Impact of Three Industrial Technologies Developed by DOE

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EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) has been involved in research into industrial energy efficiency technologies for over two decades now. This report looks at three different technologies developed with the Office of Industrial Technologies' (OIT) sponsorship, including: how the technology evolved; how it was used in the marketplace; the significance to both manufacturers and end-users; and the role OIT played and continues to play. These technologies are intended to provide illustrative examples of the importance of government-sponsored industrial research and development (R&D).

More than half of the economic growth during the past quarter of a century has resulted from technology improvements. Studies have estimated returns to individual companies from R&D to be 20-30 percent, while returns to society as a whole are more than 50 percent (Eisenhauer 1996). Recently, commitment to R&D has diminished, with both federal and industrial R&D dollars declining. Many industries are closing their corporate research laboratories and focusing their efforts on more near-term activities. This is manifest in a shift from basic and applied research toward more commercialization. Since much government research is done cooperatively with industry, this decline in corporate research activities also reduces the effectiveness of government-funded research. In addition, government's R&D focus has been moving to more near-term activities as well.

A 1995 study by the Secretary of Energy Advisory Board identified more than 50 economically successful industrial technologies that DOE had played a role in developing. It is estimated that in 1995 these technologies resulted in savings of about 135 trillion British thermal units (Btu). Cumulative energy savings to date from these technologies are estimated to be approximately 0.9 quad (Moore 1997). Each technology has its own unique story and has developed in different ways. For this study, three diverse technologies with different target industries were selected for review: hyperfiltration; computer controlled ovens; and the catalytic reactor. They represent good examples of how OIT has played a facilitation role in developing industrial technologies. Two of these technologies have emerged to address important needs in industry, though not in the way initially anticipated by the research. The third addressed an important need that has more recently diminished in importance as a result of other technological innovations.

DOE has played a pivotal role in bringing all three technologies to the market. While its monetary contributions to each have been modest, its funding and support occurred at a critical point in the development of each technology. Additionally, DOE's participation conferred intangible benefits upon the projects, including visibility and access to demonstration facilities, which would likely not have otherwise been afforded to the technology developers.

None of the technologies evolved in the marketplace as was anticipated when DOE became involved more than 15 years ago. Rather than this being an indictment of the Department's lack of foresight, these examples confirm the importance and value of R&D in the face of uncertainty. In each of the cases described, events that could not have been foreseen affected the course of the technology. As a result, applied technology development efforts need to be flexible in order to respond to evolving market conditions.

These examples also demonstrate the value of working directly with the private sector on applied R&D. These companies had a clear incentive to identify market niches and see product used in manufacturing plants, as opposed to national laboratories and academia for which the research is frequently an end in itself. These stories also illustrate the importance of patience when dealing with R&D. It usually takes 10 years or more to discover whether the product of an R&D effort will have any market potential at all and additional time to assess whether it is a "winner."

INTRODUCTION

Purpose of Study

The U.S. Department of Energy (DOE) has been involved in research into industrial energy efficiency technologies for over two decades now. Over the years, a broad range of research and development (R&D) projects have been undertaken by the Office of Industrial Programs, now renamed the Office of Industrial Technologies (OIT) (OIT 1995). OIT estimates that in 1995 these technologies resulted in savings of about 135 trillion British thermal units (Btu) (Moore 1997). Much of OIT's R&D activities have been undertaken cooperatively with industry, with industry using the government resources to leverage their own (OIT 1995).

These numbers, however, tell only part of the story because energy savings represent only part of the total benefits. OIT's role as a facilitator of this R&D has allowed important technologies to be developed and commercialized, ready to meet needs that have emerged later in the marketplace. R&D, however, is not a sure thing, since future technology needs cannot always be anticipated. It is thus important to view R&D as a portfolio of activities, some which will fail to produce but others will yield handsome returns. This report looks at three different technologies developed with OIT's sponsorship, including: how the technology evolved; how it was used in the marketplace; the significance to both manufacturers and end-users; and the role OIT played and continues to play. These technologies are intended to provide illustrative examples of the importance of government-sponsored industrial R&D.

Context—the Role of R&D

Research and development is the process by which new ideas are developed and transformed into commercial products and services. It is this innovation process that fuels U.S. economic growth and has allowed industry to achieve the impressive energy efficiency and environmental emissions gains seen over the last quarter of a century (Steinmeyer 1996). The period since World War II saw a sustained commitment to R&D by both the private and public sector. Economic studies have concluded that innovation increased industrial output in the United States more than any other factor. More than half of the economic growth during this period has resulted from technology improvements. The studies have estimated returns to individual companies from R&D to be 20-30 percent, while returns to society as a whole are more than 50 percent (Eisenhauer 1996).

Research can be categorized as representing the stages from initial discovery and understanding, through the application of the knowledge to problem-solving and on to the development and deployment of commercial products and services. The National Science Foundation (NSB 1993) identifies three phases:

- *Basic research* has the goal of advancing scientific knowledge or understanding of a subject, without specifying immediate commercial applications.

- *Applied research* is aimed at gaining knowledge or understanding needed to address a specific need, with the goal of creating a commercial product or service.
- *Development* applies the results of research toward *the production of useful material, devices, systems, or methods*.

The Industrial Research Institute (IRI) adds a fourth category, *technical services*, which covers activities required to ensure that existing commercial products and services meet accepted standards, performance, and quality (Eisenhauer 1996).

From this categorization, it is clear that research is a continuum of activities, all phases of which must take place if innovation is to become applied in the marketplace. The results of research are seldom sure since they involve discovery. While an area may initially appear promising, as the technology evolves and markets change, the potential may not materialize. Conversely, technologies developed for one purpose may emerge as important in unforeseen applications. A broad range of activities at all stages of R&D is essential for both near- and long-term technology advancement.

Recently, the commitment to R&D has diminished, with both federal and industrial R&D dollars declining (see Figure 1). As part of corporate cost reductions, many industries are closing their corporate research laboratories and focusing their efforts on more near-term activities. This is manifest in a shift from basic and applied research toward more commercialization. In 1988, about 6 percent of corporate research budgets were directed at basic research and over 20 percent went to applied research. By 1995 these shares had fallen to about 2 and 16 percent respectively (Eisenhauer 1996). Since much of government research is done cooperatively with industry, this decline in corporate research activities also reduces the effectiveness of government- funded research as well. In addition, government's R&D focus has been moving toward more near-term activities as well.

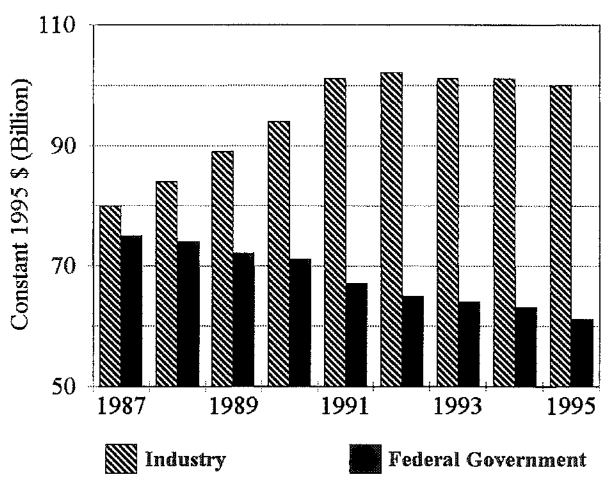

Figure 1. Recent R&D Expenditure Trends (Eisenhauer 1996).

Selected Technologies

Beginning in the mid-1980's, OIT began to track the development of technologies that emerged from OIT's sponsored R&D activities. A 1995 Study by the Secretary of Energy Advisory Board identified more than 50 economically successful industrial technologies that DOE had played a role in developing since the Department was established in 1977. The study indicated that in 1995 the Department's $1.1 billion cumulative investment had yielded about $2.5 billion in energy savings and capital savings, with the savings increasing from the past investments and from new units as they are sold. The office estimates that in 1995 these technologies resulted in savings of about 135 trillion Btu. Cumulative energy savings to date from these technologies are estimated to be approximately 0.9 quad (Moore 1997).

Each technology has its own unique story and has developed in different ways. As the two examples in the accompanying side bars demonstrate, the technology has led in some cases to a new product, while in others have changed the way products are made. For this study, three diverse technologies with different target industries were selected for review: hyperfiltration, computer controlled ovens, and the catalytic reactor. They represent good examples of how OIT has played a facilitation role in developing industrial technologies. As the following sections report, two of these technologies have emerged to address important needs in industry, though not in the way initially anticipated by the research. The third addressed an important need that has more recently diminished in importance as a result of other technology innovation.

Inverter Welding

In the late 1970s, OIT provided a grant to a private company, Cyclomatics, to develop an inverter welding technology. The technology offered potential for improving energy efficiency of welding units, reducing their size and weight, and improving weld quality. The grant provided the venture capital for Cyclomatics (now PowCon) to develop and introduce this technology to the market in the early 1980s. At about the same time a Swedish competitor, ESAB, introduced a similar unit. These two companies remained the exclusive providers of this technology until about 1991. At that time, the three major domestic welding equipment companies entered the marketplace. Lincoln Electric and Hobart introduced machines of their own design, while Miller Electric entered the market by acquiring PowCon.

The inverter power supply technology has evolved over the years due to advances in power electronics. The early units used SCR technology, while many current units use MOSFET technology. State-of-the-art units now use IGBT technology, which addresses some of the reliability and power quality problems associated with switching power supplies.

Inverter based welding now represents 20 percent of the domestic welding equipment market and is the fastest growing segment of the marketplace. The market has perceived the main advantage to these units as their increased portability over traditional transformer power supplies because of the smaller size, and with more recent designs, low noise and high power factor. PowCon's business is now solely focused on the marketing and further development of the inverter welding technology. Their sales have continued to increase, with 1996 sales approaching 8,000 units. OIT estimates that annual energy savings from this technology exceed 2 trillion Btu, with additional savings being realized from the reduced amount of copper required to construct the power supplies (Hughes and Moore 1994).

Source: Butter 1996.

Improved Diesel Engines

Beginning in the mid-1980s, Cummins Engine Company, the leading domestic manufacturer of diesel engines, established an ongoing collaborative relationship with DOE and the National Laboratories focusing on the design of engines. This work has been in two distinct areas: modeling and experimental combustion research.

As part of its national security mission, Los Alamos National Laboratory (LANL) developed the KEVA model, a multidimensional numerical reaction model. Cummins worked with LANL to integrate this computer model into their combustion chamber design process. The use of the model has shortened the design decision process and decreased the risk associated with making design changes. Cummins has now expanded the use of the KEVA model to all combustion chamber design work across the company, including both diesel engines (mobile, stationary, and marine), as well as their natural gas spark ignition engines. Roy Primas, a Cummins researcher described the impact as "the difference between having a slide rule and a computer on your desk."

While KEVA and similar commercial computer design tools are now used extensively throughout all industry, DOE and the lab's involvement accelerated Cummins's integration of computer combustion modeling into their design process. The improved modeling has allowed Cummins to improve the efficiency of engine designs while allowing for better control of nitrous-oxide and soot emissions. Annual energy savings resulting from these advanced designs exceed 50 trillion Btu (Hughes and Moore 1994).

Concurrent with the adoption of the KEVA model, Cummins began working with Sandia National Laboratory on combustion research. This research used advanced sensors developed at the laboratory in actual combustion chambers to validate the KEVA modeling work, and provided insights into the combustion phenomenon. Cummins had research staff onsite at the laboratory for three years, and has now funded a Ph.D. candidate to continue the research. The research has allowed Cummins to gain an understanding of the design factors leading to durability problems resulting from combustion products contaminating lubricants. As a result of this work, an engine design modification was introduced in 1991, significantly increasing engine durability.

Source: Primas 1996

Hyperfiltration

Introduction

Hyperfiltration, a membrane separation technique, was originally developed at Oak Ridge National Laboratory for use in desalination of sea and brackish water (Jernigan 1995). Beginning in the late 1970s, this technology underwent further development for use in industrial separation processes. Several government agencies, including the Environmental Protection Agency (EPA), the Department of the Interior (DOI), the Department of Energy (DOE), and the National

Aeronautics and Space Administration (NASA), contributed to the expansion of membrane applications. DOE's involvement began in 1978 with the first of two projects (Azimi, Pelagrino, and Margolis 1995).

The first project, begun in 1978, investigated the use of hyperfiltration for dye separation in the textile industry. Dying and other "wet processes" account for about two-thirds of the total energy used in textiles manufacturing, with dying being one of the most energy intensive operations. In traditional, once-through dying processes, heated wash water is continually discharged into the plant's waste stream. The energy loss to wastewater discharge accounts for about one-third of the thermal loss from the dying process (Badin and Lowitt 1988). Hyperfiltration can be used to separate the hot water from the dyes so that both can be reused. Reuse reduces water heating energy requirements, as well as chemical and waste disposal costs. Carre, Inc., with funding from DOE and technical assistance from Oak Ridge National Laboratory, developed appropriate membranes for the application. Subsequently, a test demonstration was conducted at a textile dying facility in South Carolina (Jernigan 1995).

In 1980, DOE began the second project sponsoring research into the application of hyperfiltration in food processing. The food processing industry is one of the major energy consuming industries in the country. Water removal from product streams is an important, as well as energy intensive step in the processing of many foods. The two most common alternative techniques, vaporization and freeze concentration, can have deleterious effects on the quality of the final product. Hyperfiltration, on the other hand, separates water from juices and other food products using less energy while still maintaining a high level of product quality. The project identified a class of membranes that could be used to replace evaporators and distillation equipment in food processing (Energetics 1984; OIP 1989).

Since the initial work, DOE has continued its involvement by coordinating demonstrations at different food processing plants, and by sponsoring investigations into additional applications of the membrane configurations developed by project research (Azimi, Pellagrino, and Margolis 1995). The membrane manufacturers, such as Graver Separations and Niro Atomizer, have also continued their R&D developing additional membranes and membrane configurations, allowing for a broader range of possible applications, including food and beverage processing, dairy products, biotechnology, pharmaceuticals, wine and brewing, waste water, pulp and paper, and others (Jernigan 1995; Keefe 1995).

History of the Technology

Membrane technology has long been used for the desalination of seawater. The membranes involved in this application were relatively simple, needing only to filter out salt and suspended solids. DOE's first membrane project investigated the possibility of applying hyperfiltration techniques to the textiles industry. Prior to the project, filtration was possible only for relatively large particles, in the micro- and ultra-filtration range. DOE's contractor on the project, Carre, Inc. (later acquired by Dupont Separation Systems and more recently acquired by Graver

Separations), developed a new membrane system which would separate hot water, dyes, and chemicals from waste streams, and pushed the technology into the ultra- and hyperfiltration range (Jernigan 1995).

Carre was formed, mainly of a group of Clemson University professors working on membrane systems, to develop and market a new hyperfiltration system that could withstand harsh operating conditions. The process involves applying pressure to a waste stream while it is in contact with the membrane. The pressure, coupled with the higher permeability of the membrane to water than to other components of the solution, drives the water out of the solution across the membrane. This process concentrates the dyes and chemicals, in the reverse of the dilution process of normal osmosis (from there the origin of the term reverse osmosis). Other membrane systems were available at the time, but Carre's design made a wider range of applications possible, such as in the textile industries (Jernigan 1995).

The project demonstrated the technology at a LaFrance textile dying facility in South Carolina. The closed-cycle demonstration began in 1981 on a production dye-range system that dyed, bleached, and scoured velour fabrics. Based on the pilot test data, the unit was designed to recycle 90 percent of the dye washwater at a process temperature of 185°F and remove 97 percent of the color from the water. The concentrated dyes and chemicals were reused in the dying operation. Over the course of the demonstration, more than one million yards of dyed fabric were washed using reclaimed water from the hyperfiltration unit. No adverse effects on fabric quality were observed, and in only one case was the recycled dye deemed unsuitable for reuse. Carre's analysis of the demonstration reported annual operating and maintenance (O&M) costs of $63,000 for the $484,000 system. Energy, water, and chemical savings were estimated at $275,000 per year (OIP 1983). Thus, even accounting for O&M costs, the simple payback of the project was only 2.3 years. Despite these promising results, it was concluded that the technology was not viable for the textile industry in the absence of strong environmental regulations relating to plant effluents. In additional, difficulty was encountered with cleaning the filters, and the operation of the demonstration unit was discontinued after 15 months of operation (Jernigan 1995).

Carre used the demonstration to identify the limitations of the technology in the textile industry. They went on to sell units to other textile plants in applications better suited to the use of hyperfiltration. The LaFrance site is the only one that is not currently in operation. Concurrently, Carre began to look for possible applications in other industries, and was able to sell enough units to remain in business until 1988, when the company was bought by Dupont Separation Systems. Under Dupont, development of the technology continued, and operations expanded. In 1994, Dupont Separation Systems was sold to Graver Separations, and the systems are currently being sold under the Graver name (Jernigan 1995).

In 1980, DOE began co-funding, with the National Food Processors Association (NFPA), a series of R&D projects to replace the energy-intensive evaporative concentration operations with membrane technologies in food processing. The projects involved both laboratory and field studies on thin-film composite membranes. Various existing candidate membranes developed by different companies were identified, and their performance tested on various food process streams in different configurations (Merlo 1995). A Carre system was initially considered because of its ability to operate at high temperatures, but was soon found to be unsuitable for the processes in question. The project eventually decided to use a tubular membrane developed by Patterson Candy International (PCI). This membrane was found to be suitable for a tomato processing application under consideration (Merlo 1995).

The hyperfiltration technology was installed in a production facility for the separation and recombination of tomato products at the Tri-Valley Growers' (TVG) tomato processing plant in Modesto, CA. Hyperfiltration was to be used in the concentration step of a new process for converting fresh tomato juice into tomato puree. While the process incorporated other new concepts, it was basically a new combination and application of existing technologies. Research efforts in this phase of the project also included storage studies, and comparison testing of whole juice versus serum (i.e., liquid left after filtering the juice) evaporation (OIP 1989).

The NFPA evaluated the economics of modifying other plants to accommodate the new system based on the performance of the tomato processing unit. NFPA estimated a simple payback for the investment to be 2.1 years. The estimate was based on an initial investment of $1.2 million; O&M costs of $0.2 million per year (including membrane replacement); and energy, containerization, and transportation cost savings of $1.04 million per year (OIP 1989). In addition to adding a membrane system, this particular application also included centrifuges, resulting in additional costs, as well as energy savings. Thus, all the cost and savings cannot be attributed to hyperfiltration. Nonetheless, the demonstration showed that hyperfiltration could be applied to applications in the food processing industry with favorable results.

Membrane systems were also incorporated into a trailer mounted Mobile Test Demonstration Unit with the necessary filtration equipment. The NFPA performed "open houses" at different food processing sites, inviting members of the industry to see the technology perform and learn about the possibilities of hyperfiltration technology in their facilities (Merlo 1995).

Both of these projects spawned further research into additional applications. Early membranes had typically been made from polymers, but continued development led to the introduction of ceramic and metallic membranes allowing a broader range of applications. Furthermore, the variety of membrane equipment available expanded, offering different membrane configurations including flat and tubular. Currently, in addition to the textile and agro-food industries, the technology is being used in pulp and paper processing, chemicals and bioprocessing, electronics manufacturing, hazardous waste concentration, sludge dewatering, and gas separation. According to Chris Merlo of the NFPA, the past 15 years of research performed on applications of membrane technology could not have gone forward without DOE's support of the initial project (Merlo 1995).

The food processing industry did not begin adopting membrane technology at a significant rate until 1990, when the NFPA launched another demonstration project. With the support of the Electric Power Research Institute (EPRI) and a number of individual utilities, the NFPA commissioned Del Monte to construct another mobile test demonstration unit (MDU) to take the latest membrane technologies to various sites throughout the country. The California Institute for Agricultural Research played a pivotal role in the development of the proposals that led to this demonstration project, and currently owns the trailer unit (Shoemaker 1995).

The project distributed surveys to food processors to determine where to carry out demonstrations. Based on the responses to the surveys, eight sites were chosen for the first phase of demonstrations. After the third demonstration, DOE approached the NFPA about the possibility of becoming involved in the project. The DOE request came through Pacific Northwest Laboratories (PNL) who had been tracking OIT developed technologies. DOE and PNL were interested in demonstrating some of the membrane technology they had worked on, as well as supporting ongoing work on further development (Shoemaker 1995).

The program has been quite successful. The MDU is currently equipped with 50-60 different membranes, and the modules can be arranged in a variety of combinations in order to best fit the needs of the particular plant. In general, the MDU spends approximately two months on site. The first portion of the time is used to test different membrane systems and combinations of systems. Then, once a system has been decided upon, a report is written, and in most cases an open house is held in which members of the industry are invited to observe the operation and learn more about the process. In this way the information becomes public (Shoemaker 1995).

To date, there have been seventeen such demonstrations at food processing, dairy, and wine facilities in eight states. These demonstrations have resulted in the installation of five membrane systems, with a number of additional facilities still considering the option. In addition, the demonstrations have encouraged others in the industry to consider installing their own membrane systems by providing solid evidence that the technology can work. The joint DOE/EPA NICE^3 program[1] has provided additional support for the demonstrations (Rohrer 1995; Shoemaker 1995). The research effort has also identified additional applications in other fields, such as the pulp and paper industry (Shoemaker 1995).

Energy Benefits

To understand how the hyperfiltration technology saves energy, it is useful to first examine the technology it replaces. In many cases, hyperfiltration is used in the separation or fractionation

1. DOE's National Industrial Competitiveness through Energy, Environment, and Economics (NICE^3) program provides cost-sharing grants to state and industrial partnerships that develop and demonstrate technologies that save energy, prevent pollution, and enhance industrial competitiveness (OIT 1996).

step of a process. Traditionally, this step is carried out using vaporization or freeze concentration. In vaporization, a mixture is heated to a temperature at which one component changes from a liquid to a vapor. The vapor is extracted and condensed, effectively separating the different constituents. In freeze concentration, heat is removed from a mixture until one component crystallizes and can be easily removed. Freeze concentration requires significantly less energy than vaporization, although the capital costs are similar (EPRI 1988). In some cases, such as the textile industry, it has not been economical to attempt to separate out parts of a waste stream using conventional technology, so the streams are simply treated and released.

Membrane technology separates mixtures based on differing physical properties of the components, such as particle size or concentration. The only energy required is to pump the liquid through the system. Pressures vary depending on the actual process in question, but in general, membrane systems consume only one-tenth the energy of evaporation processes (EPRI 1988).

Depending on the application, the use of hyperfiltration can offer indirect energy savings as well. In the food processing industry, for example, concentration of juices can lead to significant energy savings in other steps in the process due to the fact that concentrated foods require less packaging, and less energy for preservation and transportation. In the textile industry, hyperfiltration allows for recycling wastewater, which reduces the amount of energy required for water and wastewater treatment at a facility.

OIT has estimated direct energy savings from hyperfiltration units installed as part of their projects. Estimates are based on savings realized from the operation of eleven units in the food industry and seven units in the textiles industry as of 1996. DOE estimates cumulative energy savings of over 2.5 trillion Btu for those units in the food industry, and approximately 0.7 trillion Btu for the textile industry (Hughes and Moore 1994), for a total of over 3.3 trillion Btu. While this is an impressive figure in and of itself, it is important to realize that these figures reflect only the savings achieved by those units using the specific systems developed in the two projects supported by DOE. Applications of related membrane filtration systems in other industries or other processes were not included in the energy savings calculations.

Other Benefits to Manufacturers and End-Users

The benefits of membranes extends beyond just energy savings, and in many cases, the other benefits have motivated the installation of the systems. Membranes are used at the Sunkist Growers' San Joaquin, CA processing plant to remove bitterness from orange juice. This process is the result of ten years of research which has allowed Sunkist to sell juice in ways that it could not previously. The hollow-fiber polymer membrane system, installed in 1989, clarifies juice before passing it through a resin that absorbs the bitterness. Initially, the plant experienced some problems with the membranes bursting, but the membranes have now improved to the point that this is no longer a problem, and the life of the $1,500 membranes has been extended to two years, from one year with the initial membranes (Nelson 1996).

Dr. Sharon Shoemaker with the University of California at Davis reports that water and wastewater have become big concerns for the food processing industry, especially in California. During a recent drought in California, many firms started taking a serious look at hyperfiltration as a means of conserving water. Biological oxygen demand (BOD) has also become an important issue. As described in the sidebar on TirValley Growers, this problem has been a critical challenge for the olive industry. Other olive processing plants may go out of business if they can't address their discharge problems as TVG has (Shoemaker 1995). Duane Rohrer with TVG indicates that processing olives is an environmental problem wherever you go. Some other plants may be able to flush the wastewater into municipal systems, or directly into waterways, but many others will be forced to close unless they address this problem. Rohrer indicated that the application developed for TVG could easily be applied to wastewater problems at other types of plants processing products such as peaches or cherries (Rohrer 1995).

Sunkist Growers, in addition to their process applications, has installed a ceramic membrane system to treat their wash water waste stream. The membrane allows them to recover NaOH, which is used to clean the orange juice concentration equipment, and produce a waste water stream that can be discharged without further treatment. The membrane replaces a steam driven evaporation system that was used previously to recover the NaOH. John Ayers at the San Joaquin Plant reports that the system has exceeded expectations, and "is amazed at what is happening." The unit arrived skid mounted and then they "just hooked up the utilities" and it was running in two days. Niro Atomizer indicated that the longest running application is still functioning after seven years, so they are hoping for a ten-year or longer membrane life. The unit is fully automated and has had no unexpected O&M costs. The $264,800 system was initially expected to pay-back in one year, but the plant recovered all this cost through savings in the first six months. Ayers feels that membrane technology has contributed to making the process the most efficient he knows of, and has placed them in a very competitive position (Ayers 1996).

The technology has also created business opportunity for the manufacturers. Initially, the manufacture and sale of hyperfiltration systems for textile facilities comprised all of Carre's business. Once Dupont acquired Carre, however, it began seeking additional industrial processes that might benefit from the use of rugged hyperfiltration equipment. The nuclear industry was one such area. Dupont installed several million-dollar systems in nuclear facilities in the late eighties and early nineties. Although nuclear applications have dropped off, there is some indication that this may change (Jernigan 1995).

Another large market for the Dupont systems has been in the wet corn milling industry. This is an example of an application of hyperfiltration technology that resulted in a product improvement because the product did not have to be heated. As an example, when American Maze expanded their corn syrup production facility in Indiana, they applied a TiO_2 coated stainless steel membrane instead of a vacuum filter system using diatomaceous earth in a coarse filter. The diatomaceous earth had to be replaced regularly and disposed of, creating both material and disposal costs for the company. Roy Moulesong with American Maze reports the company has been very pleased with the membrane system, citing ease of maintenance versus

TRI-VALLEY GROWERS

TVG is a food processor located in Modesto, California. In the late 1980's, DOE and NFPA conducted a demonstration of separating tomato juice into pulp and concentrated serum though a process involving: separating the pulp from the serum in a centrifuge; freezing the pulp; and concentrating the serum by hyperfiltration. The products could then be reconstituted with water at the point of use to produce tomato puree. The goal of this process was to reduce the energy use and the costs associated with processing, storing, packaging and transporting the product. The demonstration validated the technical feasibility of the process. The analysis of the demonstration estimated a payback for the system of 2.1 years (OIP 1989). However, no commercial tomato juice processing systems have been installed in the United States because the price of steam has fallen from about $5 per thousand pounds of steam when the demonstration was conducted to around $1.50 per thousand pounds currently. However, six of these U.S.-made tomato juice membrane processing systems are currently operating in Europe. U.S. processors have indicated that they will begin installing the systems if steam prices increase (Pain 1995).

In 1992, TVG had the NFPA demonstration unit conduct a test of waste water treatment at their olive processing facility. TVG disposed of their waste water in clay lined ponds where it was allowed to evaporate. These ponds leaked, contaminating the ground water. Several years ago they switched over to plastic lined ponds, which did not address the problem completely. TVG was told by regulators that they had to find an alternative treatment method or shut down the plant. The test was motived as a way of addressing this pressing problem. It would have cost them $140,000 per acre to retrofit the more than 160 acres of ponds. Since hyperfiltration proved successful, TVG is installing a system for the treatment of wastewater in their olive processing plant in Modesto. They have also received a grant from the DOE/EPA NICE[3] program for the project. The system came online in mid-1996. The new system will allow TVG to reuse 80 percent of the wastewater flow. The other 20 percent, the solids, will be sold as animal feed. In addition, the system will allow TVG to expand plant capacity because they are no longer constrained by the amount of land needed for the drying ponds, and help reduce the use of chemicals due to changes in the pretreatment process. The land used for ponds will be sold as the ponds dry up. They anticipate a net energy savings out of the system, though this was not part of the motivation for installing the equipment (Rohrer 1995).

the previous system as a major factor. They encountered no startup or operating problems and the systems performed as promised (Moulesong 1996).

The popularity of membrane systems is rising, with several large ($3 million) units currently in operation. The current owner, Graver, continues to aggressively seek out new applications for the systems, and to date has sold 24 units. Capital costs of new systems are size and application dependent, and can range from $150,000 (10 gpm) to $3 million (850 gpm), with payback periods ranging from six months to two years (Wittwer 1994). The diversification of applications has helped to maintain the marketability of the systems over time, as the economic and regulatory environment has varied in different industries.

Other organizations, like Niro, entered the hyperfiltration business more recently as an expansion of their existing business. Niro added hyperfiltration to their existing international spray-drying business, which focused on dairy and other food processing applications, to expand their options to meet customers' needs. While it is unclear that DOE involvement directly impacted their business, the demonstrations did create a receptive market environment (Keefe 1995).

PCI, one of the NFPA contractors in the early stages of the project, has seen continued benefits from the early demonstrations. Although their involvement in the projects mentioned above has been minimal over the past ten years, they have continued to market and sell membrane systems on their own. At this stage, they are one of many membrane manufacturers and system designers that are filling the growing demand stimulated by work supported in part by DOE (Pain 1995).

The application of hyperfiltration systems in the United States has begun to attract interest abroad as well. Tomato processing plants in Italy currently use American-made hyperfiltration systems, which were offshoots of the work supported by DOE. In addition, Russia and India have shown interest in using some of the systems that have been demonstrated in the United States (Keefe 1995).

Conclusions

In essence, the two DOE-sponsored efforts, one originating in the textiles industry and one in the food processing industry, have resulted in a wide variety of end-use applications in many industries. In both cases, DOE's financial support has been instrumental in helping to ensure that the technology was developed and tested in real-world situations. These tests, many performed in cooperation with NFPA, coupled with the support of DOE and other organizations such as EPRI, have helped plant owners decide to install membrane systems where they might not have even considered them before.

While energy has been an important factor, in many cases the non-energy benefits, such as improved product quality, reduced materials requirements, and reductions in wastes disposal costs, have been the deciding factor in installing systems. In addition to these proven benefits, the increased use of hyperfiltration technology promises to provide additional benefits as well. One focus of the current work is in the reduction of BOD in waste streams. Indeed, the decision to install a system can be heavily influenced by its ability to help a facility meet effluent requirements. The systems can also save water, which can be particularly attractive in drought-prone areas such as California (Shoemaker 1995).

Membrane technology existed prior to DOE's involvement in the projects discussed herein, so the benefits associated with the end use of membrane technology cannot all be attributed to DOE. However, with the support of DOE, existing technology was upgraded to allow the filtration of increasingly finer particles and under a broader range of operating conditions. While private companies also carried out their own research in these areas concurrently, the demonstration of an unproven technology under real-world operating conditions provided the impetus for an increased rate of adoption. In this respect, DOE played a vital role in ensuring that the market was made aware of the benefits associated with membrane technologies so that it was profitable for the private companies and other non-governmental groups to develop the technology even further.

COMPUTER-CONTROLLED OVENS

Background

Solvent-based coatings have been used for a long time in a broad range of applications including automobiles, furniture, trucks, paper, fabric, metal coil, appliances, small metal parts, tapes, labels, and beverage cans. During drying, volatile organic compounds (VOC) are emitted as the solvents are evaporated. To accelerate the drying process many applications use curing ovens. VOCs are flushed out of these ovens by large volumes of air. The small concentrations of VOCs and the large volume of air make it difficult to control these emissions. In additional, VOC can pose an explosion risk if concentrations in the oven become too high. As a result, curing ovens were generally operated at ventilation rates far in excess of the rate required to cure the product in order to maintain the solvent concentration below its lower explosive limit (EPA 1984).

In 1980, OIT, the Environmental Protection Agency (EPA), and the Chemical Coaters' Association combined their resources to try to address this VOC emissions problem. A computer-controlled oven system was developed that used hydrocarbon (HC), temperature and pressure sensors, and a microcomputer controller to regulate the air flow. The microcomputer regulates the air flow rate, operates safety controls, monitors temperature throughout the oven, calculates the incinerator destruction efficiency, and allows the operator to vary the system as required (Hughes and Moore 1994).

Since initial development of the system, 15 units have been sold, including installations in which the computer controls were deemed unnecessary, and only HC sensors were installed (see Figure 2) (Hughes and Moore 1994). In general, sensors and controls have been installed as a means of meeting state or federal EPA requirements. The primary obstacle to further market penetration of the system is cost. A 1990 report estimated that there were approximately 565 curing ovens capable of using the technology. The report cited an industry expert as estimating that only 10

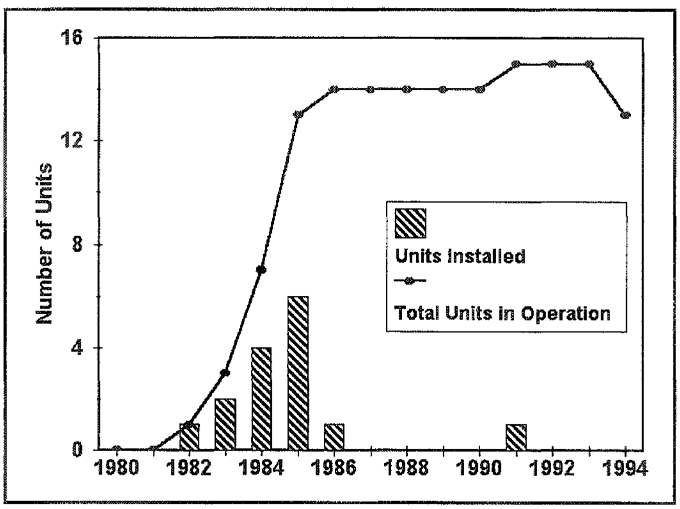

Figure 2. Installations of HC Sensors Systems on Curing Ovens (Moore 1996).

percent of the market will actually adopt the technology (Energetics 1990). This information is somewhat misleading, however, since many manufacturer now include computer controls without HC sensors into their ovens (Ryals 1995).

Another barrier to expanded use of the technology has been the advances in low-VOC, waterborne, and powder coatings in the late 1980s, which address the same emission and safety concerns at a lower capital cost (Ryals 1995). These developments in coatings were not foreseen at the time, as indicated by a 1984 EPA report which identified performance and cost of these coatings as major barriers. The drop in interest in computer-controlled ovens after 1985 corresponds with the introduction of these new coatings products and processes.

Development of the Technology

In 1980, OIT awarded a contract to CENTEC Corporation to demonstrate the feasibility of a microcomputer-based control system in a curing-oven application (OIP 1981). These activities took take place in the 1980-1982 period. The major tasks involved in the project were as follows:

- Survey typical plant sites and applications to collect data necessary for the system design,
- Select a typical plant to host testing in order to assure widespread applicability of the technology,
- Design and estimate costs of the system,
- Install and start-up the system,
- Monitor the energy consumption and long-term reliability of the system, and
- Document the results of the program and provide the necessary information for implementation of the technology by other plants in the coating industry.

This system was to regulate curing-oven ventilation by monitoring and controlling operating parameters, including solvent concentrations and vapor pressure. Under the contract, a demonstration prototype system was built and installed at the Mack Trucks Inc. assembly plant in Allentown, PA in 1981. The site was chosen because the operations of the plant were such that it allowed for testing under a wide variety of operating conditions. Although an ideal system would have included controls on all the ovens in a system, the prototype installed at Mack only included controls on the dip oven. This setup was chosen because solvent loadings in the dip oven were generally higher than those in the primer and color ovens. The unit continued to operate successfully until the facility was closed around 1990 (Hughes and Moore 1994).

The equipment installed consisted of temperature, pressure, and HC sensors, inlet and exhaust dampers, and condensate and fuel oil meters, in addition to the computer-related hardware, such as a central processing unit, monitor, keyboard, and printer. The combined capital and installation cost of the equipment was approximately $240,000 (Energetics 1981). The equipment performed the following primary functions: adjusts the ventilation air flow; performs safety functions in the event of microcomputer or analyzer failure; and performs basic computer functions such as providing displays of operating conditions, printing of reports, and keyboard control of the entire system.

Comparisons were made of air flow rates and fuel consumption in the ovens during two consecutive eleven-day periods, first without the controls, and then with them. Hourly fuel savings were found to be 1.53 million Btu/hr. At this rate, the plant expected $60,800 in annual energy savings. Had controls been used on the other two ovens in the system, it was estimated that annual savings would have risen to $125,500 (EPA 1984).

The demonstration at Mack Trucks showed that the system worked as expected and that it could indeed provide the energy savings that its developers claimed. The project also highlighted a number of issues that ended up playing a role in the subsequent rate of adoption of the technology. While the system of analyzers and controls did indeed produce energy savings, the energy savings from a single coating step in the process of manufacturing a truck were not significant in the context of total facility operating costs. As a result, CENTEC focused their marketing efforts on industrial customers, such as coil coaters, for whom energy costs were a significant portion of the total cost of production. In addition, the demonstration made clear that the computer controls are only necessary in applications where the solvent load changes on a regular basis. In processes where the solvent load remained relatively constant, all that was required were analyzers that could be used to determine the optimum flow rate, so that the dampers could be set accordingly (Ryals 1995).

In 1987, the rights to the system were sold to Analyzer Systems for the purpose of marketing and manufacturing. Analyzer Systems continues to supply and maintain such systems, although the oven manufacturers often incorporate the computer controls directly into the equipment themselves, rather than retrofitting them into existing ovens (Ryals 1995).

Energy Benefits

Prior to the introduction of the sensor and computer control systems, curing ovens were generally operated at ventilation rates far in excess of the rate required to cure the product and to maintain the solvent concentration below its lower explosive limit (LEL). Researchers recognized the potential for energy savings if the air flow rate could be reduced safely. In addition to decreasing the amount of fuel needed for heating the air, reducing airflow can decrease capital costs significantly, reduce fan power requirements, and reduce treatment cost because of the increased solvent concentration in the exhaust stream (EPA 1984).

Most facilities have based air flow rates in their ovens on safety codes that required the solvent concentration to be kept below 25 percent of LEL inside the oven or below 50 percent of the LEL when appropriate analyzers and safety systems are installed (EPA 1984). Air flow rates are designed to accommodate the maximum evaporation rate expected in the ovens. Since many plants operate much of the time at far below this maximum rate, they tend to operate at excessive ventilation levels, thereby increasing the amount of fuel required to heat the air.

Reduced air flow is the key to energy savings in the computer controlled oven system. Savings are achieved on a number of levels:

- Reduction in the amount of fuel needed to heat air in curing ovens,
- Reduction in the amount of fuel needed to operator incinerators (used to meet VOC emissions requirements), and
- Reduction in fan energy required for air movement.

The actual magnitude of energy savings of course depends on a number of process variables, but the main variables are baseline pumping rate, amount of excess air, and exhaust temperature. There can also be feedback effects if a heat recovery system is used on the incinerator. Higher solvent concentrations translate into a higher heating value for the air. The heat recovered from the incinerator can then be put back into the system, further reducing the amount of fuel needed for heating (EPA 1984).

OIT has estimated, based on plant reporting, that the 15 computer-controlled oven systems that they have tracked since 1982 have produced cumulative energy savings of approximately 22.31 trillion Btu (Hughes and Moore 1994). Since the technology is applicable to such a wide variety of processes, the level of plant energy savings cannot be generalized for all industries.

It must be remembered that potential savings are highly dependent upon actual operating conditions in individual plants. Since the technology is applicable to such a broad range of industries, potential energy savings must be considered on a case-by-case basis. However, it seems that the technology can achieve significant savings while at the same time offering less expensive emissions controls and automatic safety features (Ryals 1995). These estimates also do not capture energy benefits from new curing ovens that have integrated computer controls without HC sensors.

Other Benefits to Equipment Manufacturers and the Curing-Oven Operators

Expansion of the market is limited by a number of factors. Although the original application of this technology involved the use of computer controls and HC analyzers in curing ovens, it has since been found that controls are not necessary in many applications in which the solvent loading does not vary with time. In such applications, the same function can be performed with the HC analyzers alone. In the case of the steel curing industry, the curing is performed at such high temperatures that controls are unnecessary as well. A significant portion of coatings is now being done with water-based or powder coatings, neither of which entail the risks associated with solvent-based coatings and hence do not require controls. Furthermore, in many cases the maintenance of the HC sensors has proven to be prohibitively expensive (Welzel 1995).

Since most plants do not require the computer controls in order to achieve the benefits of the system, Analyzer Systems has focused primarily on supplying the instruments to industry. In its capacity as a supplier of HC analyzers, Analyzer Systems provides maintenance services on the system for a number of installations. In general, when computer controls are installed, they are installed directly by the curing-oven manufacturer. Although the analyzers are currently manufactured in Germany, Analyzer Systems is investigating manufacture of the instruments themselves (Ryals 1995).

There is reason to believe that these factors will not obviate the need for computer controls entirely. To begin with, aluminum, which is cured at a much lower temperature than steel, appears to be an area in which the use of computer controls will make economic sense. In addition, the focus has recently been placed upon identifying equipment coaters for whom coating is the majority of their business. For such customers, the economic benefits associated with energy savings are much more visible. Early maintenance problems encountered with the HC sensors have now been resolved with new designs, and the systems can now be operated without significant downtime and maintenance expense (Welzel 1995).

Curing-oven manufacturers, such as Hunter Engineering, have capitalized on the advances made in computer controls, and are looking to capture some of these markets as well. Although Hunter reports only three installations of computer controls used in conjunction with HC analyzers over the past 15 years, this figure must be viewed in the context of total oven sales. Hunter Engineering estimates that only four to six coating lines are installed in a year worldwide, and each of those coating lines might have two curing ovens. Most of these ovens have computer controls, that are now used to regulate exhaust airflow or LEL. Those manufacturers that have installed computer control systems have continued to operate and upgrade the system, and seem to be satisfied with their performance. So, while the market is not expanding rapidly, it does seem to be growing (Welzel 1995).

Conclusions and Future Prospects

DOE's funding was critical to moving the technology into the marketplace. One of the individuals involved with the original project, Tom Snyder (1995), indicates that without DOE's sponsorship, the technology would never have been commercially successful. The production of the system of computer controls and HC sensors represented a new industry. For the oven manufacturer, on the other hand, the technology created a new product to fill a niche market, one which did not exist before the development of the controls. In both cases, this has resulted in new business opportunities (Ryals 1995).

CATALYTIC REACTOR

Background

In 1978, Chemical Research and Licensing Corporation (CR&L) developed an innovative catalytic distillation (CD) unit for producing methyl-tertiary-butyl-ether (MTBE) that used the heat of reaction of the feedstock chemicals to drive the distillation process, avoiding separate energy input. MTBE was use at that time as an octane enhancer for gasoline and in the manufacturer of other chemical products. In 1980, CR&L and Neochem Corporation received funding from DOE to install and test the process for MTBE production at a Charter International Oil Company (Charter) refinery in Houston Texas, and to develop the process for production of other octane-improving compounds (Crossland 1995). Although the future importance of the market for such a process was unforeseen at the time, the Clean Air Act Amendments of 1990 created a need for these products.

In an attempt to reduce carbon monoxide and hydrocarbon emissions, the Clean Air Act Amendments of 1990 mandated the use of oxygenates in gasoline in non-attainment areas for those pollutants. The act has created a large market for gasoline additives such as MTBE and tertiary-amyl-methyl-ether (TAME), both of which satisfy the requirement. Japan, South Korea, and many European countries have enacted similar legislation, creating new markets for MTBE and TAME in those countries. In the face of such developments, U.S. oil refiners reexamined their production processes in an attempt to determine how they could be modified to meet the new demand for these products. At the time of the Act, production capacity of MTBE was limited by the supply of isobutylene and the yield from the conventional process. As a result, refiners were not in a position to meet the new demand (Rock 1992).

Two process innovations evolving from the DOE-sponsored work helped remedy the situation. First, a catalyst was developed that increased isobutylene output from fluid catalytic cracker (FCC) units by 50 percent (Rock et al. 1992). This development, combined with the increased yield from the CD MTBE process, allowed refiners to come closer to meeting the demand for isobutylene using the FCC byproducts rather than the more capital-intensive dehydrogenation of isobutane. The second innovation was the adaptation of the catalytic conversion process to produce TAME from isoamylenes. Not only is TAME also an acceptable oxygenate for gasoline blending, but it also removes one of the most reactive hydrocarbons (isoamylenes) from the gasoline pool. These two advances together have made it possible for refiners to meet demand for oxygenates in a cost-effective manner.

Development of the Technology

MTBE and TAME are ethers that have traditionally been made by reacting methanol with an iso-olefin, isobutylene or isoamylene respectively, over an acid resin catalyst. This ether production process is an exothermic, equilibrium reaction, which under normal conditions, cannot proceed to completion because a reversible reaction occurs as the system approaches equilibrium. As the reaction proceeds, the ether accumulates until equilibrium is achieved. Any additional rise in temperature will shift the reaction back to the starting components. This limits the amount of the ether which can be produced. This reversible reaction places a practical limit on conventional production yields of MTBE and TAME of about 95 percent and 70 percent, respectively (Rock, Smith, and Chen 1992).

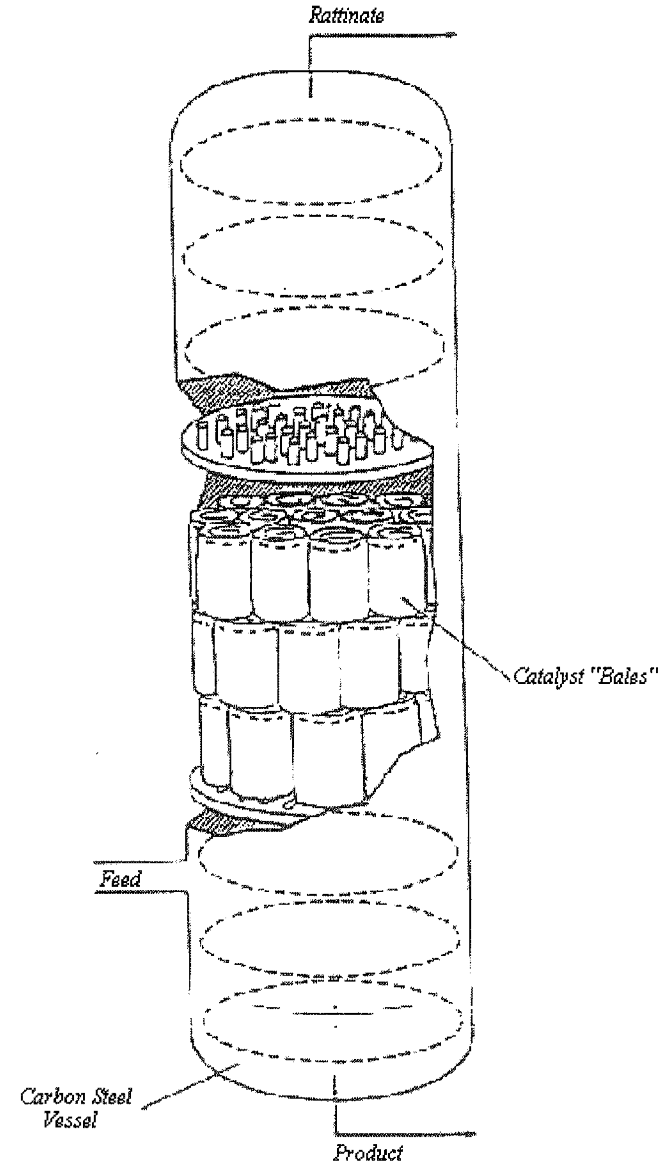

Figure 3. Catalytic Distillation Column (Rock et al. 1992).

In 1978, CR&L developed a new and improved concept for the production of these ethers and other chemicals. The improved process used a special catalyst packing for distillation towers consisting of a fiber-glass and stainless steel support structure and a catalyst (see Figure 3). This process removes the reaction products while catalyzing the reactions, allowing the forward reaction to proceed to greater levels of conversion. Previous attempts to run distillation simultaneously with catalysis had proved difficult because of high attrition rates, due to fragmentation and entrainment, and flooding of the column. The CR&L concept, however, involved containing the catalyst in pockets on a fiberglass-cloth matrix permeable to both liquid and vapor, thereby holding the catalyst in place without impeding the distillation. Using CD process, the conversion rate of isobutylene to MTBE can exceed 99 percent compared to 95 percent using the conventional process, and isoamylene to TAME exceed 95 percent compared to 70 percent (Rock, Smith, and Chen 1992).

In 1980, CR&L and Neochem Corporation received $1.3 million from DOE to co-fund the design and testing of a demonstration unit for MTBE production, and develop the process for production of other octane-improving compounds. In addition to providing funding, DOE enlisted the help of Charter International Oil Company (Charter) in providing the location for the demonstration. The CR&L/ Neochem team designed and installed the unit, which was a distillation tower retrofitted to accommodate a new catalyst system, at a Charter refinery, now Phibro, in Houston, Texas. The demonstration began in April 1981, and ran for 15 months, with CR&L/ Neochem monitoring and evaluating the unit's performance. CR&L/Neochem provided 12 percent of the project cost. In addition, a portion of the royalties were returned to the federal government as part of the agreement (Crossland 1995; Hughes and Moore 1994).

Although the technical viability of the technology was demonstrated with the pilot project at Charter, the market for the technology was limited. At the time, MTBE was used primarily as one of several alternatives for octane enhancement in gasoline, and as a chemical feedstock. Before the clean air act, production of MTBE was less than 50 thousand barrels per day (Rock et al. 1992).

At an energy savings rate of 45 billion Btu annually for a 1000 bbl/day plant. Capital costs for such a plant are about $1.2 million. The primary types of fuel saved would be electricity and propane, which translates into approximately $200,000 in energy savings per year. Based on the energy savings alone, the system payback would be about six years (OIP 1988).

However, the Clean Air Act Amendments of 1990 mandated that gasoline related pollutants be reduced by restricting the aromatics and butane in gasoline. The amendments also mandated the use of oxygenates in gasoline to reduce carbon monoxide (CO) emissions in CO non-attainment areas, and hydrocarbon emissions in ozone non-attainment areas (Rock 1992; Rock et al. 1992).

Most US refiners expressed a preference for ethers rather than alcohols options for compliance with the reformulated gasoline provisions of the Act. This preference is due in large part to the water susceptibility and high blending vapor pressures of methanol and ethanol. Their evaluation led many to choose MTBE as the oxygenate of choice. However, as mentioned above, production techniques at the time were inadequate for the expected demand. The FCC improvements and new TAME production methods helped solve this problem, with one source estimating a 250 percent increase in refinery ether production from these innovations over pre-1990 levels (Rock et al. 1992).

As of 1995, 66 catalytic distillation units were operating worldwide. CR&L joined with ABB Lummus Crest, Inc., to create CDTECH, which continues to develop the CD process and markets the technology worldwide. CDTECH now has almost 80 MTBE and TAME units licensed (CDTECH 1995).

At the same time the United States was moving towards reformulation of gasoline to achieve environmental objectives, so are countries throughout the world. Europe is in the midst of its own lead phase-out and is finding MTBE to be one of the desirable solutions for lead replacement. Recently, environmental legislation in Japan and South Korea has opened the door for MTBE in those gasoline markets. As of 1995, CDTECH has licensed the process to 24 customers in other countries in Europe, Latin America, Asia, and Africa (CDTECH 1995).

Energy Benefits

The main energy benefits of the catalytic reaction process come from using the heat of reaction directly for the distillation of the products. In the conventional process, the heat of reaction is removed by an external heat exchanger and is often rejected into the environment. As a result, external energy must be continuously supplied to a subsequent distillation step in order to separate MTBE or TAME.

Energy saved from the operation of catalytic reactor unit was on the order 50 billion Btu per year up until 1985 when unit sales began to increase (OIP 1988). By 1993, cumulative energy savings had risen to approximately 5.01 trillion Btu (Hughes and Moore 1994). Since the end of 1994, CDTECH shows 17 new plants in operation, with the total number of plants approaching 80 by the end of 1995 (Rock, Smith, and Chen 1992).

Benefits to Equipment Manufacturers and the Petrochemical Industry

At this point, the primary producer of CD equipment is CDTECH, a 50/50 partnership between CR&L and Lummus Global, Inc. UOP/Koch and Sulzer market competing devices, but the patent situation is in dispute. CDTECH has continued CD research and development, and is currently employing upwards of 75 full time employees in the development of catalytic demonstration processes. This research has not only refined the MTBE and TAME processes, but has also led to the introduction of a number of units to produce additional refinery products, and that allow the use of a new range of by-products. While these other applications were developed by CD technologies, subsequent to the initial DOE-supported project, Clifford Crossland (1995) of CR&L states "(w)ithout DOE support, the first successful demonstration might not have occurred."

The major benefit of CD technology to refiners has been to enhance their ability to meet market demand for reformulated gasolines. The alternative production methods are more costly, and involve more steps increasing the initial cost of installing capacity, so the CD technology has become the technology of preference. The technology can be retrofitted into existing conventional MTBE production units to increase conversion capacity (Rock et al. 1992). In addition, the energy savings and ability to use FCC by-products reduce operating costs. In some operations, the CD technology has reduced the load on alkylation reactor systems increasing plant capacity somewhat (Crossland 1995).

All major refiners, including such companies as Amoco Oil, Chevron, Exxon Chemical Company, Mobil Oil Company, and Shell now use the CD technology (CDTECH 1995). As expected, the technology was rapidly adopted following the Clean Air Act Amendments. Domestic oxygenate production capacity has increased significantly since 1991 (see Figure 4).

In 1991 there were only seven units operating in the United States and 12 operating worldwide (Hughes and Moore 1994). By 1995, 27 additional overseas and 18 domestic MTBE plants had been added. The first TAME-producing plants began operations in September 1992. In 1995, 68 MTBE and TAME units were in operation worldwide supplying an average production of two million barrels of these ethers per day (CDTECH 1995).

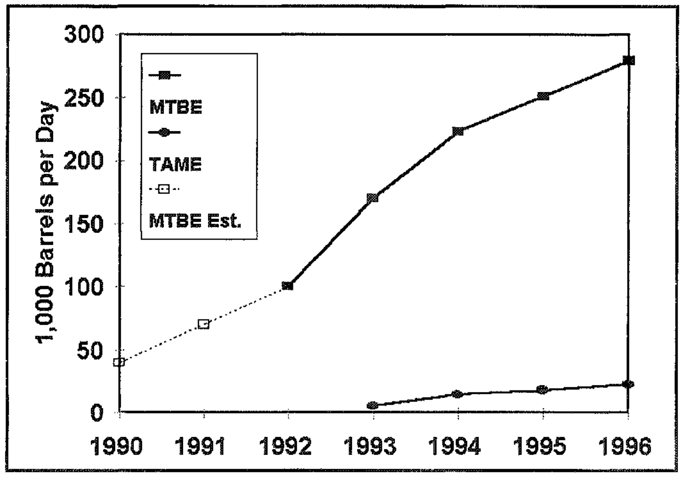

Figure 4. U.S. Domestic Oxygenate Production Capacity for Use in Reformulated Gasoline (EIA 1993, 1995, 1997; and ACEEE estimates).

Conclusions

While the magnitude of DOE's financial commitment to the development of the CD technology was modest, it played a facilitator role at a critical point in the commercialization of the technology. DOE obtained a site for and helped to fund the first demonstration of the technology, thus starting it down the road to commercial success. It was, however, not until over a decade later that an external market event (the passage of the Clean Air Act amendments) created an opportunity for which this technology was waiting. The energy and cost savings to the refining industry have been substantial. In addition, the application of this technology has allowed the implementation of the more stringent gasoline requirements with minimal economic cost to the consuming public.

Overall Conclusions

DOE has played a pivotal role in bringing all three technologies profiled in this report to the market. While its monetary contributions to each have been modest, its funding and support occurred at a critical point in the development of each technology. In additional, DOE's participation conferred intangible benefits upon the projects, including visibility and access to demonstration facilities, which would not likely have been otherwise afforded to the technology developers.

While all three of the technologies have been successful to some degree, none of the technologies evolved in the marketplace as was anticipated when DOE became involved more than fifteen years ago. Rather than this being an indictment of the Department's lack of foresight, these examples confirm the importance and value of R&D in the face of uncertainty. In each of the cases described, events which could not have been foreseen affected the course of the technology. As a result, applied technology development efforts need to be flexible in order to respond to evolving market conditions.

- In the case of membrane technologies, energy prices and environmental regulations did not evolve as was anticipated. However, the evolution of the technology and other environmental problems, such as the water crises in California, created a new need for the technology that not only saves energy and protects the environment, but also preserves jobs that would otherwise have been lost to business closings. As the technology continues to evolve, it is finding new applications, and its potential is yet to be realized.
- The evolution of non-VOC and low-VOC coatings has addressed the major problem that the HC-sensor computer-controlled ovens was intended to address. The revolution that has occurred in the last 15 years in coatings could not have been foreseen, with today's coatings offering equal or superior characteristics to the solvent coatings of 1980. While the HC-sensor remains as a special niche market, computer controls using other sensors are now almost universally used by oven manufacturers.
- The catalytic reactor was intended to save energy, but proved a critical enabling technology to meet Clean Air regulations. Had the catalytic distillation technology for MTBE and TAME production not been available, refiners would have been hard pressed to comply with the demand for reformulated gasoline, and consumers would have had to bear the greater cost of the alternative production methods. While other applications of the technology are possible, they await a critical market demand such as was created by the Clean Air Act Amendments.

These examples also demonstrate the value of working directly with the private sector on applied R&D. These companies had a clear incentive to identify market niches and see product used in manufacturing plants, as opposed to national laboratories and academia for which the research is frequently an end in itself. These stories also illustrate the importance of patience when dealing with R&D. It usually takes ten years or more to discover whether the product of an R&D effort will have any market potential, and additional time to assess whether it is a "winner."

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