	0.000	0.007	5.650
Nickel Aluminide Components For High Temperature Applications	0.00	0.00	0.000	0.000	0.000	0.000	0.000
Nitrogen-Methanol Carburization	11.77	0.54	0.018	0.035	0.000	0.824	665.005
No-Clean Soldering Process	0.02	0.00	0.004	0.000	0.015	0.006	1.340
On-Site Aluminum Recycling	0.04	0.02	0.006	0.000	0.023	0.009	2.815
Oxy-Fuel Firing	1.94	0.65	0.003	0.006	0.000	0.136	109.610
Particle Size Distribution Sensor	0.00	0.00	0.000	0.000	0.000	0.000	0.000
Pattern Coating Consistency	0.00	0.00	0.000	0.000	0.000	0.000	0.000
Pinch Analysis and Industrial Heat Pumps	0.39	0.09	0.039	0.001	0.141	0.067	24.083
Plating Waste Concentrator	2.60	0.57	0.008	0.005	0.104	0.182	178.100
Precision Pattern Production - Air Gauge	0.00	0.00	0.000	0.000	0.000	0.000	0.000
Real-Time Neural Network for Combustion	1.00	1.00	0.002	0.003	0.020	0.070	62.500
Recuperators (GTE)	24.11	0.00	0.078	0.048	0.964	1.688	1651.535
Reverse Brayton Cycle Solvent Recovery	1.42	0.37	0.005	0.003	0.057	0.099	97.270
Reversible Chemical Association Separation	0.00	0.00	0.000	0.000	0.000	0.000	0.000
Slot Forge Furnace/Recuperator	13.25	0.29	0.043	0.027	0.530	0.928	907.625
Solar Process Heat	0.05	0.01	0.000	0.000	0.000	0.004	2.825
Solvent Recovery from Effluent Streams	5.40	4.50	0.027	0.005	0.432	0.378	434.700
Supercritical CO^2 Cleaning	0.15	0.15	0.000	0.000	0.000	0.000	0.000
Ultrasonic Tank Cleaning	0.02	0.02	0.000	0.000	0.001	0.001	1.370
Waste Energy Recovery Systems	27.14	4.40	0.136	0.027	2.171	1.900	2184.770
TOTAL	776.59	135.04	103.576	1.452	382.607	167.009	63933.780
Technologies No Longer Commercially Available	109.82	N/A	0.247	0.275	2.844	7.857	6733.93
GRAND TOTAL	886.41	135.04	103.823	1.727	385.451	174.866	70667.710

Program Benefit/Cost Analysis

The Cumulative Production Cost Savings Minus Cumulative Appropriations curve of Figure 1 provides an estimate of the direct net economic benefit of the OIT program since its inception. The method used to compute net economic benefits is based on several factors:

- Cumulative energy savings - the accumulated energy savings (Btu) produced by OIT-supported technologies that have been commercialized and tracked since the program began. As of FY 1995, this figure was 886 trillion Btu.

- OIT appropriations - the total cumulative budget dollars expended by OIT for all purposes since the program began. As of FY 1995, this number was $1,229,154,000.

- Weighted average cost of industrial energy - the average fuel price (dollars/Btu) that would have been paid to purchase energy, usually an average of industrial energy prices over the last 10 to 20 years, weighted by the mix of industrial fuels saved by OIT commercialized and tracked technologies. For 1995, the weighted average cost of industry energy was about $3.50 per million Btu.

- Levelized cost of industrial energy efficiency - the average "efficiency" fuel price (dollars/Btu) that was paid based on a 1988 study of 43 OIT-supported technologies[10] . Estimation of this factor takes into account differences between the OIT technologies and the technologies they replace.

  For each technology, differences in annualized capital costs, operating and maintenance costs, and non-energy production costs are summed and then divided by the annual energy savings to yield a net "price" per million Btu of energy benefits. This net levelized cost for each technology is then multiplied by the cumulative energy savings for that technology to yield cost savings per year. The sum of these cost savings for all 43 technologies, divided by the cumulative energy savings for all 43 technologies, then provides the final levelized cost of industrial energy efficiency, which is $0.71 per million Btu.

  This analysis necessarily omits details such as annual cash flows, tax effects, and risks assumed by early adopters. To increase confidence in the cost estimates to over 90%, given the variability in estimates, and ensure that cost savings are conservative, the cost-benefit analysis doubles the levelized cost to $1.42 per million Btu.

- Average energy cost savings rate - the difference between the weighted average cost of industrial energy and the levelized cost of industrial energy efficiency. Thus, for 1995, the average energy cost savings rate was $3.50 minus $1.42 per million Btu, or $2.08 per million Btu.

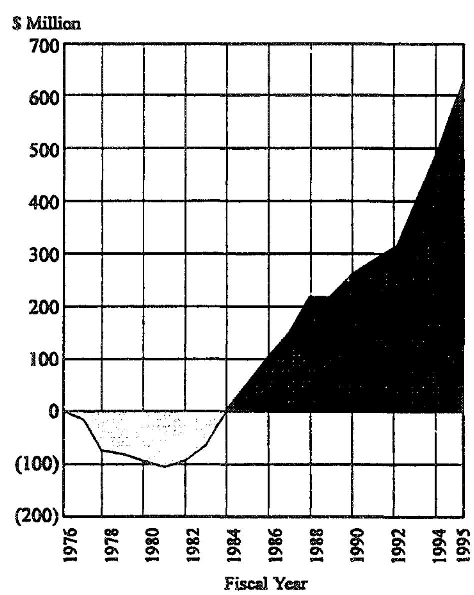
To develop the Program Benefit/Cost curve shown in Figure 1, the cumulative production cost savings minus appropriations must be calculated beginning in 1976. Cumulative production cost savings are calculated by multiplying the cumulative energy savings times the average energy cost savings rate. The net economic benefit is then the difference between cumulative production cost savings and cumulative OIT appropriations, or:

Cumulative Production Cost Savings
- Cumulative OIT Appropriations

= Net Economic Benefit

For 1995, this calculation yielded a net economic benefit of more than $600 million, as follows:

Figure 1:
Program Benefit - Cost Curve



($2.08 per million Btu) x (886 trillion Btu)
- $1,229,154,000

= $614,578,800

The net economic benefit was then plotted on a graph as a function of the fiscal year from FY 1976 to the present, as in Figure 1[1].

SPECIAL STUDIES

OIT augments the system of annually-updated quantitative impact analyses described in the above with other retrospective studies performed for special purposes. These studies are designed to enrich understanding of the impacts of individual OIT-supported technologies as well as to improve knowledge of industrial technology diffusion processes. Two such studies were addressed to (1) "secondary impacts" and (2) "ripple effects" of OIT technologies. Summary discussions follow.

Secondary Impacts of OIT-Supported Technologies

Secondary, indirect impacts of technologies developed with OIT support have been analyzed from time to time during the past 15 years[5,6,7,8,9]. Each such study has addressed social effects of the technologies secondary to their direct energy and pollution reduction results. The studies indicate very positive, nearly universal interconnections between the energy, economic, and environmental benefits of a broad range of energy-efficient technologies.

The most recent such study examined secondary impacts of 20 completed OIT technologies commercialized during the period 1982 - 1992. Because all of the selected technologies were included in the annually-updated impact tracking system, data on the number of units in operation, annual energy savings, and annual pollutant reductions were available. The study objective was to gather additional information on economic impacts and impacts on resources. Economic impacts included effects on productivity, product quality, employment, capital productivity, and pollution control and abatement costs. Impacts on resources included effects on waste reduction/conversion/utilization, use of raw materials and feedstocks, fuel flexibility, and land and water use. Sources for the secondary impacts data included the industrial developers and end-users of the technologies, topical reports, technical articles, and DOE or national laboratory staff associated with the related R&D.

Employment effects and capital productivity effects of the introduction of the technologies were estimated using an economic input-output technique. The basic principles underlying the methodology are the same for both effects. First, net changes in the economy occurring as a result of implementing and using OIT-developed technologies were defined for individual industries, and the dollar value of those changes were determined for each technology in each year. Input-output analysis of these changes produced final dollar outputs for each industry in the United States. Employment-output ratios and capital-output ratios were then applied to determine industry impacts, which were summed over the economy to obtain national impacts.

Total employment effects resulting from the adoption and use of the technologies in 1992 were made of three components -- one for the change in employment resulting from the installation of new units, one for the change in employment resulting from the operation of existing units, and one resulting from the reinvestment of freed capital attributable to the use of the new technology. The third component reflects the reinvestment of capital made available through adoption of efficient, energy-saving technologies. One factor complicating interpretation of the employment impact is that the employment effects of any new technology vary over time during the period of the technology's penetration into the market.

The employment and capital effects found in this study for individual OIT-funded technologies generally corroborate the work of many investigations which have suggested that energy efficient production technology innovations benefit industry and society beyond just their energy savings and pollution reductions. In particular, the profitable implementation of these technologies improves productivity and thus stimulates the economy, which in turn creates new employment opportunities. Of lesser economic importance, but another positive result, is that the substitution of highly engineered technologies for energy in production creates demand in relatively labor-intensive technology industries while suppressing demand in the extremely capital-intensive energy sector.

A technology example from this study is the Catalytic Reactor distillation process. Distillation is one of the most energy-intensive industrial processes, accounting for over 40 percent of the energy consumed by the chemical processing industries every year. A new single-stage, catalytic reaction/distillation process was developed with OIT support. The new process was developed in conjunction with Chemical Research and Licensing Corporation for the production of hydrocarbons such as methyl tertiary butyl ether (MTBE) and tertiary amyl methyl ether (TAME), both commonly used gasoline additives.

The Catalytic Reactor saves energy by utilizing the heat released by the equilibrium reaction to drive the distillation process, eliminating the need for a separate energy input. In the conventional multi-stage distillation process, MTBE or TAME are produced by reacting methanol with isobutylene or isoamylene over a catalyst; product yields are limited to about 97 percent and 70 percent, respectively. The Catalytic Reactor increases yields to 99 percent for isobutylene and 95 percent for isoamylene by simultaneously catalyzing the reaction and removing the reaction products. When compared with the conventional process, single-stage catalytic distillation is more energy efficient, provides better product yields, and requires a lower capital investment.

The Catalytic Reactor saved 0.55 trillion Btu in 1992, while resulting in the following emission reductions: NO_x, 39 tons; CO_2, 31,070 tons; VOCs, 2 tons, and particulates, 1 ton. The 1992 study of secondary impacts found that the single-stage process coupled with higher product yields increased productivity, reducing unit production costs. The elimination of multi-stage processing was also found to reduce maintenance time and costs. The higher product yield achieved with catalytic distillation was found to increase product purity by 25 percent for isoamylene conversion to TAME.

Pollution abatement costs were also found to be reduced by the new process. The report stated that catalytic reactor will help refiners to more cost-effectively reconfigure plants to meet gasoline oxygenate requirements of the Clean Air Act Amendment of 1990. Most refiners now prefer ethers rather than alcohols to meet these requirements. TAME production also removes atmospherically reactive isoamylenes from the gasoline pool. Because the new technology produces higher yields than conventional distillation, its use reduces the amount of hydrocarbon feedstock materials required for these products. Input-output economic results showed that in 1992 the catalytic reactor technology resulted in increased employment by 167 man-years[2].

Market penetration of the catalytic reactor has continued since 1992, with more than 52 units currently in operation worldwide, 27 of them in the United States. Cumulative energy savings have exceeded 9 trillion Btu[1]. Qualitative topics covered in the secondary impacts study, including impacts on product quality, waste utilization, and natural resources, have been added to the annually updated impact analysis system.

Technology Case Histories -- "Ripple Effects" of Innovation

In the following are presented the results of a preliminary investigation of the "Ripple Effects" of five completed R&D projects supported by the Office of Industrial Technologies. The purpose was to provide an account, from limited contacts with manufacturers' officials and other knowledgeable individuals, of how each technology came to its present extent of commercial use. The discussions focus on the connections between the intent of the original R&D projects, subsequent technological developments, regulatory actions, unexpected market opportunities, and competitive forces in shaping the commercial fate of these advanced technologies. Three technologies are selected to illustrate the results of this study.

The findings of this study of ripple effects include:

(1) the original market intent of R&D projects, used in assessing the potential of the technology at the time, may not be realized but is sometimes eclipsed by unexpected market applications, often more directly involved in production,

(2) completion of an R&D project in many cases does not really *complete* a technology but rather begins a wave of competition-driven technological innovation and improvements that may continue for many years, and

(3) the quantitative efforts to date aimed at tracking the numbers of OIT technology units in use and their estimated energy savings may only scratch the surface of richer, more compelling stories of technology revolution ignited by public investments in industrial energy efficiency R&D.[3]

Ripple Effects: Inverter Welding Power Supply

In the late 1970s a start-up company, Cyclomatics Industries, now called PowCon, developed an Inverter Welding Power Supply (IWPS) with support from the Department of Energy's Office of Industrial Technologies. The company has successfully built a substantial business since its beginnings in the late 1970s in designing, manufacturing, and marketing IWPS systems and related welding equipment, recently employing approximately 100 people. PowCon is considered a technology leader within the welding equipment industry.

The advantages of IWPS technology are high efficiency, dramatically improved power factor control, light weight, and improved welding control. The earliest interest in this type of equipment was in ships and ship yards due to its small size, portability, low quantities of heat release, and good weld control. After PowCon began to develop other U.S. markets for IWPS in the 1980s, all major welding equipment manufacturers introduced similar inverter-based power supplies. This technological breakthrough reduces the size and weight of welding power supplies by up to 75% while providing energy savings of as much as 45% over conventional power supplies. The technology can be used in virtually all arc welding processes and in plasma cutting applications.

Market penetration has been rapid in some industrial welding applications, with reliability questions and a cost premium cited as factors limiting more rapid and wide market acceptance. Other limitations on the rate of sales of this type of equipment are the long useful lifetime of the existing inventory of welding equipment, the large number of small plants where welding operations are performed, and the large number of small firms assembling and selling welding equipment. Never-the-less, inverter power supply technology is considered the best engineering option for nearly all welding applications (the exception being straight resistance welding), and adoption of the technology will likely continue. Nationwide, by the end of 1995 high-efficiency weld units saved an estimated total of 20.7 trillion Btu, equivalent to 3.5 million barrels of oil. Estimated annual savings in 1995 were 4.7 trillion Btu.

In the inverter welding power source, AC input is converted to DC by a full-wave rectifier. Using a high-speed electronic switch, the DC voltage is converted to a high-frequency AC output. This output is rectified and filtered to produce a smooth, low-ripple DC welding output. The high-speed electronic switch improves arc initiation, increases control over the output power, and responds faster to changing weld conditions. Each unit can produce a multitude of arc characteristics for different weld processes.

IWPS systems have given a boost to the development of robotic welding systems, which benefit greatly from the high degree of weld control, reduced spattering, and the 100% duty cycle operation afforded by these power supply systems. Additionally, several manufacturers have incorporated artificial intelligence features into inverter-based welding power supplies.

Improvements have become possible in IWPS technology due to the availability of high frequency power switching devices like MOSFETs and IGBTs. The average efficiency of IWPS systems now is approximately 85% as compared to 75% when the first PowCon systems were sold. Design experience has also contributed to improvements in equipment reliability, which should lead to an increased rate of market penetration in the near future, according to an industry source.

While welding equipment industries in many nations are producing IWPS technology, notably Japanese manufacturers, U.S. exports of welding equipment have been growing over the past decade. Between 1989 and 1994, welding equipment imports to the United States dropped by 5% while exports increased by 35%, according to Department of Commerce data. Current world technology leadership in this area appears to reside in the United States.

PowCon's development project with DOE has not been solely responsible for this technology revolution, which has a parallel in electric motor drive controllers based on similar power inverter technology. It is difficult to assign a particular level of cause and effect, but PowCon is widely recognized as a pioneer of inverter technology in the

United States and remains an important technology leader; at the time the DOE contract was awarded, PowCon was virtually a start-up operation. At the least, DOE's project played a seminal role at the beginning of a revolutionary change in welding technology that has already had important effects on productivity, weld quality, use of robotics, and U.S. exports, and will continue to impact world industry for many years to come.[3]

Ripple Effects: Oxy-Fuel Firing

In 1991 Praxair, Incorporated (formerly the Linde Division of Union Carbide) introduced Vacuum Pressure Swing Adsorption (VPSA), a novel point-of-use oxygen supply process that made the use of 90-95% purity oxygen more economical and convenient. VPSA immediately began to be adopted in the fiberglass and container glass industries to supply oxygen for oxy-fuel combustion in glass melters, dramatically improving their energy efficiency, reducing NOx emissions, improving product quality, and reducing production costs. The development of this technology touched off a continuing technological race among several competitors to supply oxygen for the world's glass manufacturing industry, which had previously used only low oxygen-enrichment levels for limited applications.

In the burning of a fossil fuel, heat is generated when oxygen in the combustion air chemically combines with hydrogen and carbon in the fuel to form water and carbon dioxide. The nitrogen in the combustion air, on the other hand, is chemically inert; it dilutes the reactive oxygen and carries away some of the energy in the hot combustion exhaust gas. Fuel efficiency can be improved by using pure oxygen or air from which some of the nitrogen has been removed. Known as oxy-fuel firing, the use of high levels of oxygen concentration for combustion significantly reduces energy requirements.

In the 1980s, Praxair had developed a family of advanced oxy-fuel burners intended to enable efficient, low-NOx, 100% oxygen combustion systems to be used in steel reheat furnaces. This was a significant technical achievement because conventional burners could not use high oxygen enrichment levels without melting; the new oxy-fuel burners also reduced NOx levels by reducing combustion temperatures. When business and economic conditions changed, temporarily eliminating the steel market from consideration, Praxair turned to glass melters.

The remaining issue connected with using oxy-fuel combustion in the glass industry was the availability of economical oxygen supplies at the oxygen demand levels appropriate for glass melters. Many glass furnaces were too small to support a dedicated cryogenic oxygen plant, and merchant liquid gas supply had proven too costly. The firm undertook an R&D program co-funded by DOE's Office of Industrial Technologies to develop a point-of-use, 90-95% oxygen-supply process targeted to glass melters and designed to be more economical than conventional liquid oxygen supply. The new VPSA air separation system is based upon a highly selective molecular sieve material that allows oxygen to pass through, while adsorbing nitrogen from ambient air. As the air passes through one of two adsorbent beds, nitrogen is adsorbed by the synthetic zeolite sieve material and the enriched oxygen passes through for use. While one bed is adsorbing the nitrogen, the other is purging it; periodically the pressure swings and the beds reverse functions.

When Praxair introduced its point-of-use oxygen supply system commercially in 1991, it initiated a trend within the container glass and fiberglass segments of the U.S. glass industry. Today, when glass melters are rebuilt, many are being converted to oxy-fuel firing to reduce energy use and reduce nitrogen oxide emissions. According to a company representative, the VPSA system is only one of several point-of-use oxygen-generating systems now available, though Praxair still dominates the market and VPSA continues to be the most energy-efficient option. Competing processes, also based on proprietary molecular sieves, include Liquid Air's Vacuum Swing Adsorption process and improved versions of the older Pressure Swing Adsorption technology. Additionally, smaller cryogenic oxygen production plants have recently been developed and commercialized, but are most competitive at larger scales than the adsorbent-type air separation systems.

The impact of the VPSA system in driving a transition to oxy-fuel combustion in glass industry markets has been due not only to the bottom-line cost advantage over alternative methods of supply, but also to the relative simplicity of point-of-use oxygen supply equipment. Average energy savings for glass furnaces vary from up to 45% on a small furnace to 15% on large furnaces. NOx emissions are reduced by up to 90%, carbon monoxide by up to 96%, and particulates by up to 30%. Under certain circumstances, glass furnace production rates can improve by up to 25% in comparison with unenriched combustion air, while defects in glass products are reduced. It is estimated that at the end of 1995 some 85 VPSA units were operating in the glass industry, saving a total of 0.65 trillion Btu per year.

The VPSA system has undergone many improvements in the last five years, principally in the performance of the molecular sieve that lies at the heart of the technology. These continuing improvements, as well as better engineering designs evolved through production experience, have raised energy efficiency and reduced the cost of delivered oxygen by perhaps as much as 50 percent. According to a company representative, Praxair and its competitors are engaged in a continuing technological race for a substantial and growing market for point-of-use oxygen supply systems in the glass and other industries. As oxygen supply systems become more energy and cost efficient, additional oxy-fuel combustion applications will become economically viable with attendant national energy savings.

In glassmaking plants, opportunities for conversion to oxy-fuel firing normally occur only when a melter is rebuilt after a campaign varying in duration from about 3-4 years for a dirty fiberglass application to 7-10 years for container glass applications. At present, about 15 percent of the U.S. container glass and fiberglass industry segments are using oxy-fuel firing. In these markets, VPSA is the low-cost choice up to the 120 TPD oxygen range. Beyond this, the most cost-effective option is decided on a case-by-case basis; at 200 TPD and higher (the operational level for many float glass plants), recently commercialized small cryogenic plants are usually the best option. Though only five or six years have passed since commercial introduction of the VPSA system, the trend to convert glass melters to oxy-fuel combustion appears well established, and will continue and expand to other industry segments in future.

While the DOE/Praxair cost-shared R&D program was focused on the glass melter application of oxy-fuel firing, today the glass industry represents less than 50 percent of the market for Praxair's VPSA system. The success of this technology in glass furnaces has allowed Praxair to return to the steel industry -- this time to supply oxygen to electric minimills for injection into the electric arc furnace via oxygen lances. Praxair has already installed or contracted for 27 VPSA systems in electric minimills in the United States and other countries, while competitors have installed similar systems in an additional three U.S. mills. In these applications VPSA has displaced the use of merchant liquid oxygen supply systems.

Thanks in part to the steel minimills' experience with VPSA for oxygen lancing, oxy-fuel firing will possibly be used in minimill reheat furnaces in the near future. When VPSA oxygen supply is used at a typical minimill already using VPSA for oxygen lancing the electric arc furnace, the necessary capacity would approximately double from, say, 100 TPD oxygen to 200 TPD. Praxair is presently engaged in a Department of Energy co-funded project (NICE[3]) with Bethlehem Steel and North American Manufacturing to demonstrate a proprietary system for oxy-fuel firing in a batch steel reheat furnace at an integrated steel plant. A privately-funded Praxair demonstration project is testing oxy-fuel firing in an aluminum melter, as well. Market acceptance of energy-efficient oxy-fuel combustion technology in reheat furnaces awaits successful completion of these tests, and of course is also dependent upon fuel prices and environmental regulations. The commercial success of the VPSA system, while not itself driving oxy-fuel combustion in the metals industries, has encouraged smaller facilities to adopt oxy-fuel combustion schemes and, more generally, has initiated a series of technical developments and competition-driven market changes which have lowered the cost of delivered oxygen in a variety of energy-efficient industrial applications.[3]

Ripple Effects: Solvent Recovery From Effluent Streams

In 1990 Membrane Technology Research, Inc. commercialized its VaporSep technology in a variety of applications recovering low concentrations of organic vapors from industrial effluent air streams. More than 30 units have been installed so far in waste recovery applications to recover vinyl chloride from PVC manufacturing plants, refrigerants used in chillers, CFCs and ethylene oxide from sterilizers, and VOCs from petrochemical and pharmaceutical processes. More recently, the VaporSep process has been adapted in much larger installations for the recovery of monomers and other hydrocarbons from nitrogen purge gas generated in the production of polyolefin resin and other polymers. Just one of these in-process units saves about as much energy as all of the smaller end-of-pipe clean-up units installed to date. The outlook for the VaporSep process is now even more positive than before; the technology has made an important jump into much larger-scale, productivity-enhancing applications with greater profitability potential for its developers.

Many industrial processes exhaust waste air streams containing low concentrations of organic solvents such as Freons and other halogenated hydrocarbons, naphthas, ketones, toluenes, and esters. Strict environmental regulations now require industry to clean up these air streams so final plant discharges are essentially solvent-free. However, conventional compression-condensation and carbon adsorption recovery methods or incineration are often neither economical nor energy efficient for low levels of solvent concentration.

In a 1982-1987 project funded by the DOE's Office of Industrial Technologies, MTR developed the technology necessary to produce high-quality multi-layer composite membranes for use in membrane separation systems applicable to industrial effluent streams. The system efficiently and effectively separates the effluent stream and is generally able to remove 80-100% of the organic solvent content from the feed stream. The solvents are then easily removed from the permeate through cooling and condensation. Compared to alternatives for treating a range of lower concentration level effluents, the membrane separation approach offers far higher recovery rates than compression-condensation, is more energy efficient and productive than incineration, and does not create secondary waste streams like carbon adsorption.

More recently, a new market has emerged for much larger installations designed to recover monomers and other hydrocarbons from nitrogen purge gas generated in the production of polyolefin resin and other polymers. Because both the recovered monomer and nitrogen are expensive commodities used in polymer production, their recovery within the process enhances productivity. The first such installation is paying back its $1 million-plus capital cost in just over a year, and additional large systems are on order. Energy savings from these systems will also be much larger. The first commercial applications of VaporSep technology, designed to save energy while addressing an important family of air pollution problems, have thus led to a more fundamental process improvement using the same process that will enhance productivity and competitiveness in an important, growing industry. Interest has been shown in the process by polymer manufacturers around the world, many of whom face rising costs for raw materials and the need to expand or debottleneck current operations in a supply-limited market.

Annual energy savings due to the VaporSep process were estimated at 4.5 trillion Btu in 1995, only five years after its commercial introduction. The energy savings impact is rapidly increasing as additional large monomer recovery units are put into service. Thus an R&D project originally intended to enable many industrial processes to comply with environmental effluent regulations while saving energy has resulted in a technology which has now found a still more important market in much larger capacity installations to recover valuable byproducts generated in the production of chemical polymers.

MTR has a strong patent position in this technology, but may lease the right to produce it in future. Each installation is a highly engineered system. The original system configuration has been altered substantially for some of the more recent installations, which have two stages instead of the original single stage.[3]

Ripple Effects: Other Technologies

The ripple effect study also addressed membrane technologies for (1) separating chemical components from industrial wastewater by hyperfiltration and (2) a hollow-fiber air membrane system to separate air into oxygen- and nitrogen-rich product streams. The hyperfiltration membrane technology was originally intended to enable textile manufacturers to meet wastewater discharge regulations, but, after the regulations were subsequently relaxed, the technology was successfully marketed instead as a family of productivity-enhancing, membrane-tube module systems for larger-scale applications in the food processing, pulp and paper, and petrochemical industries. These potentially more profitable applications are involved directly with production steps like clarification, filtration, and concentration, rather than with end-of-pipe wastewater clean-up. The second membrane system, originally designed to produce oxygen-enriched combustion air at 35 percent purity levels, has found a variety of other markets instead where its small size, portability, and simplicity are advantages over the conventional merchant liquid gas supply of bottled nitrogen or oxygen.

CONCLUSIONS

Annual tracking of the adoption of new industrial technologies that OIT has supported shows that there are significant amounts of energy, economic, and environmental savings. The net economic savings to the nation for 78 technologies documented to have commercial applications is over $600 million, i.e., the net production cost savings from use of the technologies minus total OIT spending for all purposes since the program's inception.

In several studies designed to explore some of the secondary impacts of technology introduction, it was found that many other benefits frequently accompany the energy savings and energy-related pollution reductions associated with OIT-supported technologies. Such benefits include improvements in labor and capital productivity, better product quality, higher employment in the economy, lower pollution control and abatement costs, and less non-energy resource use. Case histories of selected technology disseminations show that there may be whole families of innovations that can be traced to the introduction of a new technology. A new technology developed for one market may be applied in many other unexpected market areas, and a series of related innovations and improvements may continue for years to come. These "ripple" effects and spin offs are difficult to trace as there is rarely a clear linear path from old technologies to new ones.

Tracking the impact of government-supported technologies is complicated by the fact that technologies are usually cost-shared with industry and/or other partners, and that government projects may support technologies at different stages of development, making it difficult to determine how much of the benefits are attributable to the government funds. High technology industries often change quickly: ownership and personnel change over time, product lines change, and there is a tendency by some companies to adapt new technologies to establish proprietary positions in technologies to attain a competitive edge. All of these changes make it very subjective to track impacts of a new technology over a length of time. While a low-cost defensible methodology to quantitatively measure secondary and higher order effects may be elusive, technology benefits often can be cited qualitatively.

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