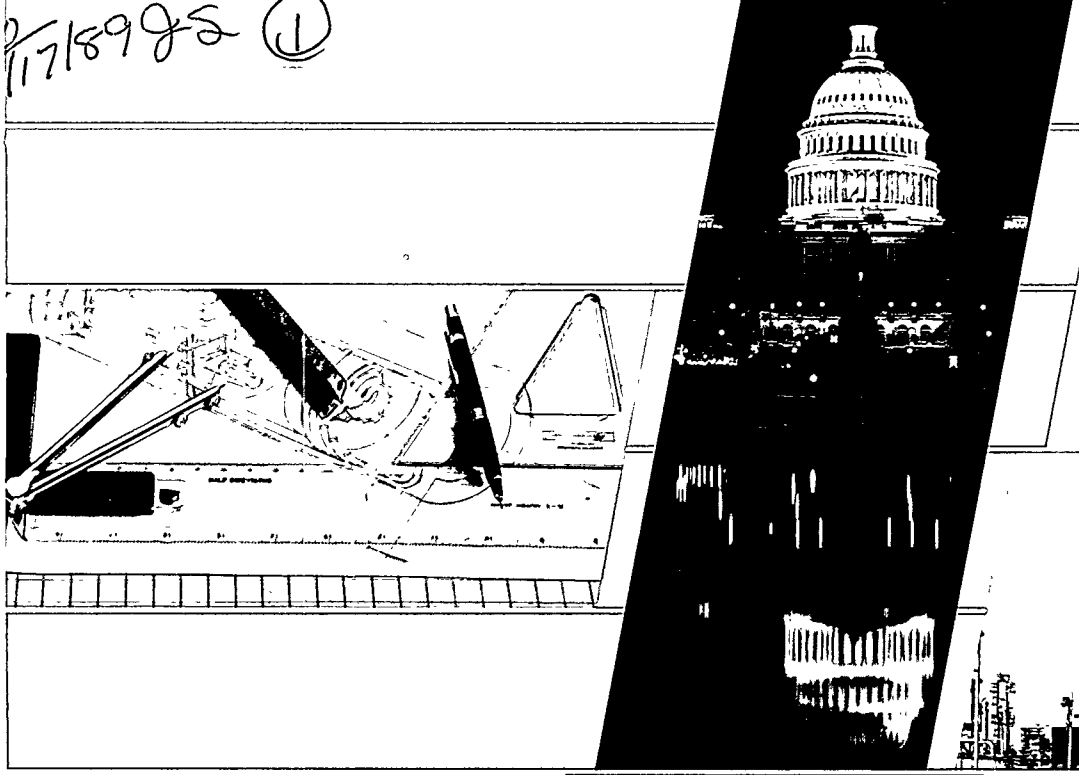

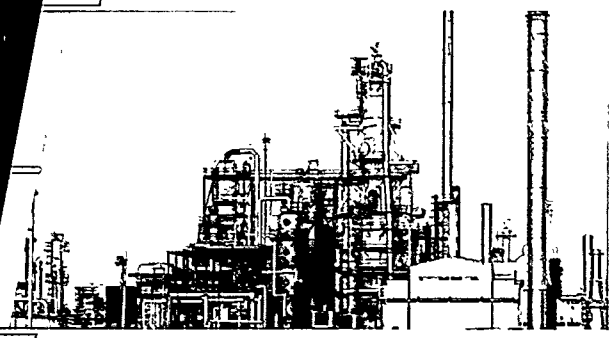

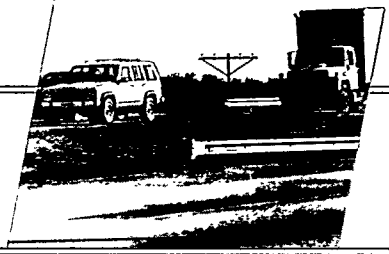

A Compendium Of Energy Conservation

Success Stories

U.S. Department of Energy

A Compendium Of Energy Conservation Success Stories

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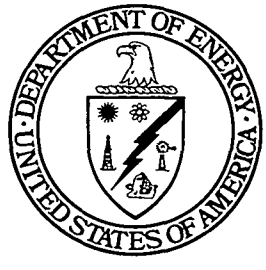

U.S. Department of Energy
Office of Conservation
Washington, D.C. 20585

September 1988

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Introduction

Prior to the 1973 oil embargo, energy conservation figured neither in American policy nor in American consciousness. As a result of the crisis atmosphere engendered by the embargo, every industrialized nation in the world has emphasized improvements in energy efficiency. In the United States this effort has been led by the Department of Energy's (DOE) Office of Conservation. Since 1978, DOE's conservation R&D program has committed almost $2 billion to hundreds of projects aimed at improving energy efficiency throughout the U.S. economy. This national effort has paid huge dividends. Despite the fact that the U.S. economy has grown by over 35 percent since 1973, fuel consumption has not increased. This represents a cumulative saving of over 150 quads of energy, worth approximately $840 billion at current energy prices.

Three-quarters of DOE's Conservation R&D funds have been devoted to technology research and development: basic and applied research, exploratory R&D, engineering feasibility studies, pilot-scale prototype R&D, and technology demonstration. Non-R&D projects have involved technology assessment, program planning and analysis, model development, technology transfer and consumer information, health effects and safety research, and technical support for rule making.

The success stories summarized in this compendium fall into three general categories:

- *Completed Technology Success Stories*: projects that have resulted in new energy-saving technologies that are presently being used in the private sector.
- *Technical Success Stories*: projects that have produced or disseminated important scientific/technical information likely to result in future energy savings.
- *Program Success Stories*: non-R&D activities that have resulted in nationally significant energy benefits.

The Energy Conservation research and development program at DOE is managed by the Office of Conservation under the direction of the Deputy Assistant Secretary for Conservation. Three subordinate Program Offices correspond to the buildings, transportation, and industrial end-use sectors. A fourth subordinate Program Office -- Energy Utilization Research -- sponsors research and technical inventions for all end-use sectors.

Buildings and Community Systems (BCS)

The buildings sector consumes more than 35 percent of the primary energy in the United States, approximately 27 quads. A major national effort to conserve energy in the buildings sector could save 20-30 percent of this total over the next 20 years. The conservation research efforts of the Office of Buildings and Community Systems are focused on five key building systems: building envelope, building equipment, indoor air quality, lighting, and design and construction systems.

In addition, BCS encourages community energy management by localities throughout the United States, conducts R&D on the centralized production and distribution of heating and cooling, and, through its recently initiated Least-Cost Utility Planning Program, conducts research on the integration of energy conservation and energy supply options in planning by electric utilities.

The 25 successful projects highlighted in this document include the following:

- low-emissivity windows which could capture 20-50 percent of the residential market by 1990;
- surface-wave fluorescent lamps which promise a 50 percent reduction in electrical energy requirements for fluorescent lighting; and,
- ground-coupled heat pumps which can pay for themselves in 3-5 years with energy savings.

Transportation Systems (OTS)

While other sectors of the U.S. economy have reduced fuel consumption, energy use in the transportation sector has grown. Transportation accounts for 63 percent of U.S. oil consumption, using 18 percent more oil than is produced domestically. At this time there is no economically feasible substitute for oil. However, there is a great potential for saving energy through the development of cost-effective fuel oil substitutes and more efficient energy-using technologies. To exploit this potential, the Office of Transportation Systems has sponsored research on innovative materials, advanced engines, alternative fuels, and electrically powered vehicles. In addition, much of the research sponsored by OTS has the potential both to lessen reliance on oil in the transportation sector and to reduce air pollution from vehicle emissions. Among the 14 OTS success stories described on the following pages are:

- the first electric vehicle with a useful range over 100 miles -- GM plans limited domestic production of a van using this technology;
- ceramic turbine rotors which allow practical application of turbocharger technology -- in 1986 the Nissan 300ZX became available with ceramic turbine rotors; and,
- ceramic coatings for diesel components that will yield a direct fuel economy benefit of nearly 4 percent for advanced diesel engines.

Industrial Programs (IP)

Until 1986 industry was the most energy-intensive sector of the U.S. economy. Of particular significance is the production of chemicals, petroleum, primary metals, paper, stone-clay-glass, and food industries, which account for two-thirds of all industrial energy use. To address the energy conservation needs of this key economic sector, DOE's Office of Industrial Programs sponsors research aimed at improving the energy-efficiency of industrial processes and energy conversion equipment; develops systems for the simultaneous production of electricity and process heat (cogeneration); and explores the potential of technologies that can use multiple fuels. IP also ensures that the technologies it develops are environmentally sound and is particularly active in technology transfer activities designed to assist small and medium-sized industrial facilities in analyzing their energy use. Twenty-nine successful IP research projects are summarized in this document, including:

- a slot forge furnace that offers energy savings of 50 percent or more;
- a high-efficiency welding unit -- 31,000 units are presently in use, saving approximately 1.1 trillion Btu per year; and,
- a low-speed diesel cogeneration system that could save as much as 171 trillion Btu by the year 2010.

Energy Utilization Research (EUR)

The mission of the Office of Energy Utilization Research is twofold. First, it is responsible for exploring and advancing emerging technologies needed in the future by end-use sectors of the economy. Second, EUR is charged with fostering invention and innovation in the private sector that could lead to energy savings or new energy sources.

The *Energy Conservation and Utilization Technologies (ECUT) Program* of EUR conducts interdisciplinary research directed toward solving problems that appear in more than one energy-consuming sector. Specifically, ECUT conducts research in the areas of combustion, thermal sciences, materials, catalysis/biocatalysis, and tribology. Emphasis is placed on technologies and processess that are well-conceived technically, that promise significant energy savings and cost-effectiveness, and that are too generic for other DOE conservation programs and private firms to pursue. The ECUT success stories summarized in this *Compendium* were selected on the basis of their contribution to expanding the knowledge base and improving the potential to realize energy savings projected for advanced technologies. Examples of successful ECUT projects in this document include:

- the RAPRENOx process that shows significant potential for reducing nitrogen oxide emissions from fossil fuel-fired combustion systems; and
- ductile ordered alloys that allow conversion technologies to operate more efficiently in high-temperatures and other severe operating environments.

The *Energy-Related Inventions Program (ERIP)* is jointly sponsored by the Department of Energy and the National Bureau of Standards and provides technical evaluation and financial support for promising energy-related inventions submitted by the general public. Successful ERIP technologies, chosen on the basis of current or projected energy savings, include the following:

- the steam turbine packing ring, a new design producing a tighter seal that can significantly improve the efficiency of utility steam turbines; and
- Alter-Break, an alternator and battery-charging system for automobiles that achieves a 10-20 percent increase in fuel efficiency.

Looking Forward

DOE's Energy Conservation Program has had a significant impact upon U.S. energy consumption. Program successes at the project level have fostered direct technological improvements as well as demonstrating to the private sector in measurable ways that energy efficiency is important on a national scale.

The need for continued efforts at the federal level to improve the nation's energy productivity remains clear despite a short-term fall in oil prices. That need rests upon compelling longer-term factors:

- Growing dependence upon oil imports once again increasingly threatens national security.
- The nation's oil trade deficit continues to drain the economy of resources that might otherwise be used to stimulate growth.
- A lag in gains of U.S. industrial productivity threatens the nation's standard of living through a declining ability to compete with foreign industry in domestic and overseas markets.

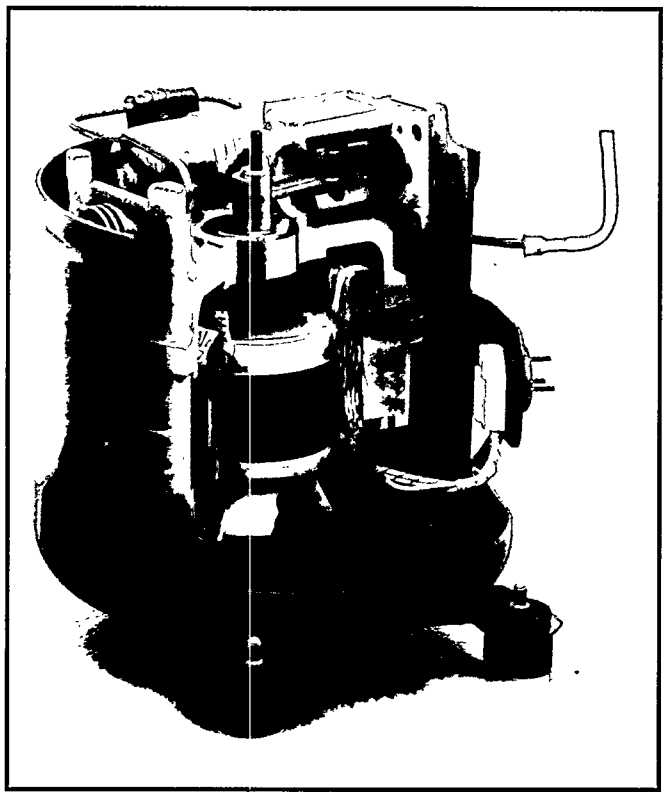
- Inefficient energy use in the United States and throughout the world may worsen global environmental conditions such as acid rain and the diminution of the ozone layer of the atmosphere.

To help counteract these trends, DOE's Energy Conservation Program will continue its support for basic and targeted research to provide energy-efficient technologies to secure the nation's future. High priority will be placed on increasing fuel flexibility and diversifying alternatives to oil, particularly in the transportation and industrial sectors. Emphasis will be placed on cost-effective new technologies that improve efficiency, particularly those that can enhance U.S. industrial productivity and gain technical leadership in key areas of international competition. And finally, when energy inefficiencies are reduced, environmental pollutants of many kinds also are reduced.

Buildings And Community Systems

High-Efficiency Refrigerator Compressor

Household refrigerators consume approximately 12 percent of the primary energy used in the residential sector. In an effort to reduce this consumption, DOE supported research by a major appliance manufacturer, the Kelvinator Company, to develop a more efficient refrigerator compressor. Through design changes in the refrigerator motor and suction muffler, Kelvinator achieved a 44 percent efficiency improvement over conventional refrigerator compressors. Kelvinator has manufactured over 30,000 refrigerators with this new high-efficiency compressor. Based on the success of the compressor design, Kelvinator recently introduced a more advanced compressor, the industry's first to be rated over 5 Btu per watt-hour. The design of the more advanced compressor is currently being offered to other refrigerator manufacturers. Full market penetration of high-efficiency compressors in household refrigerators would produce annual energy savings estimated at about 0.21 quads by the year 2010.



Cut-away view of the high-efficiency refrigerator compressor developed by DOE and the Kelvinator Company.

Solid-State Ballast for Fluorescent Lighting

Although the theoretical limit for a luminous light source is over 350 lumens per watt, standard fluorescent lamps operate at less than 70 lumens per watt. This inefficiency in standard lighting stimulated DOE to initiate a research program to improve the performance of fluorescent lamps. The program focused initially on the potential of solid-state ballasts to power fluorescent lamps at higher frequencies. Working with two small contractors, DOE developed and tested prototypes of solid-state ballasts that improved lighting efficacy by 25 percent. DOE-sponsored demonstrations of the benefits of solid-state ballasts in several office buildings convinced major lighting manufacturers to adopt this energy-saving technology in their product lines. Over 2 million solid-state ballasts are being used in U.S. buildings, saving 200 million kilowatt hours of electricity annually. Solid-state ballasts, currently installed in fewer than 3 percent of fluorescent fixtures in the United States, are expected to achieve a 50 percent market penetration by 1995.

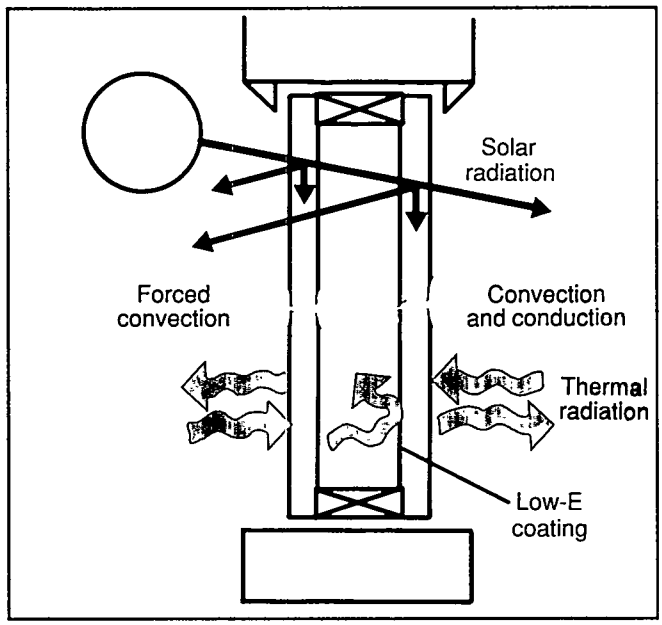
District Heating and Cooling Development

Once prevalent in almost every metropolitan area in the Northern United States, district heating and cooling (DHC) systems have been almost completely replaced in today's cities by individual space conditioning systems operating on oil or natural gas. The energy conservation and fuel substitution benefits inherent in DHC systems prompted DOE to

embark on a program of research, project demonstrations, and feasibility assessments in over 50 communities to redevelop this concept. As a result, cogeneration/district heating systems have been constructed and are operating successfully at three large universities and in Trenton, New Jersey. Together, these four systems have saved the equivalent of several thousand barrels of oil annually through combined heat and electric power production. More importantly, DOE's feasibility assessments have formed a basis for subsequent design and development using local government and private sector funding. Thirteen cities have proceeded with detailed designs for construction of DHC systems. The cities of Baltimore; St. Paul; Galax, Virginia; Provo, Utah; Piqua, Ohio; and Lawrence, Massachusetts have new district heating systems. Construction of DHC systems on college campuses has increased more than five fold since 1950. DOE's district heating and cooling development program currently yields energy savings of over 5 trillion Btu per year nationwide and has produced over $70 million of construction activity. Net energy savings in the year 2000 are predicted at 163 trillion Btu, equivalent to 28.1 million barrels of oil with a current economic value of over $421 million.

Low-E Window Coating

In response to the energy crises of the early and mid-1970s, DOE initiated a research program to identify innovative energy saving technologies that could be applied to commercial and residential buildings. Research determined long wave infrared radiation heat exchange through windows to be a major source of energy loss in buildings. Low emissivity (Low-E) glass coatings were known to reduce this problem, yet the window and glass industries were unable to commit sufficient research resources to solve numerous technological problems connected with these coatings. DOE sponsored a broad range of basic technology research activities including: Low-E coating technology research, computer simulation of alternative Low-E window designs, coating test facilities, and technology transfer programs to disseminate Low-E research program results. DOE's investment in Low-E technology research directly stimulated the glass and window industries to invest heavily in advanced coating technology. Low-E windows became commercially available in 1983, and in 1986 twenty manufacturers sold over 50 million square feet of Low-E windows representing almost 10 percent of all residential window sales. Energy savings from Low-E windows sold in 1986 exceeded 2.5 trillion Btu, currently valued at over $15 million. The industry estimates that Low-E windows will account for 20 to 50 percent of the residential window market by 1990.



Low-E coating reduces window heat loss resulting from radiation transfer.

DOE-2

The DOE-2 building energy simulation program was developed as an unbiased analytical tool in the public domain to assist in the design and evaluation of building performance and energy conservation technologies from the perspectives of energy use, efficiency, comfort, and cost. Operating on a wide variety of computers ranging from personal computers to mainframes, DOE-2 has become the stand-

ard by which similar commercially-developed programs are evaluated. DOE-2 has been used in the development of building industry standards, such as the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 90, the California Building Code, and the ASHRAE *Handbook of Fundamentals*; as an aid in developing simplified analytical tools (ADM-2, Trackload, ASEAM, BLAST, and PEAR); and as an educational tool to train engineers, designers, and architects. Since its release in 1977, several hundred copies of DOE-2 have been distributed. DOE-2 is recognized in the technical community as the most accurate building energy simulation program available.

Flame Retention Oil Burner

The high-efficiency flame retention head oil burner, although not a new technology, did not achieve substantial penetration of the oil heating market until DOE investigated its potential in the late 1970s. In a carefully controlled field test, DOE established the energy conservation benefit of this oil burner by studying retrofit options, including the use of the burner alone or in combination with other measures. A second DOE effort communicated the findings of this research through the distribution of over 70,000 copies of a consumer-oriented information booklet to the public. This booklet covered the energy conservation aspects of flame retention oil burners and other components of oil-fired heating systems. As a result of these efforts, the number of flame retention head oil burners in use increased from 100,000 in 1979 to over 2,000,000 in 1985, saving approximately 44 trillion Btu annually. The flame retention head oil burner is projected to save 0.14 quads annually by the year 2000.

Infiltration Model

Infiltration, the uncontrolled flow of air through a building's shell, is responsible for one-third to one-half of residential and commercial building energy requirements. Prior to 1980, no adequate method existed to predict energy losses due to infiltration. To meet this need, DOE sponsored the development of an infiltration model that provides simplified techniques for estimating infiltration rates in residential buildings based on building envelope parameters and climatic conditions. To predict the performance of air infiltration in the building shell, the model uses the leakage properties of the building envelope and site weather data. The model is simple enough to use with a hand calculator and is usually accurate to within 20 percent of actual figures. Described in detail in the ASHRAE *Handbook of Fundamentals*, the infiltration model is currently being used throughout the professional design community and has been incorporated into major energy performance computational programs (CIRA, DOE-2, BLAST, and TRNSYS). Residential building designs that incorporate the results of the infiltration model are typically 10-15 percent more energy efficient. The residential infiltration model is currently being extended to analyze infiltration in commercial buildings.

Insulation Thermal Resistance Measurement

The National Institute of Standards and Technology (NIST) has conducted research on heat transfer through insulation for many years. Following the energy crisis of the 1970s, insulations with thicknesses increased by more than an inch were incorporated in many building designs. At that time, test methods to evaluate the properties of these thicker insulations did not exist. In 1978-1979, the FTC proposed a plan to require manufacturers to label insulation material for thermal resistance and to base advertised thermal resistance values on product testing. Because precise measurement of the thermal resistance of thick, low-density insulation is difficult, DOE and NIST co-sponsored the development of the 1 meter line-source guarded hotplate to accurately measure insulation performance. This device is capable of heat transfer measurement in insulation up to 15 inches thick. The insulation industry was given calibration trans-

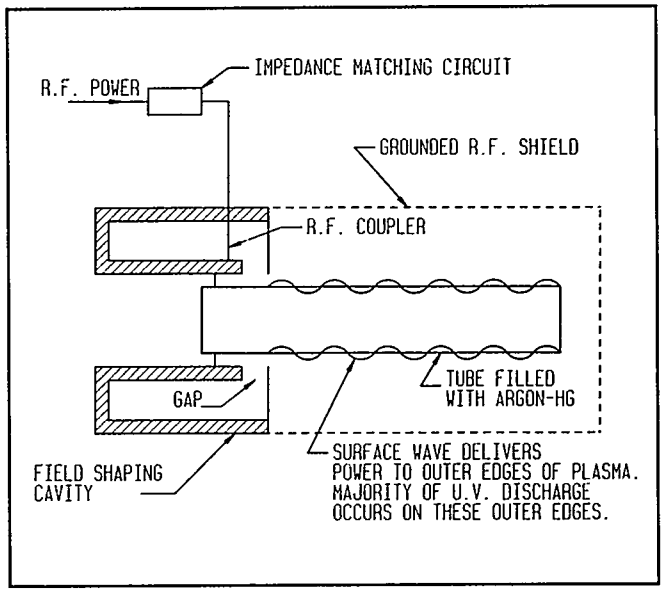
fer specimens with which to measure and label its products. Accurate heat transfer measurement eliminates the need for manufacturing insulation of excess thickness, thus reducing costs. In 1984, the U.S. Department of Commerce estimated that the improved measurement capability developed through this project saves consumers $90 million annually.

Appliance Efficiency Test Procedures

Legislation passed in 1975 required DOE to develop standard sets of test procedures to accurately measure the energy consumption and efficiency of thirteen categories of major household appliances. Since the testing and labeling program began, the average energy efficiency of new major appliances has increased significantly. As consumers reject less efficient models with higher operating costs, manufacturers are producing new designs with energy efficiency improvements of 50 percent over older models. Four national trade and professional associations representing manufacturers of major appliances have adopted the DOE appliance test procedures in their own industry guidelines and product certification programs.

Surface Wave Lamp

In 1980, DOE began a program directed at improving the efficiency of converting electrical energy to useful light. Fluorescent lamp efficiency is limited by electrode losses, by self-absorption of ultraviolet radiation within the lamp's plasma and by the efficiency of the lamp's phosphor in converting ultraviolet radiation into visible light. Several techniques to improve efficacy, including exciting fluorescent lamps using very high (gigahertz) frequencies, were explored. Unlike lower frequency lamp excitation, which concentrates ultraviolet radiation generation in the fluorescent lamp's center, very high frequency excitation using surface waves creates a greater ultraviolet generation close to the lamp's outer walls. Test results of surface wave lamps have revealed a 40 percent efficacy improvement over conventional fluorescent lamps. When fully developed, this concept is expected to result in a 50 percent reduction in electrical energy requirements for fluorescent lighting and to improve lamp life to over 40,000 hours.



Surface wave lamps promise a 50 percent reduction in energy use and over 40,000 hours of lamp life.

Supermarket Refrigeration Systems

Supermarkets consume about 4 percent of the nation's electricity, much of which is used in refrigerated display cases. To reduce this energy consumption, DOE and a leading manufacturer of supermarket refrigeration equipment developed a novel concept. An innovative design, featuring multiple parallel compressors and advanced microprocessor controls, reduced energy consumed in display cases by more than 40 percent. As a result of this DOE research, all leading manufacturers now offer advanced refrigeration systems with multiple unequal parallel compressors. Such systems accounted for 25 percent of the supermarket refrigeration equipment market in 1987. Advanced supermarket refrigeration systems are expected to save between 0.25 and 0.37 quads of primary energy in the year 2000.

Ground Coupled Heat Pumps

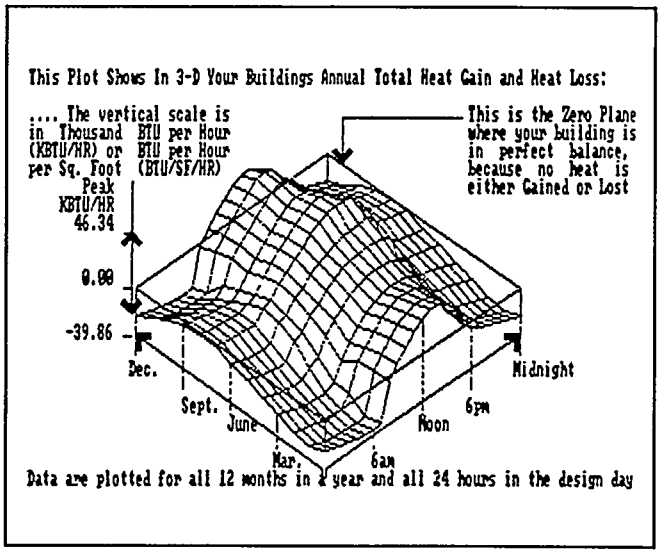
About one-third of new homes are heated and cooled by air source heat pumps. Because ground coupled heat pumps can save over half of the energy used by air source heat pumps, DOE initiated a multifaceted research and development program to develop an advanced ground coupled heat pump. Analytic design tools were developed, tested, validated, and distributed to the private sector to assist manufacturers in designing more cost-effective ground coil heat exchangers and more efficient mechanical packages for the heat pump. These design tools were applied in the development of an advanced ground coupled heat pump system. DOE, a utility company, and a leading manufacturer jointly collaborated in the design, fabrication, and field evaluation of two experimental prototypes. The advanced systems improved the cost effectiveness of ground coupled heat pumps by reducing the payback period from 6-10 years to 3-5 years. The participating utility company estimates that the improvements should increase sales of ground coupled heat pumps by about 60 percent. Ground coupled heat pumps using this advanced design will save approximately 0.32 quads by the year 2010.

Program for the Energy Analysis of Residences (PEAR)

DOE recognized the need for an easy-to-use, nontechnical energy analysis tool to assist residential builders to make choices among energy-conserving building design options. These options include home insulation levels, window types and glazing layers, infiltration levels, amount of thermal mass, and equipment efficiency. PEAR is an energy analysis tool that enables builders and designers to estimate the annual energy use of new houses with different infiltration rates and equipped with various conservation measures such as ceiling, wall, and floor insulation, and thermal or storm windows. Using PEAR, builders and designers can also determine the effects of innovative measures such as changes in roof and wall color or an attached sunspace. PEAR can perform energy analyses for new residential buildings throughout the continental United States.

Solar-5

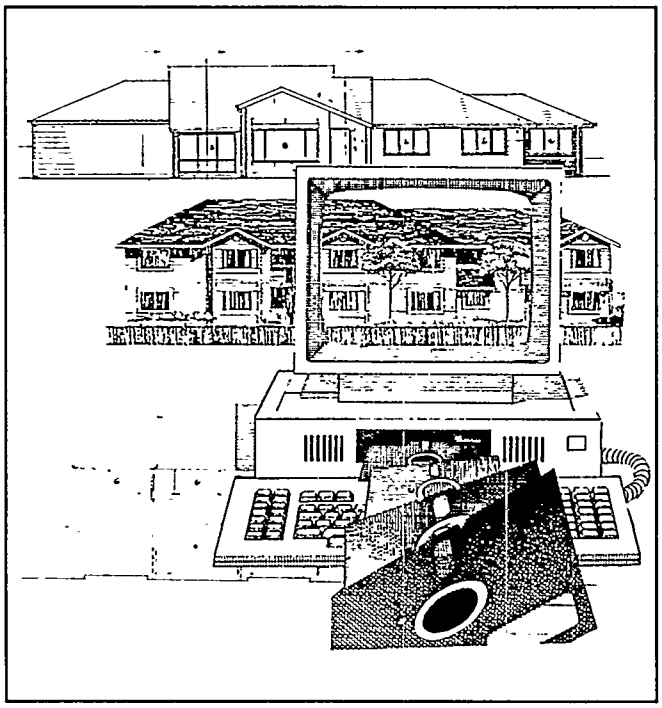
A building's future energy efficiency is often determined in the early stages of the design process. Designers lacked a way to assess the effect of different design strategies on energy performance until DOE developed Solar-5 to provide a visual display of building energy flows at the design stage for residential and commercial buildings. Solar-5 uses a matrix to display data and provides the results of its energy analysis immediately. This enables users to revise a design and to see instantly the results displayed on the matrix. A user can combine up to nine different schemes into one design and observe a graphic presentation of the resulting energy flows. Solar-5 has received the *Progressive Architecture* magazine award citation and a DOE award for excellence. It is the most popular computer program available from the Designers Software Exchange, with approximately 500 copies sold to date.



This computer-generated plot, produced with the SOLAR-5 program, shows a building's total heat gain and heat loss. Data are plotted for all 12 months and all 24 hours.

Computer-Based Conservation Standards for New Federal Residential Buildings

Early energy conservation standards for federal housing projects used simple criteria to guarantee improved energy efficiency in new homes. Unfortunately, these criteria often did not capture the most cost-effective energy conservation measures. In additon, there was no way to take account of the additive effects of combining conservation methods. These shortcomings prompted DOE to develop Energy Conservation Standards for New Federal Residential Buildings, the first computer-based standards in the United States. This user-friendly computer program calculates the most cost-effective combination of conservation measures and checks compliance with standards. Builders can now explore a wide variety of energy conservation measures quickly and inexpensively, submitting the most cost-effective combination when bidding on federal housing projects.



Computer-based standards for new federal residential buildings facilitate the calculation of the most cost-effective combination of energy conservation measures for federal housing projects.

Indoor Air Quality Field Studies Data Base

Experts believe indoor air quality is one of the most important public health issues of the 1980s. A better knowledge of indoor contaminants and their effect on people is required. The growing number of field studies on indoor pollutants has made obtaining information from technical literature overly time consuming. Consequently, DOE, EPA, the Electric Power Research Institute (EPRI), and the Gas Research Institute (GRI) have initiated an effort to create and support a computer data base of field studies that monitors concentrations of indoor pollutants in buildings in the United States and Canada. The Concentrations of Indoor Pollutants (CIP) Data Base provides information in microcomputer format on indoor air pollution concentrations in buildings from over 300 references. The CIP Data Base can be used to calibrate, verify, or modify macromodeling efforts designed to predict or characterize indoor pollutant concentrations. Over 200 groups or individuals have used the data base.

Window 3.0

Windows play an important role in the energy efficiency of a building, yet today there is no standard in the United States for determining the thermal performance of window systems. Industry support is growing for the establishment of a standard based on calculation procedures validated with lab or field tests. Developed by DOE in conjunction with the Lawrence Berkeley Laboratories (LBL), Window 3.0 is a PC-based program for calculating window ultraviolet light transmission, shading coefficients, and surface temperatures of glass layers. Window 3.0 is expected to become a key element in industry consensus standards and Congressionally mandated requirements. The program incorporates the best features of LBL's Window 2.0 program, now used by over 600 firms in the window industry. ASHRAE has used Window 3.0 to calculate new guidelines for window performance, incorporated into the ASHRAE *Handbook of Fundamentals*. The program is

facilitating the design of LBL's "superwindow" technology. Other uses range from design of more conventional windows by architects and engineers to development of data by manufacturers for product specification sheets.

DHC Development: Kent County, Michigan

District heating systems can save substantial amounts of energy on a community-wide basis. When combined with a waste-to-energy facility, district heating has the added advantage of helping to solve one of the nation's most serious environmental problems -- disposal of municipal solid waste. In 1986, DOE provided Kent County, Michigan with $50,000 to assess the feasibility of a district cogeneration system. As a result of this study, Kent County is constructing a 625 ton-per-day waste-to-energy cogeneration facility. The facility will serve six communities with a total population of approximately 320,000, including Grand Rapids. The system will deliver 115,000 pounds of steam per hour to the county-owned district heating loop and generate 19 megawatts of electricity to be sold to a community power company. The project serves as an example of how a local government can develop a community energy system that provides an alternative to the use of oil or gas.

City-Wide Energy Conservation: Phoenix, Arizona

As a result of skyrocketing oil prices throughout the 1970s, the city of Phoenix, Arizona, made a firm commitment to energy conservation. Since 1978, Phoenix has saved over $20 million through a comprehensive energy conservation program that cost the city only $2.5 million. A series of annual DOE grants through the Urban Consortium Energy Task Force provided a $576,000 supplement to the city's investment and have resulted in more than $2 million in energy savings/cost avoidance since 1981. The projects focused on energy savings in three

Facility	**Estimated Energy Savings** (KWH)	**Energy Use Without Savings** (KWH)	**Cost Avoidance** (Dollars)	**Percent Energy Savings**
Libraries	3,283,637	7,315,320	295,527	45
Municipal Building	4,627,812	11,499,492	416,503	40
Other Downtown Bldgs	2,877,363	7,440,403	258,963	39
Police Department	4,866,517	14,780,064	437,987	33
Cultural Centers	741,675	4,526,715	66,751	16
Fire Stations (14)	308,151	2,122,029	27,734	15
Human Resources Dept.	358,027	3,922,193	32,222	9
Service Center	78,483	1,269,700	7,063	6

City of Phoenix Energy Conservation Program: Annual savings, 1978-1987, at major municipal facilities.

areas: (1) wastewater treatment, (2) water treatment and pumping efficiency, and (3) heating and cooling efficiency in municipal buildings. In 1983 the city established the Energy Conservation Reinvestment Plan, to reinvest 50 percent of general fund energy savings in new projects. Phoenix has participated in workshops sponsored by the Energy Task Force to assist other cities in developing conservation programs. The Phoenix program demonstrates that city-wide energy conservation is feasible and economically sound.

Single-Family Retrofit Research and Technology Transfer Program

In a recent analysis of home ownership costs, the Alliance to Save Energy found that energy costs are the second largest expense after mortgage payments. Reductions in energy costs through greater efficiency therefore would improve housing affordability. DOE, in conjunction with the Alliance, sponsors a program that leverages state and private sector resources to improve conservation programs, provide better technical training, and increase research activities. The program brings together product manufacturers, utilities, national laboratories, local community groups, and private contractors to use the latest research innovations to improve the effectiveness of residential energy conservation efforts. During the past several years, the program has: (1) improved the energy savings and cost effectiveness of 27 state weatherization programs, (2) provided training to 1600 energy auditors and private heating contractors in new efficiency technologies, and (3) developed an innovative approach to leverage state and private sector resources to stretch limited DOE research funds. Over 20,000 homes have been retrofitted through this program.

Radiant Barriers for Single-Family Housing

In single family housing, 7 to 8 percent of winter heat loss and 17 to 20 percent of summer heat gain occurs through attics. In a jointly funded effort, DOE and the Tennessee Valley Authority (TVA) performed field tests of a low-cost, easily installed aluminum foil product that promises significant reductions in attic heat transfer, thus saving energy for heating and cooling. The product's two reflective surfaces reduce the radiant component of heat transfer between the attic and the underside of the roof. Most home owners can easily install this radiant barrier material over existing attic insulation. Results of DOE tests of radiant barriers installed in three single-family homes in Tennessee indicate a reduction in cooling energy requirements by 17 percent and in heating energy requirements by 9 percent. Assuming homeowner installation, radiant barriers provide a two-year payback in energy savings. Most effective in hot climates, this product has the potential to save .17 quads per year in the South's 22 million homes. Its benefits also are sufficient to make the radiant barrier marketable in northern climates.

Acoustic Leak Detection System

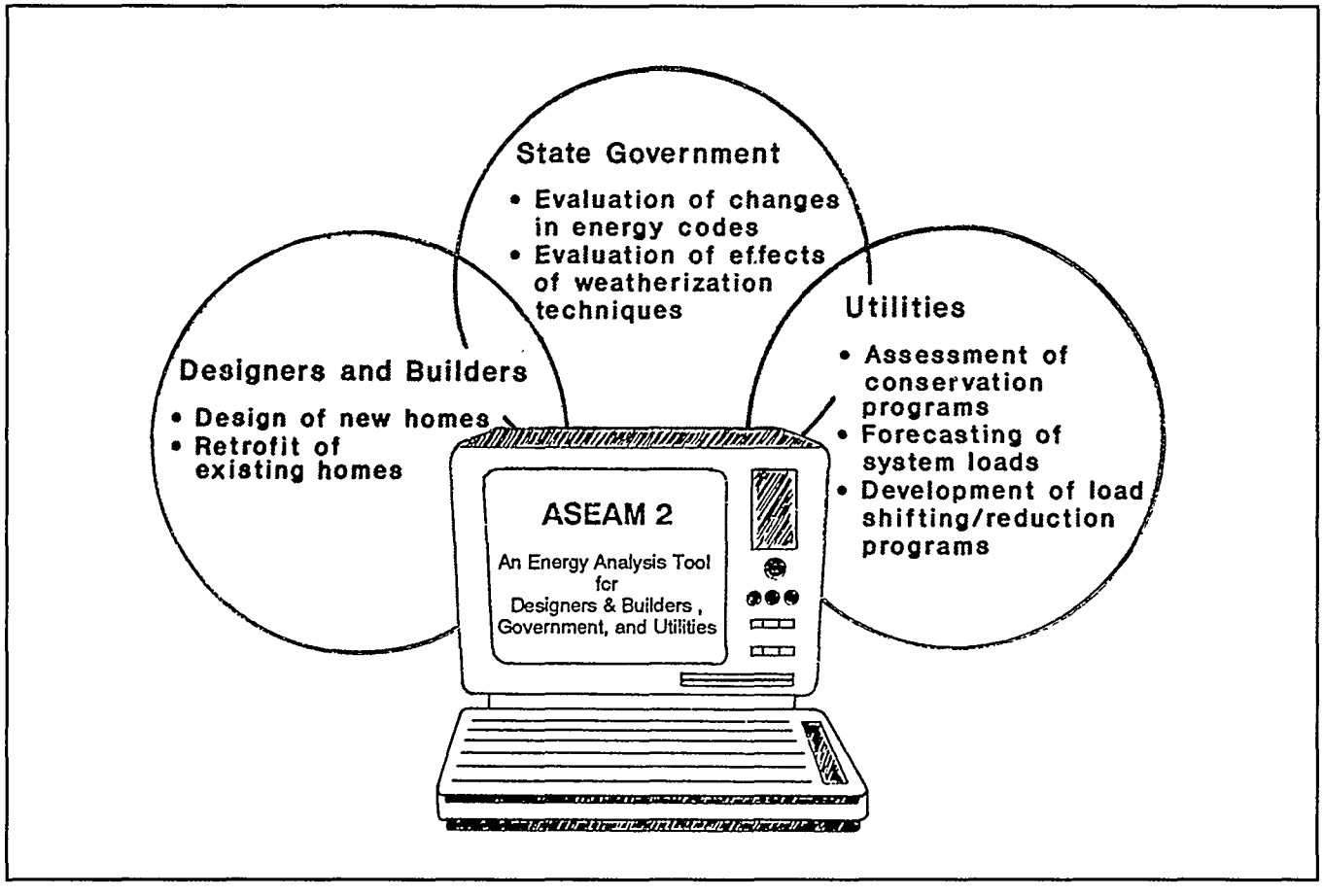
Many industries use pipelines to carry steam, water, gas, and oil. The costs of detection and repair of leaks in these pipelines are high in terms of lost productivity and repair time. The District Heating and Cooling Leak Detection Research program, cofunded by Consolidated Edison and the Fluid Conservation Systems Corporation, allowed scientists at Argonne National Laboratory to develop a computer-based acoustic monitoring system that can accurately locate underground pipe leaks. The detector records sounds created when pressurized gas or liquid escapes from a damaged pipe. The data is fed into a computer which provides information on the location, size and type of the leaks. Experiments on district heating pipes demonstrated that water leaks can be detected at a distance of 500 feet and escaping steam at 1,500 feet. Utilities may be able to save thousands of dollars per week by using the acoustic leak detector system for location and repair work.

A Simplified Energy Analysis Method (ASEAM-2)

DOE developed ASEAM-2 to provide an accurate, easy-to-use energy analysis tool in the public domain for design and retrofit applications. This computer program is modular in design, allowing users to integrate it with other software, such as life-cycle costing and daylighting programs. ASEAM-2 can simulate thirteen different types of HVAC distribution systems, model up to ten energy load zones within a building, and size systems automatically. Users can evaluate the effects of changes in lighting, heating/cooling equipment or increased insulation; estimate energy results for life-cycle cost analysis; and assess the benefits of retrofit options. The system is of great benefit to state governments; the effects of proposed changes in state energy codes can be analyzed, consistency in the results of energy audits can be established, and the effects of different weatherization techniques can be reviewed. Applications for utilities include assessment of conservation programs, forecasts of system loads, and development of load-shifting and load-reduction programs.

Energy Institutes

To promote the transfer of energy-efficient building design technologies and ensure continued interest in energy-efficient design and engineering, DOE has sponsored several faculty institutes in cooperation with the Association of Collegiate Schools of Architecture and the American Consulting Engineers Council. To date, the institutes have attracted 350 faculty members representing 90 percent of the U.S. schools of architecture and 180 faculty members



ASEAM-2 provides a wide variety of users with public domain software for design and retrofit of HVAC systems.

from 150 of the nation's engineering schools. Although the energy benefits associated with this project are difficult to quantify, surveys and testimonials from participants indicate that the institutes have resulted in increased attention to energy-efficient design in the curricula of the architecture and engineering schools which educate this nation's future building and equipment designers.

Building Foundation Design Manual

A 1985 DOE study found that over 95 percent of existing and 70 percent of new residential buildings lack foundation insulation. The DOE/Industry Foundations Review Panel suggested that clear information on the cost-effectiveness of foundation insulation in most U.S. climates was not readily available to builders and designers. With the help of extensive industry review and technical support provided by the DOE/Industry Foundations Review, DOE prepared the *Building Foundation Design Manual*, a comprehensive handbook for architects and engineers. The *Manual* covers energy-efficient building foundation design and recommends practices for structure, drainage, waterproofing, radon mitigation, and termite control. The volume includes a simplified method to estimate cost-effectiveness for foundation insulation in all regions of the United States. Although the manual focuses on new residential construction, the information also pertains to small commercial buildings and retrofit applications. Adoption of designs recommended in the handbook could save the nation as much as one-half quad per year.

NORDAX: Least-Cost Utility Planning in the Northeast

In recent years heightened public concern about the consequences of utility planning decisions has led state regulatory commissions to increase their scrutiny of utility decision-making processes. Many of these regulatory commissions now require that utilities include demand-side considerations -- e.g., energy conservation, load leveling and cogeneration -- along with traditional evaluations of the need for additional sources of energy such as new power plants. Least-cost utility planning (LCUP) is an approach to utility resource planning that evaluates both supply- and demand-side options for their potential contribution to providing adequate supplies of energy safely, reliably, and at the least cost. State regulators and utilities in thirty-seven states are presently conducting some form of LCUP. In recent years DOE has supported research on least-cost planning in order to provide a national perspective on the many independent LCUP efforts. Of particular note in DOE's LCUP program is the Northeast Region Demand-Side Management Data Exchange (NORDAX). The primary objective of the NORDAX project is to enhance integrated least-cost planning by utilities in the Northeast through the exchange of information on demand-side management programs and technical options. During Phase I of the project, data on over 110 conservation and load management programs are being collected and entered into a high-quality, user-oriented, relational database. As a result, utilities, utility regulators and other interested parties in the Northeast now have access to a large body of information on utility characteristics, technical option costs and load impacts, program costs, marketing methods and market penetration. In addition, the NORDAX project has created a national directory of demand-side management planners, researchers, evaluators and implementors. The NORDAX project has attracted financial support from the Edison Electric Institute, the New York State Energy R&D Authority, and 17 major utilities in the Northeastern U.S. Phase I of the project has been so successful that participating utilities are proceeding with Phase II at their own expense, without additional federal funding. Phase II involves the establishment of an organization to continue development and enhancement of the database as well as other information exchange activities.

Transportation Systems

Thermal Barrier Coatings for Diesel Components

DOE is sponsoring cost-shared programs with Caterpillar, Incorporated and the Cummins Engine Company, Incorporated to develop reliable and durable thermal barrier coatings. These coatings have significant potential for improving heavy-duty diesel engine fuel economy and vehicle performance and reducing emissions. An extensive data base was instrumental in the development of successful coatings for diesel engines. Caterpillar and Cummins are working to further develop and transfer coating technology to future diesel engines designs. Engine tests during this program have advanced the production and application of reliable thermal barrier coatings for diesel engines. Engine performance modeling indicates that the level of insulation provided by these coatings will yield a direct fuel economy benefit of nearly 4 percent for an advanced turbocharged and turbocompound diesel engine.

Transformation-Toughened Ceramics Data Base

Transformation-toughened ceramics, such as partially stabilized zirconia, tetragonal zirconia polytypes, and zirconia-toughened alumina, offer important options for advanced engines because of their high strength and toughness, high coefficient of thermal expansion (similar to cast iron), and good thermal insulation properties. Ceramics are highly complex materials and early experiments found that satisfactory performance in engines was unpredictable. Under the Advanced Materials Development program, a comprehensive data base of mechanical and physical properties as a function of time, temperature, stress, relative humidity, and thermal history was developed. Over 25 different materials were characterized at four different laboratories. The data from this research have been compiled in a computerized data base and have been released to industry where the information aids designers in the development of advanced engines for commercialization. The Data Base for Transformation-Toughened Ceramics is a part of the second phase of the DOE Advanced Materials Development program, focusing on initiating contacts with industry to integrate new information on ceramics into engine design research.

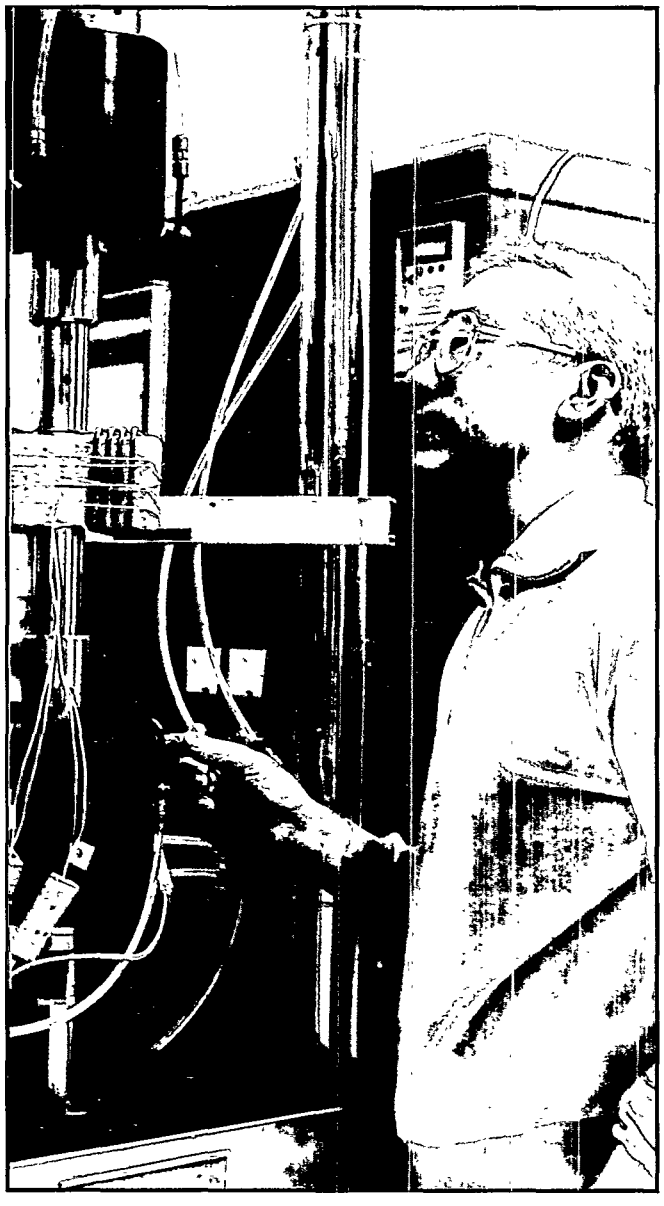
Whisker-Toughened Ceramic

Engine components made of ceramics are more durable and lighter (thus, more energy efficient) than those composed of metal. In addition, they are corrosion resistant and can be manufactured from low-cost, non-strategic materials. Past application of ceramics in engine construction was limited by the brittleness of the material. Following successful research by the ECUT program, the DOE Advanced Materials Development program developed a silicon nitride matrix with a silicon carbide whisker composite, known as whisker-toughened ceramic. This new material is 40 percent tougher and 25 percent stronger than conventional, nonreinforced ceramics. Whisker-toughened ceramic materials will be used by GTE in the production of auto parts.

Tensile Testing System for Ceramics

A major thrust of the Advanced Materials Development program has been to produce uniaxial tension test data on structural ceramics for use in advanced engines. For tension testing data to be useful to engine designers, the testing system must be able to apply pure uniaxial loads to the testpiece, but the high modulus and brittle nature of ceramics make this very difficult. Many past attempts had limited success or were abandoned because of the high cost of performing the test or the questionable results ob-

tained. Under the Advanced Materials Development program, DOE developed a high-temperature ceramic tensile test device with self-aligning grips. This hydraulic flexible coupling will not transmit bending moments and is completely self-aligning during a test, thus achieving the requirement for alignment on most testing machines. This testing methodology and the data generated will be critical to the designers of future advanced engines. The technology has been licensed to USA Instron and is being marketed as the "Super Grip System".



Dr. K.C. Liu, of Oak Ridge National Laboratory, using the "Super Grip System" to measure fatigue of ceramics at high temperatures.

Alumina-Based Ceramic

DOE has supported basic materials science research focused on developing high-strength, high-temperature materials for applications in automotive and light truck heat engines. Over the past six years, these research efforts have concentrated on developing alumina-based ceramic composite materials. As is often the case with basic research programs, successful results occurred in unanticipated areas. In this case, significant advancements in machine tool technology resulted from the alumina-based ceramics research. The composites developed possess many of the attributes required for automotive applications, but do not yet have sufficient high-temperature resistance. Alumina-based ceramics have been marketed for use in cutting tools and have potential applications for manufacturers of various products subject to mechanical wear (e.g. automotive parts). Cutting tools and machine tools that use this material demonstrate increased strength and improved performance compared with conventional machine tool technology. Oak Ridge National Laboratory (ORNL) has initiated an aggressive technology transfer program to disseminate alumina ceramic composite research program results. ORNL estimates that the industries identified above represent a $500 million dollar market and that licensing agreements can be reached with 80 percent of the firms in those industries. The benefits from development of this product will include royalties from licensing agreements with a variety of industries and substantial energy savings due to increased productivity, reduced weight and reduced levels of friction.

High Temperature Materials Laboratory

The efficiency of heat engines is limited by the ability of known materials to withstand stress under high temperatures. This materials factor restricts the efficiency and reliability of advanced energy conversion systems and is a barrier to high energy efficiency in many industrial processes. The DOE

High Temperature Materials Laboratory (HTML) serves as a national center for high-temperature materials research. At the HTML, a multidisciplinary staff investigates new ceramic and alloy materials with potential for high-temperature structural applications. In addition, the HTML functions as an experimental user facility providing industry and university researchers with advanced techniques and instrumentation. For example, the high-temperature flexure test facility in the HTML Mechanical Properties User Center is the first air-cylinder-based, completely computer-controlled flexure strength facility in the world. The HTML with its equipment, staff, and user centers is a critical component in the U.S. effort to compete in the international effort to develop high temperature structural materials.

Ceramic Turbine Rotors

Turbocharged automotive engines have long been recognized as offering distinct advantages over conventional engines, including better performance, increased flexibility in engine design, increased efficiency, and potentially lower costs. A major barrier to automotive market penetration by turbochargers has been the lack of a reliable, low-cost, load-responsive turbocharger rotor that can operate in a very high-temperature environment for extended periods. DOE has sponsored extensive research in the development of ceramic turbine rotors for applications such as turbochargers. Development of a ceramic turbocharger rotor will allow a 66 percent reduction in overall rotor weight, thus resulting in better energy efficiency. Research ac-

The High Temperature Materials Laboratory (HTML), pictured above and located at Oak Ridge National Laboratory, is a center for research on the ability of materials to withstand stress under high temperatures.

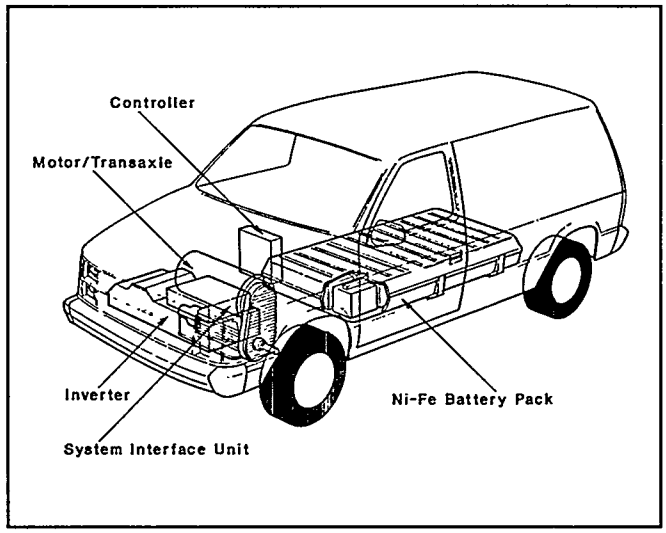
tivities have focused on materials development, fabrication processes, ceramic-to-metal joining processes, and nondestructive evaluation techniques. While research is yet to be completed for full-scale gas engine applications, major automobile manufacturers have incorporated DOE research program results into the production of ceramic turbocharger rotors. A ceramic turbocharger rotor application, the Nissan 300 ZX with a ceramic turbine supplied by Garrett Corporation, was first commercially available in 1986. Estimates of the turbocharger market potential exceed 6 million units worldwide by 1992, with ceramic turbocharger rotors projected to capture in excess of 75 percent of that market. Typically, turbocharging results in 5 percent efficiency improvements in spark ignition engines and 10 percent in diesel engine applications. Projections of fuel savings attributable to the use of advanced design turbochargers equipped with ceramic rotors range from 0.63 to 1.0 billion gallons of motor fuel annually, equivalent to 87 to 145 trillion Btu per year.

Electric Vehicle Site Operations Program

DOE has supported a wide range of electric vehicle-related research activities in conjunction with academic institutions, other federal agencies, and the private sector. These research activities are consistent with directives contained in the Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976. The DOE Electric Vehicle Site Operations Program provides a means of testing and evaluating the effectiveness of electric vehicle (EV) technology research products, primarily in the areas of advanced electric vehicle systems, subsystems, and vehicle components. Numerous EV technological developments have occurred since the initiation of DOE-sponsored research activities. Since its inception, this program has evaluated over 20 electric vehicle types and 16 specific product improvements. The results of testing indicate that research objectives are being met and often exceeded. EV energy consumption has been reduced by over 50 percent, reliability levels have increased by 78 percent, maintenance costs reduced by 60 percent, and overall life cycle costs reduced by 67 percent. The EV Site Operations Program provides design validation and unbiased information on specific applications for EVs to potential private sector investors.

Dual Shaft Advanced AC Propulsion System

Market studies have determined that the development of a commercial van would provide the first market niche for electric vehicles. The Dual-Shaft Electric Propulsion System Program (DSEP) is developing electric vehicle technology through the use of subsystem technologies developed by the Eaton Corporation and Eagle-Pitcher Industries, Inc. under contract to DOE. The major emphasis of the DSEP research is to advance existing battery and powertrain subsystem technologies in the context of an overall propulsion system technology. Industry is provided with an advanced electric vehicle propulsion system technology that is not only practical for light-weight van applications in the near term, but quite sensible from the standpoint of the overall system technology. An important achievement of this program was the completion of the first test-bed



Major system components in the Chrysler T-115, test vehicle for the development of light-weight, battery-powered commercial vans.

vehicle, a Chrysler T-115 mini-van, that uses a nickel-iron battery.

Gel Cell Lead-Acid Battery-Powered Electric Vehicles

DOE has sponsored numerous research activities with the goal of achieving viable, cost-effective electric vehicle technology. Maintenance costs of EVs were identified as a major barrier to their marketability. Beginning in 1982, DOE initiated an aggressive research effort with universities, the private sector, and federal agencies, to develop technology to reduce EV maintenance costs. Gel cell lead-acid batteries were identified as a technology that could reduce EV maintenance requirements and improve safety conditions and efficiency levels. Through research program support, DOE has stimulated private sector investment in automated gel cell production facilities that will decrease overall production costs by 50 percent and thus reduce the capital costs of gel cell batteries. Specific results of the gel cell battery research program include a 50 percent reduction in EV maintenance costs, an increase in EV energy efficiency of over 50 percent, 50 percent longer battery life, and increased levels of operating safety due to the sealed design of gel cell batteries. Gel cell battery technology developed in this program also can be used in mobile communications systems, mining, computer power supplies, and other applications requiring low-maintenance, long-life, and high-efficiency batteries.

Low-Cost/High-Temperature Alloy

Stirling engine technology uses power from an external heat source to fuel vehicles. The engine transmits thermal energy and must operate in adverse environments of extreme heat, corrosion, stress, and repeated cycling. Engine efficiency increases with higher operating temperatures which require special alloy materials for high efficiency, reliability, and longer lifetimes. Prior to 1981, Stirling engine structural components were fabricated from high-cost imported materials, such as cobalt, chromium, and nickel. Although these alloys performed well, commercial introduction of Stirling engine technology was impeded by economic factors and by the lack of a reliable source of the alloy components. DOE, in conjunction with NASA, sponsored research by academic institutions and private sector firms to develop a low-cost replacement alloy with equivalent properties. Surpassing expectations, the new alloy exhibits superior lifetimes, is far cheaper, and relies upon the use of entirely domestic resources, with the exception of nickel imported from Canada. In addition to its Stirling engine applications, this alloy has the potential to penetrate high-temperature structural materials markets throughout the U.S., particularly markets for conventional automotive heat engine applications. Energy efficiency benefits are expected to rise as the alloy achieves market penetration, because this material will make higher engine operating temperatures possible. By reducing dependence on strategic imported materials, this research effort has directly enhanced national security in the United States.

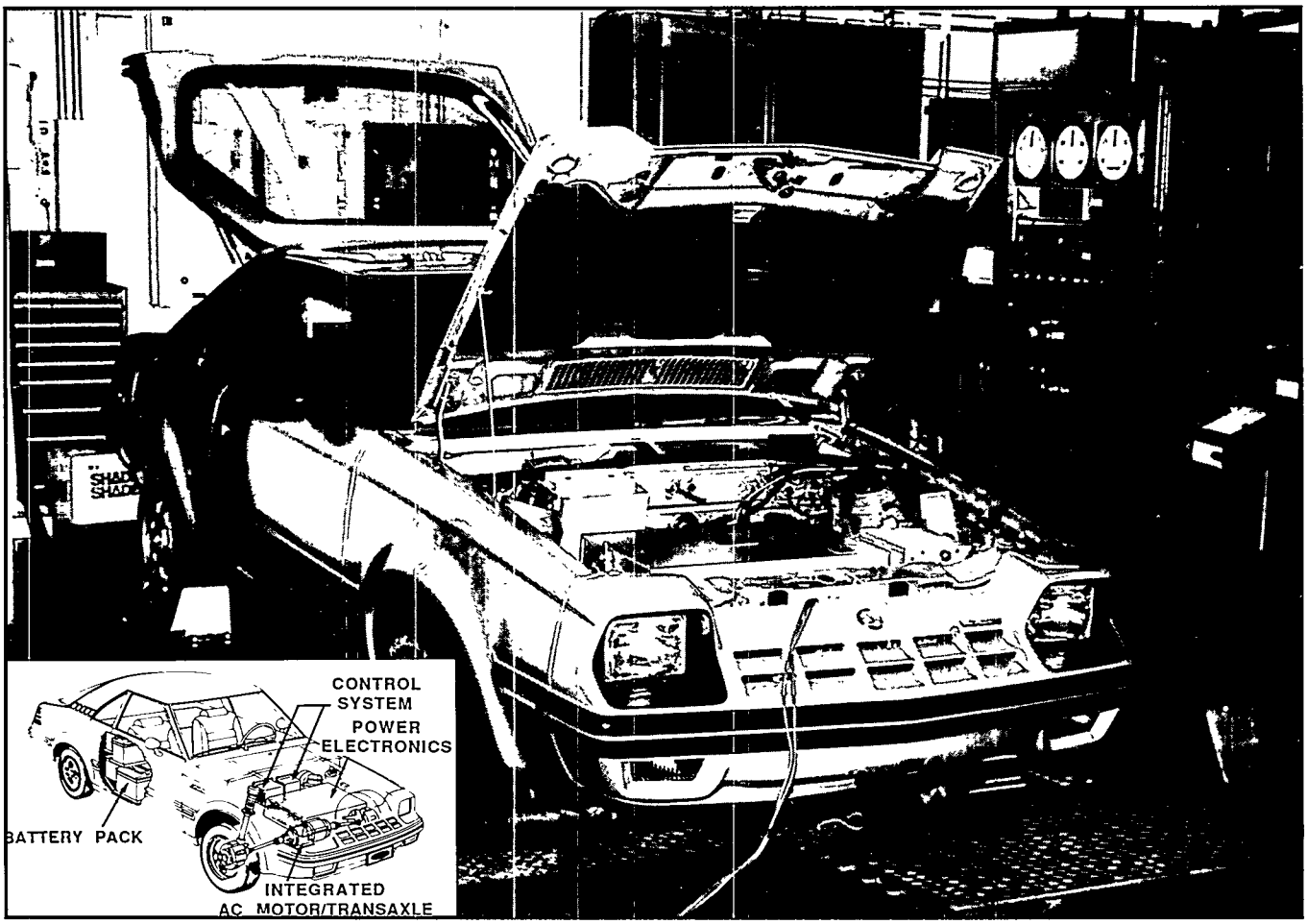
Nonautomotive Stirling Engine Applications

Stirling engines employ an external heat source to provide usable mechanical energy. Stirling engines feature low noise, high efficiency, low pollution, and low vibration levels, making this unique technology particularly useful in certain applications. The capability to use any source of heat as fuel, including solar or nuclear heating, makes this technology an attractive candidate for remote applications such as in-orbit power supplies, where conventional power systems are not feasible. As DOE-sponsored Stirling engine technology research began to demonstrate the validity of using Stirling engines in automobiles, other uses for this technology became apparent, including applications in solar power modules, irrigation systems, and mobile power generation systems. Associated research programs, such as high-temperature/low-cost alloys projects, will result in increased levels of Stirling engine efficiency. Limited market penetration in remote

power generation systems has already occurred, and demonstrations of Stirling engine technology sponsored by other federal agencies and private sector firms are currently underway.

Single Shaft Electric Propulsion Vehicle

One of the most successful of DOE's electric vehicle (EV) technology research programs was the ETX-I project, conducted by the Ford Motor Company, General Electric Company, Exxon Research and Engineering, and Lucas Chloride EV Systems. Applying an integrated systems approach, this project advanced EV technology through the use of alternating current (instead of direct current) and zinc-bromine, sodium-sulfur, and tubular plate batteries. The ETX-I vehicle is the first electric vehicle to demonstrate a useful range in excess of 100 miles. The ETX-I powertrain met or exceeded its design objectives for energy efficiency, acceleration, gradeability and driveability. In comparison to earlier electric vehicles, such as the ETV-I, the ETX-I demonstrates significant technological improvements such as a 50 percent weight reduction, a 40 percent reduction in size, and a 25 percent improvement in acceleration, without compromising efficiency. The ETX-I research program has demonstrated that EVs can effectively compete with conventional vehicles in certain market segments. The project validated the use of the integrated sys-



With the use of alternating current and advanced battery technlogy the EXT-1 electric vehicle demonstrated that EV's can compete with conventional vehicles in certain markets.

tem design for effective use of resources in EV research and development. GM has announced plans to introduce an electric van using this technology. The GM electric "G" van is scheduled for limited domestic production in 1989.

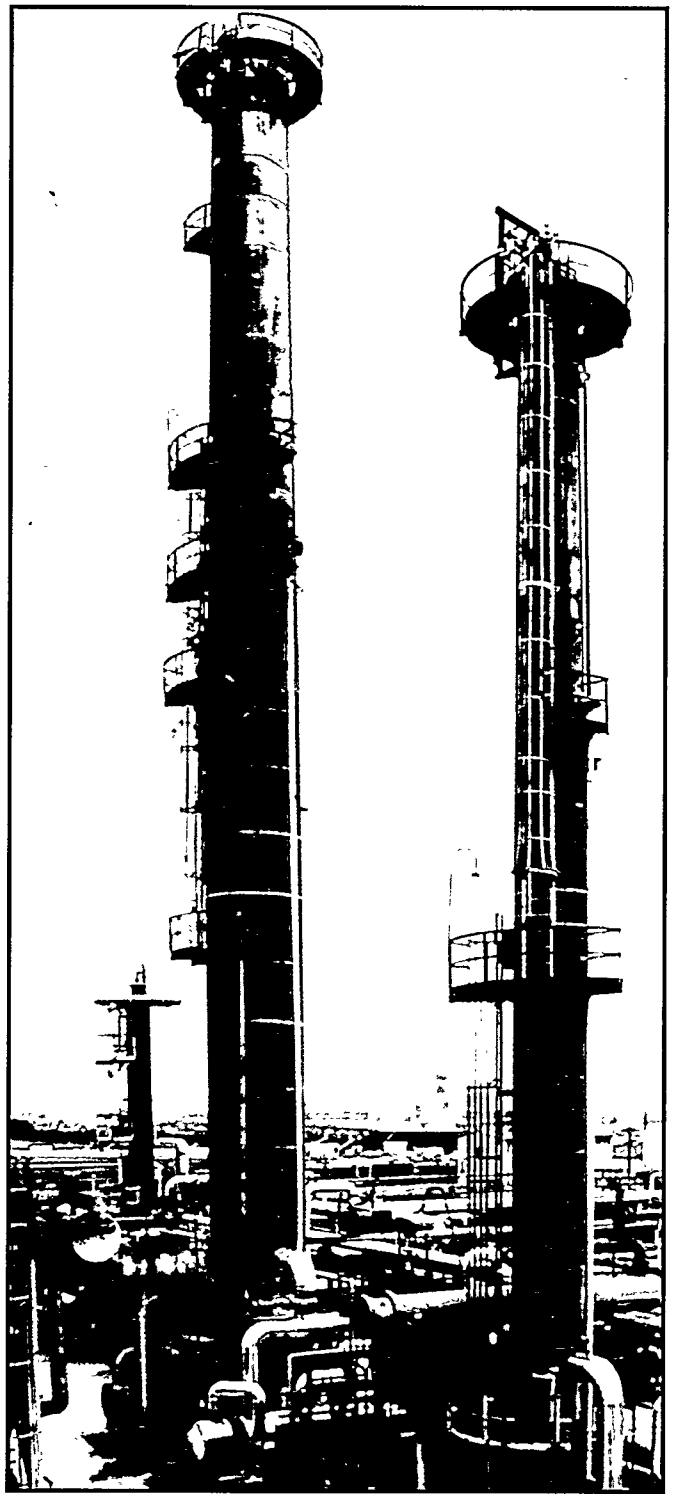
Alternative Transportation Fuels

The transportation sector relies almost entirely on petroleum products as a source of energy. Recognizing the vulnerability of this sector, DOE has sponsored research activities to develop alternative fuels. In cooperation with the Department of Transportation, numerous academic institutions, and private sector firms, DOE research initiatives have focused on long-term, high-risk basic research oriented towards the development of an alcohol fuels technology base to supplement and replace conventional hydrocarbon fuels. This initative has developed neat and near-neat alcohol-fueled vehicles and stimulated private industry to develop and market oxygenated fuels and additives such as ethanol, methanol, tertiary butyl alcohol, and methyl-t-butyl ether. These and other oxygenates are now blended with gasoline in quantities up to 10 percent by volume, replacing over 24 million barrels of oil (139.2 trillion Btu) on an annual basis. Oil import requirements have been reduced as a result of the implementation of these research results, and a broad technology base has been established that directly contributes to national security. The combustion characteristics of oxygenated fuels, particularly ethanol and methanol, also contribute environmental benefits, especially in regions which have not attained air quality standards, such as Southern California. DOE is working with the Environmental Protection Agency, the California Energy Commission, and the California Air Resources Board to develop alcohol fuels implementation strategies that will simultaneously reduce petroleum dependence levels and enhance environmental conditions.

Industrial Programs

Catalytic Distillation

A number of processes in the petroleum refining and petrochemical industries involve producing hydrocarbons via equilibrium reactions. Equilibrium reactions tend to be energy intensive because when equilibrium is reached the product must be removed before the reaction can proceed. The conventional procedure requires reiterative reaction and product separation steps, as in distillation, until the concentration of product and reactants is too low for further affordable recovery. Many of these processes release waste heat. A new single-stage catalytic reaction/distillation process was developed by DOE with Chemical Research & Licensing, Inc. for equilibrium hydrocarbon reactions. Compared to conventional multistage processes, the new catalytic distillation process is more energy efficient and lower in capital cost for a number of petrochemical and petroleum refining applications. Energy savings are realized because the new process directly uses heat released by the equilibrium reaction to remove reaction products by distillation, thus eliminating external heat exchange and its consequent energy losses. As of the end of 1987, five units are in operation in the United States and one each in France, Spain, and China. Estimated current energy savings in the United States are 0.23 trillion Btu per year. Estimated savings in 2010 are 43.3 trillion Btu per year.



External view of distillation towers used in petroleum refining. A new catalytic/distillation process developed by DOE saves energy through the use of heat released in catalytic reactions.

Coal-Fired Steam Turbine Cogeneration

Cogeneration systems, when used for industrial processes, have the potential to save thousands of dollars per year. However, these systems have not been selected for certain industrial operations such as textiles manufacturing because of space limitations or because the temperature of the cogeneration system turbine exhaust is too low for the processes involved. In addition, the textiles industry

has avoided coal-fired steam systems in general, due to environmental cleanup costs and plant problems connected with coal handling and firing. To change this trend, DOE co-funded the design, installation, and evaluation of an innovative, 4.1 MW high-back-pressure steam cogeneration system with Riegel Textile Corporation at one of the firm's textile plants. The new system uses a coal-fired boiler, modified to solve retrofitting space problems, to generate steam that powers a turbine to produce electricity. The turbine exhaust steam temperature is high enough to be used in existing mains for process heat requirements and for space heating. The system achieved net energy cost savings of $250,000 per year. Five such systems operated in 1987, saving approximately 2.15 trillion Btu per year.

Beck Dyeing Modifications

A large amount of textile material and carpet is batch dyed in a "beck", a large stainless-steel tub vented to the atmosphere. The conventional dyeing process is to load the beck with undyed textile or carpet, fill it with water, add the necessary chemicals and dyes, and bring the water to a boil by steam injection. Once the boiling cycle is satisfactorily completed, the used dye-bath solution is discharged as waste and the beck refilled with water to rinse the carpet or other textile. After the load is rinsed, the used water is discharged. As a result of a DOE program conducted in cooperation with Georgia Institute of Technology, Salem Carpets, Inc., and Adams-Millis, three types of modifications that reduce the amount of energy, water, and materials used in conventional dyeing have been tested. These modifications are bump-and-run, dye-bath reuse, and hot pull. The bump-and-run modification eliminates much of the conventional energy loss by reducing the demand for steam in the dyeing process. Dye-bath reuse involves recycling the spent dye bath after it is reconstituted. The spent dye bath is analyzed to determine the amount of dye remaining, and additional dye is added to obtain a desired color. Small amounts of auxiliary chemicals are also added to replace those lost in the dyeing process. Hot pull is a handling procedure that increases the attractiveness of dye-bath reuse by eliminating the final rinse step in conventional processing, thus minimizing handling of the spent dye bath and saving the water used by the final rinse. In 1987, 69 dye units used one or more of these innovations, saving 0.25 trillion Btu. Energy savings in 2010 are projected at 7.6 trillion Btu per year.

Energy-Efficient Fertilizer Production

Fertilizer production is energy intensive. A prototype reactor that substantially reduces energy use in producing many fertilizers was developed by the Tennessee Valley Authority with financial support from DOE. The prototype reactor has a pipe-cross configuration within which raw materials are processed to produce fertilizer. In this design the reactor process heat, in conjunction with increased air flow, causes the final product to have less than one percent moisture, reducing or eliminating the thermal drying function required for conventional fertilizers that contain 5 to 7 percent moisture before drying. Ten of these innovative reactors are now in operation in the fertilizer industry, saving about 0.17 trillion Btu per year. Projected annual savings in 2010 are 5.4 trillion Btu.

Foam Processing

Conventional wet processing of textiles (e.g., desizing, bleaching, dyeing, printing, and finishing) uses water to distribute pigments or other chemicals throughout the fabric. Wet processing is energy intensive since the fabric is repeatedly wetted and dried, and drying requires large amounts of thermal energy. Working with United Merchants & Manufacturers, DOE developed a more energy-efficient process through laboratory investigations, pilot plant trials, and commercial production. The process replaces some of the water with foam in the dyeing, printing, and finishing of a variety of fabrics, thereby reducing the energy required for drying, reducing water consumption and pollution control

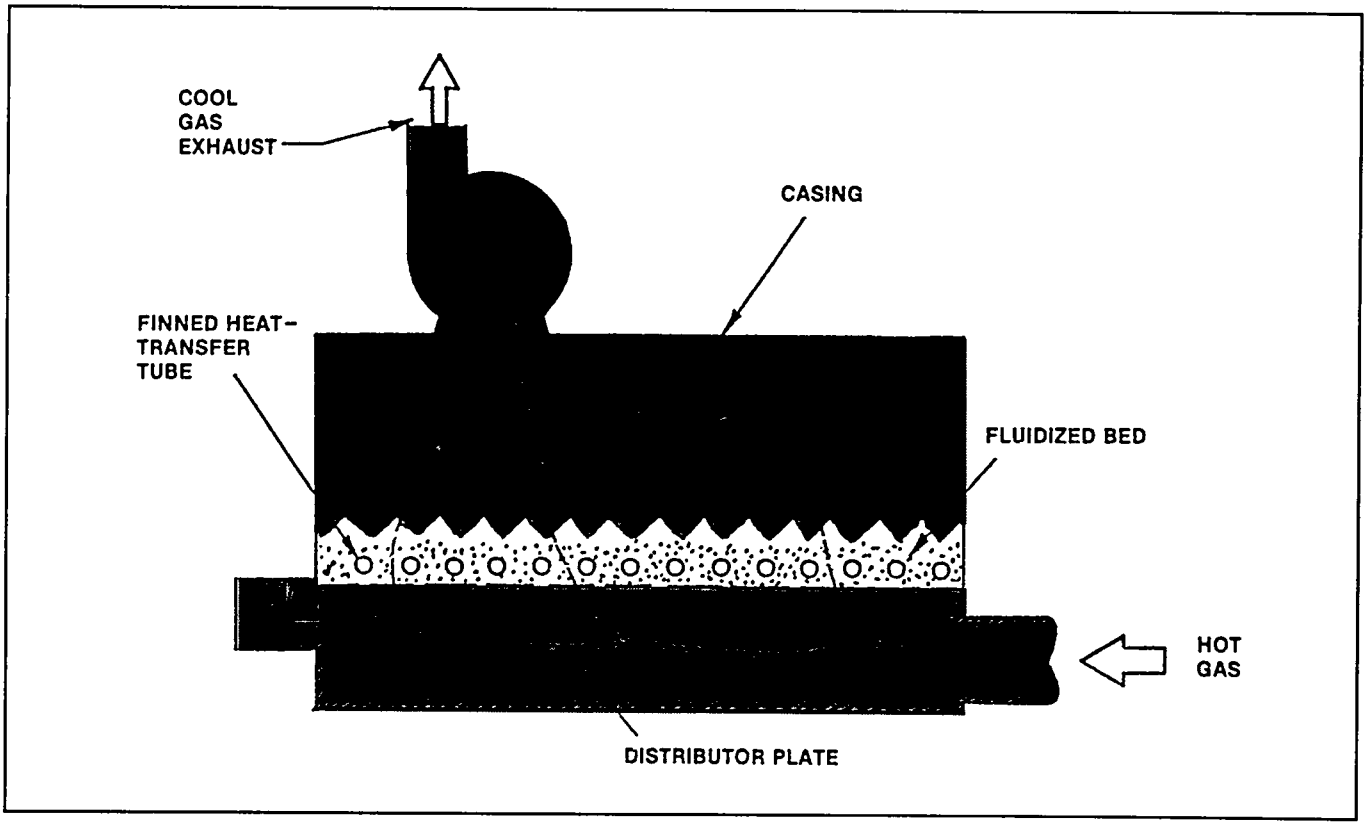
requirements, and increasing plant productivity. DOE has accelerated the adoption of the process by industry. At least 68 foam processing units are now in operation and over 2.5 billion yards of fabric and carpet have been processed, saving 1.38 trillion Btu annually. Foam processing is projected to save about 5 trillion Btu per year by 2010.

Fluidized Bed Waste Steam Boiler

In this cost-shared project, Aerojet General developed an advanced heat recovery system using a fluidized bed waste steam boiler to operate in fouling exhaust gas streams. Heat is recovered in the form of steam or hot water. The first U.S. industrial fluid bed heat recovery boiler has been installed in an ALCOA plant on an aluminum remelt furnace. The system has the potential to save 13 billion Btu per year, representing 85 to 90 percent of the energy entering the waste heat boiler. Aeroject General is now commercializing this technology, projected to save about 40 trillion Btu per year by 2010.

High-Efficiency Welding Unit

The greatest potential for significant energy savings in welding processes lies with improving power supply efficiency. Conventional arc-welding power supplies use a low-frequency transformer which is responsible for their inefficient use of power and for the large size and weight of the units. Because current continuously flows through the transformer, considerable energy is wasted when the unit is idling between steps in a welding job. Developed through funding from DOE and Cyclomatics, Inc., the "Inverter Technology" applied to arc welding power supplies has brought significant savings to the welding industry. The DOE/Cyclomatics inverter technology uses a silicon-controlled rectifier (SCR) and a high-frequency, high-efficiency transformer which together dissipate little energy. The SCR shuts off power to the transformer when the system is idling, greatly reducing electrical energy consumption. Typical power losses for the high-efficiency welding unit are 15 percent, as compared



Aerojet fluidized-bed waste-heat recovery system.

to 45 to 55 percent for conventional units. Power supply size and weight are drastically reduced as well. The DOE/Cyclomatic joint efforts are examples of successful government/industry cooperative research and development activities. Currently, there are more than 31,500 of these high-efficiency units in operation, saving an estimated 1.1 trillion Btu per year. By 2010, this technology is projected to save approximately 9.6 trillion Btu annually.

Solid-on-Solid Processing

Elimination of liquids used in the application of finishing and coloring chemicals to textiles can drastically reduce the drying requirement which accounts for half of the energy consumption in the textile industry. Three electrostatic powder concepts have been successfully demonstrated on a bench scale for dry application of chemicals to textile materials by solid-on-solid (SOS) processing. With DOE funding, this research has been conducted by Electrostatic Technologies Inc. of Connecticut and Nordson Inc. of Ohio in cooperation with Georgia Institute of Technology. Powdered chemicals containing a thermoplastic polymer component are deposited on the textiles through electrostatic attraction, followed by dry thermal flow of the polymer. This process avoids any use of extraneous liquids in the chemical application process, thus reducing energy consumption. Researchers at Georgia Institute of Technology have estimated that if half of the textile industry were to convert to SOS processing where appropriate, energy savings in the industry would be approximately 10 trillion Btu per year.

Innovative Coil Coating Ovens

In coil coating ovens, solvent-based paints on metal coils are continuously cured (to evaporate solvents and set resins) in the presence of large volumes of dilution air required to keep solvent concentrations within safe limits. Exhaust from the ovens is heated in thermal incinerators to burn the solvent vapor before release to the atmosphere. In a DOE project cost-shared with B&K Machinery and Roll Coater, an innovative coil coating system was tested and shown to be capable of reducing natural gas requirements by 74 percent. The innovative system works by recycling oven exhaust (at 600 F) to zone incinerators where the heat from the combustion of the solvent vapor is recovered and sent back to the curing oven to vaporize more solvent. Energy is saved in pollution control by reducing the volume of gases by 50 percent and by replacing the thermal incinerators with afterburners and waste heat boilers to produce process steam. A coil coating facility was retrofitted with this system, leading to the adoption of this technology by the coil coating industry. Twenty-five operating units saved 3 trillion Btu per year in 1987. Projected 2010 savings are 7.8 trillion Btu per year. As a result of this project, other coil coating system manufacturers have developed and marketed additional improvements to these systems without further government support.

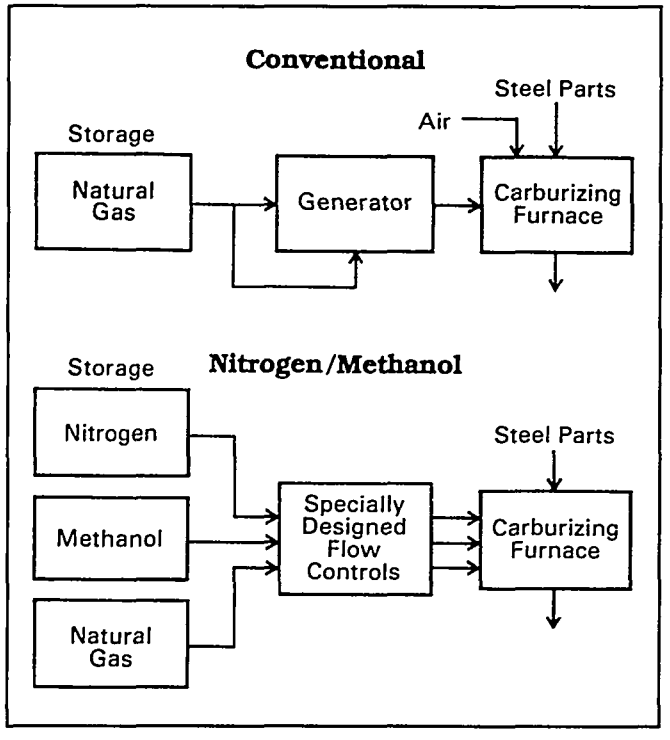
Hyperfiltration

Textile industry scouring, bleaching, and dyeing processes produce hot water waste streams containing dyes and other chemicals. The heat content and chemical content of this contaminated wastewater is normally lost when it enters the plant's wastewater cleanup system. With cost-sharing support from DOE, the U.S. Environmental Protection Agency, and the U.S. Department of the Interior, Carre, Inc. developed a pressure-driven membrane separation technique called hyperfiltration to separate the hot water, dyes, and other chemicals for direct reuse in textile processes. The hyperfiltration unit consists of zirconium oxide polyacrylate membranes dynamically formed on the interior of sintered stainless-steel support tubes. The unit was designed to recycle 90 percent of the dye wash water from a continuous dye range at a process temperature of 185 F and to remove 97 percent of the color. Current energy savings from three units in operation are 0.08 trillion Btu per year. Other potential uses of hyperfiltration include the extraction of apple juice

in the food industry, recovery of caustic solutions in the textiles industry, and concentration of radioactive sludge. The potential savings estimated for this new technology in 2010 are 112 trillion Btu.

Nitrogen-Methanol Carburization

Carburization is a method of heat-treating steel parts in a carbon-containing atmosphere to give them improved strength, hardness, and wear resistance. Pure methanol, enriched with natural gas, is broken down to produce an atmosphere containing one-third carbon monoxide (CO) and two-thirds hydrogen (H2). The conventional furnace atmosphere contains 20 percent CO, 40 percent H2, and 40 percent nitrogen. With DOE funding, a more energy-efficient methanol-based carburization process was developed and tested by Air Products and Chemicals. The process improves energy efficiency by changing the chemical composition of the furnace atmosphere. The higher concentrations of CO and H2 accelerate the rate of carburization and allow a reduction in the cycle time which saves energy. The advanced process is now in operation in 2089 furnaces and saved 3.6 trillion Btu in 1987. Projected savings in 2010 are estimated at 10.5 trillion Btu annually.



Use of methanol and flow controls to change furnace atmosphere make nitrogen-methanol technology significantly more energy efficient than conventional carburization technology.

ORC Bottoming Unit

In a conventional Rankine-cycle electricity generating system, water is alternately vaporized and condensed. Conventional Rankine-cycle systems have been the mainstay of electric power generation for nearly a century. Large power-generating steam plants can attain efficiencies of about 39 percent. However, at heat source temperatures below 700 F, steam systems become less efficient and too expensive to use. Conventional steam Rankine-cycle systems therefore cannot be used to economically generate electricity from many industrial waste-heat streams. DOE and Sundstrand Energy Systems developed and tested a new waste-heat electric power generation system consisting of a standard Rankine-cycle engine, an organic working fluid (toluene), a waste heat boiler, a waste-gas flow-control valve, system controls, and an electric generator. The system is rated at 600-750 kW, depending on temperature and mass flow rates of the waste-heat stream. This organic Rankine-cycle system is suitable for use with many types of waste-heat sources: gaseous streams above 600 F, liquid streams above 550 F, and condensing streams above 500 F. It is also readily adaptable to a wide variety of solar-energy and geothermal-energy applications. Two units operated as part of the DOE cost-shared project (in a manufacturing plant, and a U.S. Navy shore installation) achieved energy savings of .056 trillion Btu in 1987.

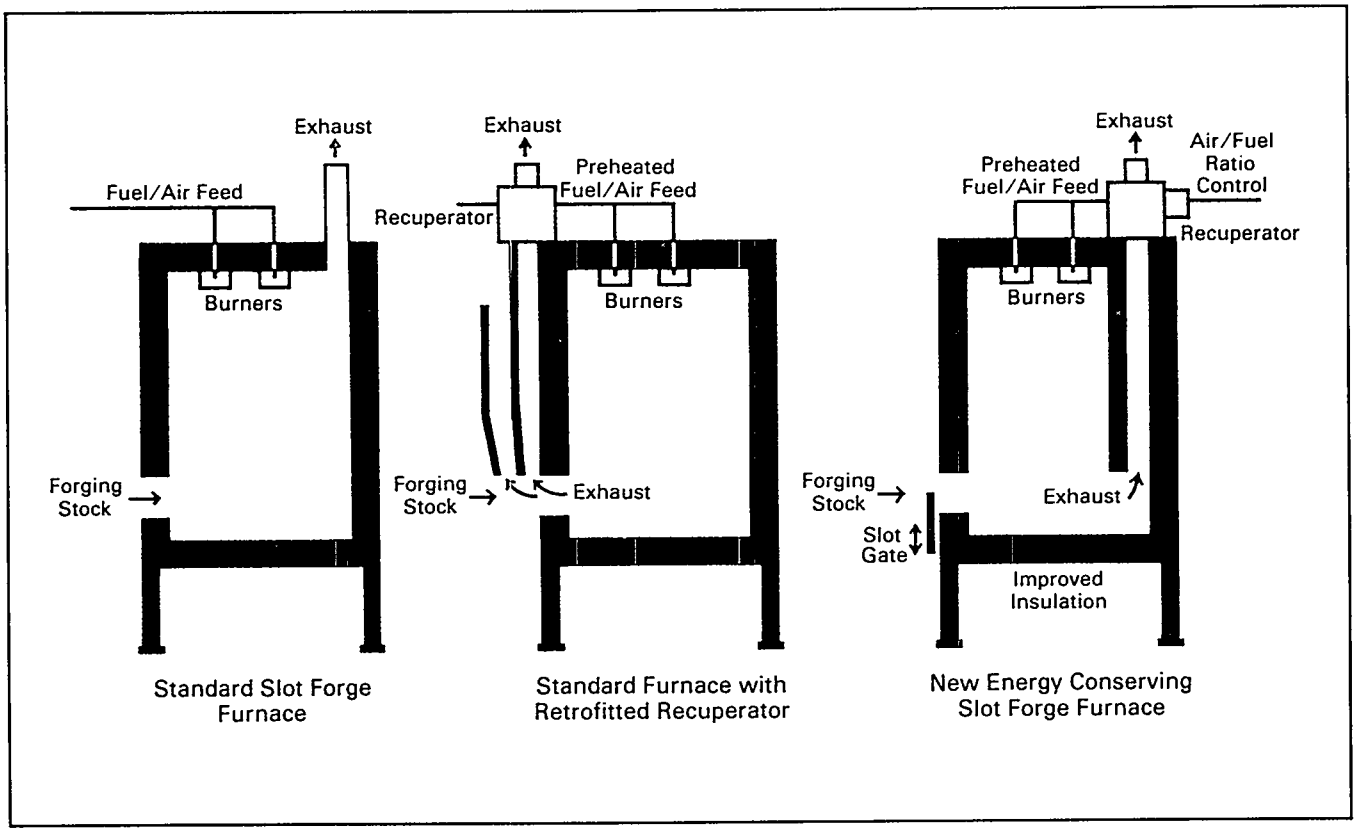
Slot Forge Furnace

Slot forge furnaces, which heat metal stock to about 2300 F prior to forging, can have thermal losses amounting to about 90 percent of the energy consumption as a result of loss of hot combustion gases,

conduction through the furnace walls and roof, and heat radiation through the slot. A high-performance slot forge furnace that minimizes these and other heat losses has been developed, tested, and demonstrated in a DOE cost-shared project with Hague International. The furnace design incorporates features that offer energy savings of 50 percent or more, while retaining the simplicity of a conventional slot furnace. The key feature is a ceramic recuperator that heats incoming combustion air with furnace exhaust gases. Other energy saving modifications include recirculation burners, improved temperature and air/fuel ratio controls, slot closure doors that open only for metal stock insertion or removal, and lightweight furnace wall insulation. Some 12,000 furnaces used in the forging industry could benefit from the improved technology. Due to a DOE acceleration effort, 21 units are now in operation, saving an estimated 0.46 trillion Btu in 1987. Projected savings in the year 2010 are 88 trillion Btu per year.

Slow-Speed Diesel Cogeneration

Low-speed, two-stroke diesel engines, used extensively in marine applications, have a higher electrical-to-thermal output ratio than alternative cogeneration system components such as steam turbines. In addition, when fired with residual oil, this engine offers a relatively compact size, excellent efficiency, greater load flexibility, lower fuel costs, and lower maintenance costs than cogeneration options presently used. To prove the advantages of such a system, DOE and Hoffman-LaRoche, Inc. cofunded the design, installation, and evaluation of an industrial cogeneration system using this technology. The system uses a low-speed, two-stroke diesel engine fired with low-sulfur fuel oil coupled to an electrical generator; a supplementary oil-fired waste heat boiler that reburns the diesel's exhaust for steam production; and heat exchangers for recovering waste heat from the engine to provide hot water. The engine system generates 23.3 MW of electricity.



Improved designs for slot forge furnaces incorporate ceramic recuperators and other energy conservation features to attain energy savings of 50% or more in comparison to standard furnaces.

Evaluations are continuing at the Hoffman-LaRoche pharmaceutical plant where this system was installed and is operating successfully. Four units are presently operating, saving 1.93 trillion Btu per year. At $4 per million Btu, this is equal to cost savings of $7.7 million annually. Estimated energy savings in the year 2010 due to this technology are 171 trillion Btu per year.

Energy Analysis and Diagnostic Centers

Large numbers of small and medium-size manufacturers lack the technical resources to perform thorough energy audits of their plants. DOE has sponsored a program to offer, at no direct cost to these manufacturers, plant energy analyses performed by engineering faculty and students from U.S. universities. The program has grown from its experimental beginnings in 1976 to include 13 participating universities located across the nation. To date, the Energy Analysis and Diagnostic Centers (EADCs) have performed over 2000 plant audits. Frequently recommended measures include the use of lower wattage lamps; insulating bare storage tanks, vessels, and lines; adjusting burners; and installing compressor air intakes in the coolest locations. From 55 to 75 percent of the recommended measures have been implemented, generally those involving smaller capital cost. Currently, the energy savings due to the EADC program are approximately 13.5 trillion Btu per year, worth about $45 million.

Boiler Workshops

Steam boilers are the most prevalent energy conversion technology in industry. Boilers are used in every industrial and commercial sector to produce process steam, hot water, and building heat. Even small efficiency improvements in the operation of these boilers can save large amounts of fuel. DOE developed a national program of energy-efficiency information and instruction for boiler operators to promote more cost-effective and efficient maintenance and operating practices. Under this program, university faculty members and boiler technology specialists taught well-attended courses all over the country. Many local and industrial organizations followed through and expanded on the pilot DOE program by continuing the courses with their own funding. These workshop courses for boiler operators are still held periodically in many areas of the United States. The energy savings due directly to this DOE project completed in 1987 are estimated at 2.8 trillion Btu per year.

Brayton-Cycle Solvent Recovery

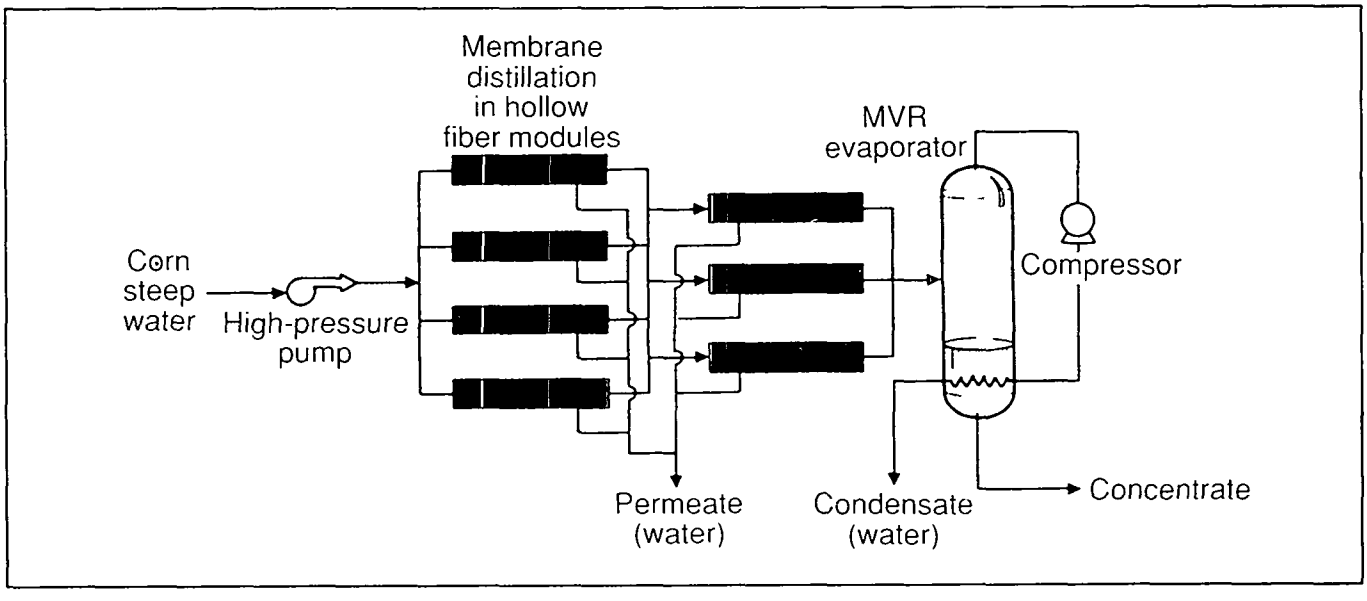
In 1980, approximately 19.3 million tons of volatile organic solvents were lost as waste emissions from industrial processes of the petroleum, organic chemicals, paint, adhesive, printing, and dry-cleaning industries. Under a DOE contract, Garrett AiResearch has developed a Brayton-cycle heat pump designed to recover volatile organic solvents from waste vapors. The inherent cooling and heating capabilities of a Brayton-cycle heat pump provide an economical, energy-efficient solvent-recovery system in which solvent is recovered by condensation. With this system, solvent-laden gas enters the Brayton-cycle compressor, where part of the heat of compression drives the turbines, augmenting the electrical energy supplied to the motor-driven compressor. The rest of the heat of compression is returned, via a regenerator, for reuse in the industrial process. Solvent precipitation begins in the condenser and continues as the gas mixture expands through the turbine. Expansion of the gas causes further condensation of the solvent, which is collected in a coalesce separator. The first installation of the Brayton-cycle solvent-recovery system by the 3M Company at its magnetic-tape production facility in Hutchinson, Minnesota is estimated to save 38 billion Btu annually. By ensuring a consistent solvent quality, the system also improves productivity in the tape-making process.

Membrane Separation in the Sweetener Industry

The dewatering of waste streams is the most energy-intensive process in the corn sweetener industry. Industry wide, about 5 billion gallons of steep water must be concentrated each year using energy-intensive evaporators which consume 5 trillion Btu per year. With DOE support, an energy-efficient membrane system has been developed by Bend Research Corporation to preconcentrate corn steep water using an improved hollow fiber membrane design. The process employs reverse osmosis, leaving a concentrated solution of organic compounds such as sugars on the feed side of the membrane. The technology for the process has been tested at a Midwestern corn milling plant. The system is capable of extracting over 50 percent of the water from the corn steep stream prior to evaporation, significantly reducing energy requirements. Compared to a conventional mechanical vapor recompression (MVR) system, the membrane distillation process combined with an MVR evaporator provides a capital cost savings of 13.5 percent and an operating cost savings of 20 percent. Projected savings in the year 2010 are estimated at 4.5 trillion Btu per year.

Oxygen Production by Chemical Air Separation

Industrial oxygen is used in thermal processes at metal, chemical, and utility plants. Currently, it is produced by the cryogenic process in which air is compressed, liquefied, and distilled into its components. This process is energy-intensive because thermal energy must be converted to the mechanical energy that compresses air, with an energy loss of about 66 percent. Typically, about 2000 Btus are used to produce each pound of oxygen. With DOE cost-sharing, Air Products & Chemicals Incorporated is developing a process, invented by Energy Concepts Company, to produce oxygen with 40 percent less energy consumption and 15 to 25 percent lower overall costs than current cryogenic processes. The chemical air separation process produces oxygen of 99.8 percent purity. Thermal energy can be conveniently supplied from high-temperature plant waste heat. Potential applications include use in the production of steel, nonferrous metals, and chemicals. Operation of the process has been demonstrated in a quarter-ton per day process development unit. Energy costs are reduced by up to 40 percent for a thermal swing chemical air separation process that is integrated with a steam



Membrane distillation in hollow fiber membrane modules can significantly reduce the energy requirements for conventional MVR evaporation of corn steep water.

boiler. In addition, electricity consumption in the new process is lower than in the cryogenic process, resulting in an overall energy savings of 44 percent. Projected annual savings in the year 2010 are estimated at 44.1 trillion Btu.

Cement Particle Size Classification

A major cost in cement production involves grinding and separation of fine and coarse cement particles. Through a cost-shared effort with Construction Technology Laboratories, Inc. (CTL), a subsidiary of the Portland Cement Association, research has been completed that shows that these costs can be substantially reduced through the use of: a) controlled particle size distribution cement, b) high-efficiency classifiers, and c) mill configuration and operating changes. Full implementation of this technology would save the average U.S. producer $400,000 per year in finish grinding costs alone. In addition, plant finish grinding capacity can be increased by more than 25 percent and product quality is higher. Thirty-two plants are using the new technology and are currently saving an estimated 0.94 trillion Btu per year. By 2010 annual energy savings could reach 11.1 trillion Btu.

Membrane Distillation

Thermal distillation processes, by which feedstock components of differing boiling points are separated, are highly energy-intensive. In the petroleum processing industries about 30 percent of energy consumption is used in separations, primarily in distillation processes. With DOE support, researchers at Allied/Signal Corporation have developed an alternative separation method which is energy efficient. This method employs a membrane system to separate light hydrocarbons from a stream of heavy oils in the petroleum refining process. The process recovers solvents used in the deasphalting of heavy oils, reducing by as much as 43 percent the amount of solvent to be stripped by evaporation, leading to significant energy savings. In the membrane distillation process, a gel layer of heavy molecules from crude oil feedstock is allowed to build on the surface of a membrane, which serves as a backing material. This gel layer, controlled for growth and stability, performs the separation. The system is stable in a hydrocarbon environment of up to 50C. Potential savings by the year 2010 are estimated at 24.8 trillion Btu per year.

Carbon Dioxide Recovery Process

The rapid expansion of Enhanced Oil Recovery (EOR) has resulted in a demand for carbon dioxide, which is used in EOR technologies. Currently, the only economical sources of carbon dioxide are natural deposits and process vents at hydrogen plants. In cooperation with the Argonne National Laboratory, DOE has successfully completed a test to recover carbon dioxide by burning coal in oxygen and recycled flue gas. The major cost components of the coal-oxygen process are the capital costs of the air separation plant and the cost of the electricity required to run the plant. The capital cost of a separation plant is approximately $21,000/ton per day for a plant of 1,818 tons daily capacity. The electrical requirement is 242 kW-hr/ton of gaseous oxygen produced. The oxygen required to produce a ton of carbon dioxide with the process is 0.8 tons.

Nitrogen Sensor for Precise Fertilizer Application

Energy for production of agricultural fertilizers represents 50 percent of the total U.S. energy expenditure in crop production. Conventionally, nitrogen fertilizers are applied evenly to entire fields, regardless of uneven soil conditions. As a result, large amounts of fertilizer are wasted in areas where application is not only unnecessary, but may also be harmful to the environment. In cooperation with Crop Technology, Inc., DOE has developed a new mobile soil nitrate sensor which automatically releases precise amounts of required fertilizer as it tests the soil. The device is comprised of electrochemical sensors attached to a leading knife which runs along a field below the soil surface. The

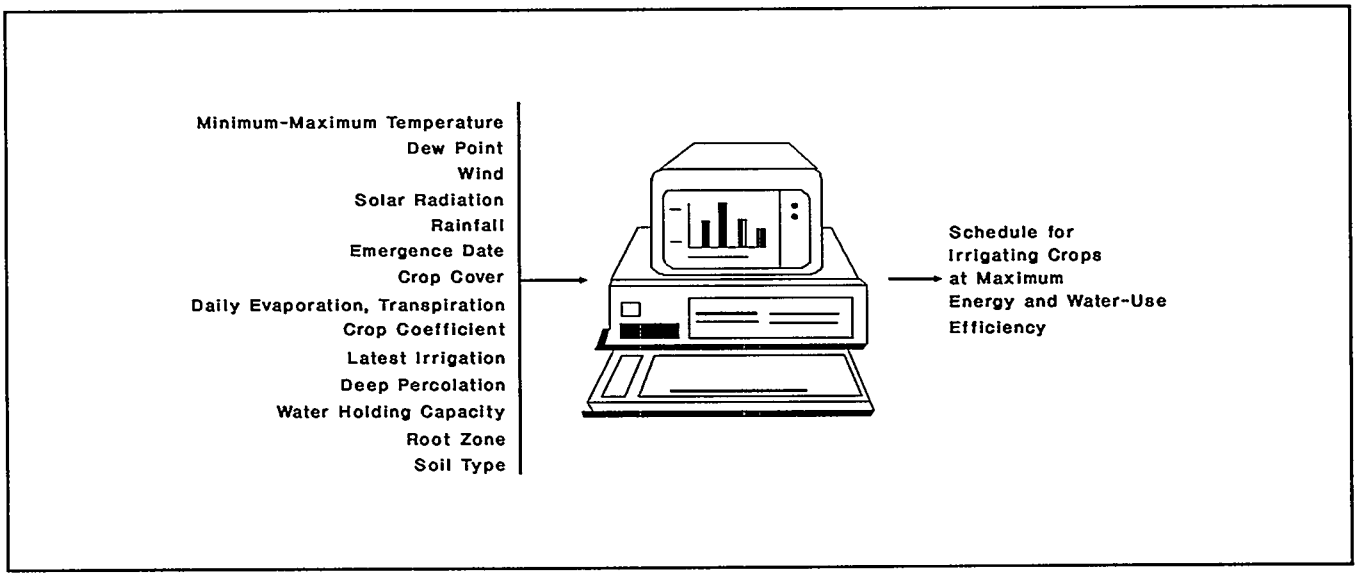
knife injects a solution into the soil at the rate of one gallon per acre, costing about 30 cents. The solution causes a chemical reaction with nitrates in the soil, which is then electronically measured. Each of three sensors takes a nitrate sample every three feet as the applicator moves across the field. A controller receives the signal and the applicator then applies the appropriate amounts of nitrogen to bring the level up to a predetermined concentration. Initial field tests report an increase of approximately 10 percent in crop yield. The system is currently undergoing additional field tests. The potential energy savings for this technology alone are estimated at 10 trillion Btu per year.

High-Purity Silicon-Carbide Powder Process

The production of ceramics traditionally has relied on comminution to reduce materials to a uniform particle size. This is accomplished through grinding and crushing operations which are typically less than one percent energy-efficient. A high-purity, low-cost, silicon-carbide powder process, developed by Oak Ridge National Laboratory and Advanced Refractory Technologies Inc., eliminates most of the comminution required in the production of ceramics. In the new process, powder is produced by a rotary kiln technique. Quantities of sample powder have been distributed to major ceramic component producers for manufacturing evaluation and properties testing. Projected material cost for this pure silicon-carbide powder are estimated at one-third to one-fourth of present powder costs, making high-temperature ceramic recuperators much more economical, as well as providing a higher-quality product.

Irrigation Systems

An estimated 60 million acres of agricultural land are irrigated annually nationwide, consuming nearly 270 trillion Btu at a cost of $1.4 billion. DOE, in cooperation with five universities and five private businesses, funded a program to develop and demonstrate new energy saving technologies for irrigation. Three resulting technologies which yielded significant energy and water savings are: 1) computerized scheduling, 2) reduced-pressure application systems, and 3) drop-tube application systems. These technologies are in use at about 12,000 sites across the country and together are saving about 3.5 trillion Btu annually. They have the potential to save 40 trillion Btu per year by the year 2010.



Computerized Scheduling for Irrigation: Computers can quickly convert a wide variety of data into useful scheduling information.

Black Liquor Gasification

Recovery of kraft black liquor, produced as a by-product in paper manufacturing, provides a significant source of energy for the paper production process. Kraft black liquor has traditionally been recovered by the Tomlinson boiler process. This process has the disadvantages of low energy efficiency, high capital and operating costs, significant air emissions, and a potential for explosions. Champion International Corporation and Rockwell International have demonstrated on a laboratory and limited pilot plant scale that kraft black liquor can be gasified in a fused salt reactor to produce low-Btu gases. The clean gases are of suitable quality to be burned directly in a gas turbine to produce electrical energy, and the combustion products can be fed to a waste heat boiler to raise steam. The gasifier will have a throughput sufficiently high and a heat loss sufficiently low to permit production of product gases with a heating value of about 100 Btu/scf. Compared to the Tomlinson boiler process, the gasification of kraft black liquor offers high energy efficiency, reduced air emissions, modularity, a higher output ratio of electricity-to-steam, and improved safety. Economic analysis indicates significant potential savings in both capital and operating costs compared with alternative systems.

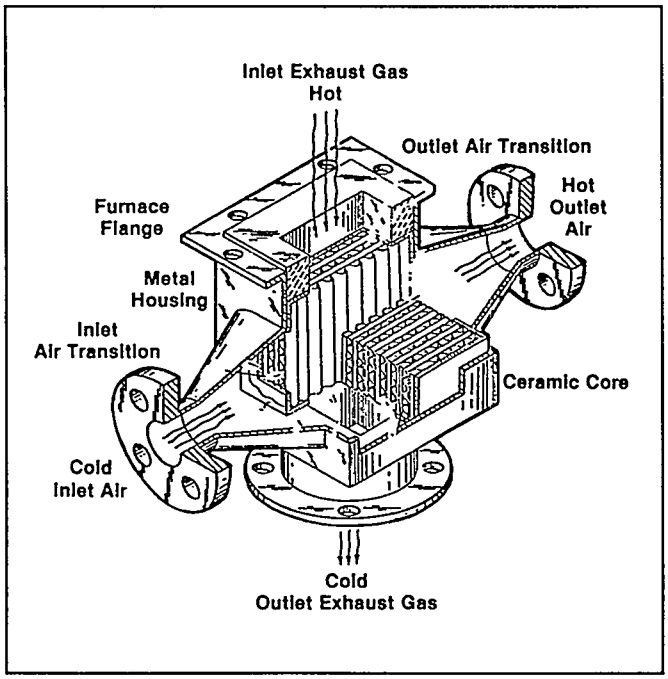
Heat Recovery Membranes in Dryer Exhaust Streams

Dryers are used throughout industry in various operations which require removing moisture from a product. Energy in the form of heat is lost to the atmosphere in the moisture-laden exhaust from these processes. With the sponsorship of DOE, Bend Research has developed a membrane-based process to recover the latent heat of water vapor in dryer exhaust streams. The key element in this process is a membrane which is permeable to water vapor and impermeable to air. The pressure difference created by the membrane is used to recompress the water vapor, delivering several times more energy than the electrical energy required to drive the compressor. The membrane-based process has been successfully tested at the Crown Zellerbach paper plant in Wauna, Oregon. Applications for the process include: drying of fertilizer during its production; drying of sugar as part of its refining process; drying of paper during production; and fluid-bed drying of coal. When applied to fluid-bed coal drying, for example, the membrane-based process can recover about 30 percent of consumed energy, with an estimated payback period of 3.7 years. It is estimated that the process can save approximately 10 to 20 percent of the 1.89 quads of energy used annually in process drying applications.

High-Temperature Recuperators

Industrial processes relying on combustion heating are highly energy-intensive, particularly at high combustion temperatures where over 50 percent of the energy consumed as fuel escapes in the process exhaust. Recuperators can recover significant portions of this wasted energy by returning heat from the exhaust to the combustion process in the form of preheated air. Conventional recuperators provide combustion air at a maximum temperature of 1300 F. The development of high-temperature burner duct recuperators allows recovery of heat from exhaust gases to product combustion air with temperatures of up to 2000 F. This significant increase in combustion air temperature results in correspondingly significant increases in energy savings.

Bayonet Ceramic Tube Recuperator - A cost-shared project between DOE and Babcock & Wilcox Corporation has developed a ceramic tube recuperator for use in steel plants. The recuperator is a two-stage unit; the first stage is a ceramic recuperator which can withstand continuing high temperatures, followed by a second-stage metallic recuperator which provides a higher level of heat recovery efficiency. Since its installation in 1982 at the Babcock & Wilcox site, this unit has achieved a 42 percent fuel saving. Projected annual savings for this type of recuperator in 2010 are estimated at 42 trillion Btu.



Cut-away drawing of the GTE ceramic recuperator. Ceramic recuperators can produce 40%-50% energy savings in furnaces by using hot exhaust gases to preheat incoming combustion air.

Cruciform Ceramic Tube Recuperator - The cruciform ceramic tube recuperator, developed by DOE in conjunction with Garrett AiResearch, uses a unique design to recover heat in the harsh environments of combustion exhaust where conventional heat exchangers fail. By preheating combustion air to 2000 F, the recuperator can save up to 50 percent of the fuel consumed in the combustion process. The first production unit of the cruciform ceramic tube recuperator was tested in a rotary forging furnace at Cameron Iron Works in Houston, Texas. Potential energy savings by the year 2010 are estimated at 43 trillion Btu per year.

Ceramic Recuperator - A new cross-flow, ceramic recuperator for use in high-temperature (1600-2600 F) relatively clean exhaust environments was developed and tested by GTE with DOE cost-sharing support. The "heart" of the recuperator is a ceramic (magnesium aluminum silicate) core composed of alternate layers of ceramic passages oriented at right angles to each other. Development and acceleration efforts have shown the recuperator to be applicable to a wide variety of industrial furnaces in several industries with resultant energy savings of 26 to 50 percent versus unrecuperated furnaces. As a result of DOE's technology acceleration program and the developer's marketing efforts, the recuperator is achieving widespread industrial acceptance and implementation. Some 694 operating recuperators of this type are currently saving an estimated 1.04 trillion Btu per year. By the year 2010, annual energy savings could be as much as 15.7 trillion Btu.

Metallic Recuperators - A metallic plate-fin recuperator to overcome exhaust temperature limitations and thus promote waste energy recovery was developed and tested by Garrett AiResearch with DOE support. This compact, stainless-steel plate-fin recuperator is designed to maximize the driving forces for heat exchange and to limit thermal stress. The plate-fin matrix consists of layers of corrugated sheet stock (fins) separated by plates. Tests show the recuperator able to perform satisfactorily with clean exhausts at temperatures up to 1500 F and to sustain a recuperator effectiveness of 85 percent for over one year while requiring no maintenance. Success of the recuperator prompted an acceleration program to expand knowledge of the operational characteristics of the device. Fifty-seven of these recuperators were operating in 1987 and saved an estimated 0.49 trillion Btu. It is anticipated that in the year 2010 this type of recuperator could be saving over 15 trillion Btu annually.

Plating Wastes Concentrator

The rinse water discharges from electroplating processes contain high concentrations of pollutant chemicals such as chromic acid, nickel sulfate, and zinc cyanide. Excessive pollutant discharge is presently avoided by high-temperature evaporation or chemical precipitation to produce a concentrate for disposal or recycling. These processes consume substantial amounts of energy and have high operating costs. An alternative way to concentrate large volumes of aqueous wastes is to boil the liquid at

pressures below atmospheric pressure, at which liquids boil at lower temperatures. This approach is used in multiple-effect evaporators that evaporate liquid in successive stages (or effects), each stage being at a lower pressure than the previous stage. A low-cost vapor-recompression evaporation system was developed by DOE and LICON, Inc. for use in concentrating electroplating wastes. The energy efficiency of the system is equivalent to that of a conventional 10- to 12-effect evaporation system. In the vapor-recompression evaporator, the energy in the latent heat of the liquid normally lost to the condenser by evaporation is recycled by the compressor, providing a temperature difference across the heat exchanger that promotes further evaporation. The only additional energy needed is power for the pressure increase to provide the temperature difference. The result is a decrease in the energy required to remove water to 50-75 Btu per lb. Seven systems are presently operational, saving an estimated 0.05 trillion Btu per year. Projected savings are approximately 11 trillion Btu per year by 2010.

Energy Utilization Research

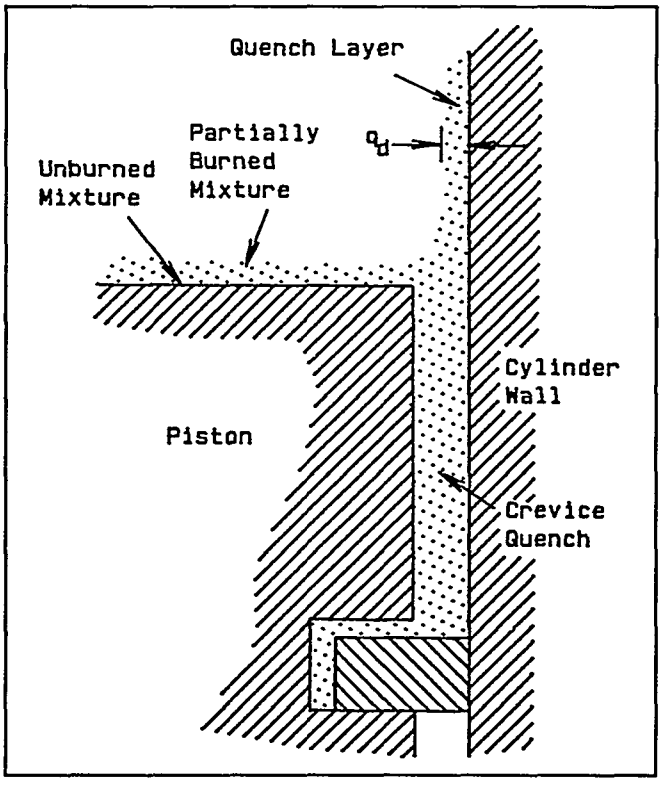
ENERGY CONVERSION AND UTILIZATION TECHNOLOGIES

Mathematical Model for Designing Automobile Engines

Advanced engine concepts have a tremendous potential to save energy; the transportation sector alone consumes about 20 quads of liquid fuels every year. The successful development of more efficient engine concepts largely depends upon the fuel spray activity in the combustion chamber of the engine and the ability of the engine to consume the fuel-air charge completely. Hence, the capability to represent an evaporating fuel spray in numerical calculations of chemically reactive fluid flows is of steadily increasing interest to internal combustion engine designers and manufacturers. DOE has developed, documented, and released into the public domain a three-dimensional engine combustion computer model, KIVA. Although developed with applications to internal combustion engines specifically in mind, because of the generality of the concepts on which it is based, KIVA can be adapted to a variety of other applications with only minor modifications. This new capability to model fuel sprays has lead engine designers and developers to address comprehensively the engine combustion problem and incorporate design changes according to the new insight gained. KIVA has now been accepted as the industry standard for automotive engine model development. Efforts continue to improve the capability of KIVA to more accurately characterize turbulence typical of chemically reactive flows. It is currently being extensively used by automotive industry researchers in developing energy-efficient, EPA-compliant engines.

Sources of Unburned Hydrocarbon Emissions from Automotive Engines

Lack of knowledge of basic thermochemical processes involved in the combustion of fuels has resulted in escalating equipment costs for pollution control and in the failure of designers and developers to exploit potential efficiency improvements in combustion systems and devices. For more than 20 years the quench layer theory dominated the technical literature as the model for unburned hydrocarbon emissions from automotive engines. A new understanding about the sources of unburned hydrocarbon emissions from dilute homogeneous-charge (DHC) engines has developed from the collective efforts of eight industry and DOE contractor research teams working primarily within the DHC cooperative group of the ECUT Engine Combustion Technology Project. The researchers have completed the experiments and analyses to prove conclusively that conventional wisdom was incomplete regarding the



ECUT engine combustion research identified "crevice quench" as a major source of unburned hydrocarbon emissions from DHC engines.

origin of unburned hydrocarbon emissions in piston engines. The process of flame quenching by the cold walls had been determined to be of negligible importance as a source of unburned hydrocarbon emissions from DHC engines. Rather, piston ring and head gasket crevice volumes and the absorption/desorption by lubricating oil filters and combustion chamber deposits are largely the controlling factors. This new understanding of the physical processes involved has allowed engine designers to focus their efforts on the difficult engineering tasks of reducing these crevice volumes and of solving the continuing problems in warm-up and transient operation. These efforts should lead to the resolution of a major technical limitation in use of the DHC engine concept.

Understanding "Engine Knock"

A significant increase in the thermodynamic efficiency and a corresponding decrease in the fuel consumption of automotive spark-ignition engines can be achieved with an increase in the compression ratio. However, increases in the engine compression ratio are limited by the onset of engine knock and the possible risk of engine damage. Knock is the engine response to a rapid, non-uniform pressure rise in the combustion chamber. Such high rates of pressure rise appear to be caused by the nearly uniform autoignition of the end gases before the flame passes through them. The results of recently completed experiments and kinetic modeling simulations of the compression ignition process have provided new insight on the problems of autoignition and engine knock. It is now known that the role of low temperature chemistry in the end gases is to provide enough heat release to increase end-gas temperature sufficiently to cause hot ignition. The exact kinetic mechanism is under continued investigation. ECUT research provides clarification of which factors are most important, so that future work can be better directed toward possible mitigation of problems. It may even be found that these thermal, fluid mechanical, and chemical mechanisms can be harnessed and controlled to provide rapid energy release, high compression ratio, and minimum risk of mechanical damage. These should lead toward higher efficiency, cheaper operation, and a better competitive position for U.S. products.

Combustion Characteristics of Alternative Diesel Fuels

Cetane numbers have been successfully used since the 1930s to rate the ignition quality of diesel fuels on the market. However, attempts to rate the ignition quality of a wider variety of alternative fuels being considered for use in diesel engines have met with limited success. The lack of an accurate rating procedure poses a serious problem for engine manufacturers and fuel producers as they try to assess engine designs and alternative fuels for use when the current supply of high-quality diesel fuel is depleted or disrupted. Recently, tests of several potential alternative fuels in diesel engines have found that ignition quality did not always correlate with cetane number. The fuels tested included possible near-term fuels and fuels being considered for emergency use. Under DOE support, the ignition characteristics of several alternative fuels for diesel engines were measured in a constant volume combustion "bomb" to investigate the shortcomings of the current American Society for Testing and Materials (ASTM) cetane rating method when applied to these fuels. In a parallel effort, the same fuels were tested in operating direct- and indirect-injection diesel engines. It was found that combustion bomb testing provides additional essential and complementary information to conventional engine testing. Important differences in the low-temperature ignition kinetics of alternative fuels were detected with the bomb technique which were not evident in the existing cetane rating procedure. The bomb tests indicated that modification of the current procedure would be required to improve the rating of future broad-specification fuels. This fundamental method of characterizing combustion of fuel sprays in diesel engines should lead to better

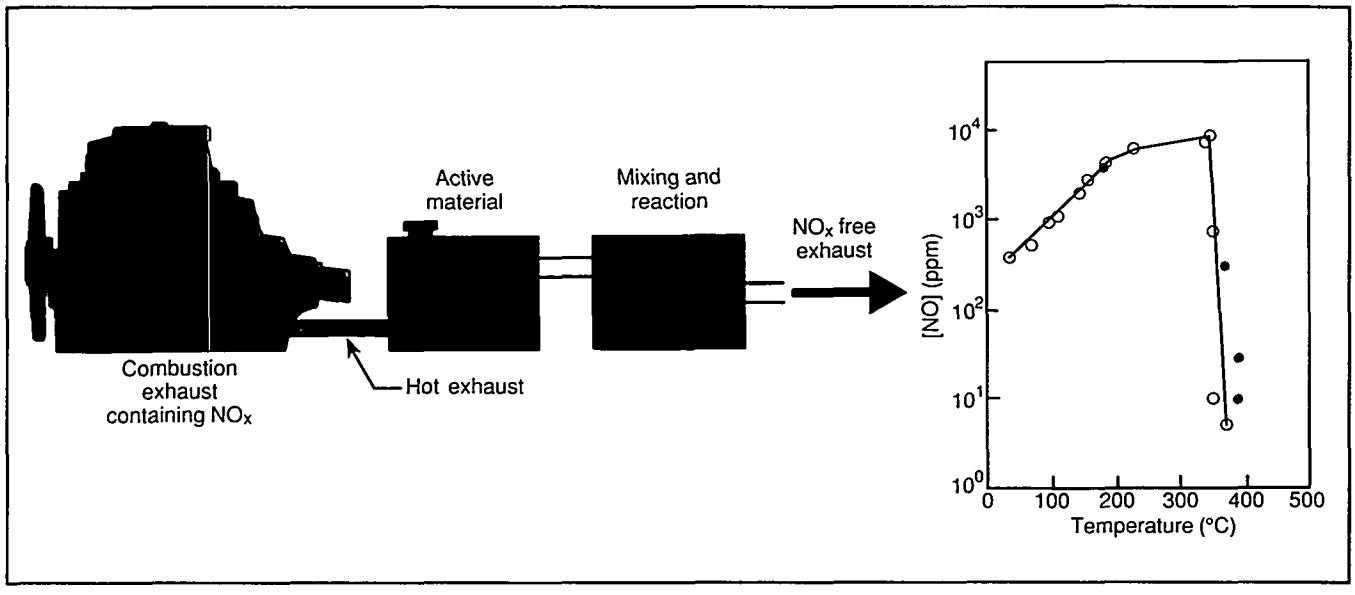
approaches to improving ignition and combustion properties of alternative fuels.

RAPRENOx Process

Nitrogen oxides are the leading contributors to air pollution today. More than 21 million tons of nitrogen oxides are released into the atmosphere in the United States each year as a byproduct of burning fossil fuels. In 1986, Sandia National Laboratories announced the discovery of a new process called RAPRENOx (Rapid Reduction of Nitrogen Oxides), which has the potential to eliminate nitrogen oxides from diesel engine exhausts and coal-burning generating plants. The first phase of the research funded by the DOE Office of Basic Energy Sciences included a series of experiments which determined the basic chemistry of the process. With DOE ECUT funding, the researchers extended the fundamental chemistry experiments by applying the process to the exhaust gases of a real diesel engine. In these applied experiments, it was shown that RAPRENOx could reduce 400 ppm of NOx to less than 5 ppm in diesel exhaust at characteristic operating temperatures. It appears that the RAPRENOx process has a significant potential for reducing NOx from practical combustion systems including stationary and mobile diesel engines, industrial scale furnaces and boilers, and other fossil-fired generating systems. The successful development of a viable product could provide an inexpensive way to comply with mandated federal pollution standards. DOE has waived patent rights to the inventor who has set up a private company, the Technor Corporation, to commercialize applications of RAPRENOx in diesel, natural gas-fired engines, and wood-fired boilers. In addition, Technor has just completed a Phase I DOE-SBIR program for coal combustion. Major engine manufacturers, electric utilities, air quality interests, and industrial processors in the United States and abroad have shown widespread interest in the process and many have begun R&D activities.

Fluid-Elastic Instability in Heat Exchangers

Flow-induced vibration has been identified as the leading cause of catastrophic failures in industrial heat exchangers. By increasing the fluid pumping rate of shell-and-tube heat exchangers, the overall rate of heat transfer can be increased. However, at a high rate of pumping, fluid-elastic pressure waves are often generated at a frequency high enough to



Experiments have shown that the RAPRENOx process can radically reduce NOx emissions.

be close to the natural frequency of the heat exchanger assembly. When this occurs, tube vibration at high amplitudes is induced and, unless corrected, ultimately leads to heat exchanger failure. Research in fluid elastic instability of shell-and-tube heat exchangers was supported by DOE to provide a better understanding of the flow regimes within which an actual heat exchanger must operate to avoid structural failure. Using an instrumented laboratory setup capable of accommodating industrial size heat exchangers, pressure drop and tube vibration data from waterflow tests were developed. In cooperation with Heat Transfer Research, Incorporated, actual cases of industrial heat exchanger failures were documented and made part of the extensive data base. A multidimensional flow velocity model for numerical simulation of shellside flow distribution was also developed for predicting tube bundle fluid-elastic instability thresholds and pressure drop. The model was validated using the extensive data base of experimental results and actual documented cases of heat exchanger failure. Improved understanding of fluid-elastic instability in shell-and-tube heat exchangers should lead to more reliable designs, better heat exchanger effectiveness, and subsequent reductions in process energy requirements. Heat exchangers are used extensively in industry, so this work should lead to substantial energy savings nationwide.

Improved Pulse Combustion Technology

Although pulse combustion technology has been known for many years, devices utilizing pulse combustion have not been widely implemented in spite of attractive characteristics such as high heat transfer and combustion intensity, low emissions of nitrogen oxides, high thermal efficiencies, and self-aspiration. The lack of information on fundamental fluid dynamics and combustion processes has caused the design and development of pulse combustors to proceed largely by trial and error, a method that does not guarantee an optimum design. In a DOE-funded research, a wide variety of in-situ optical diagnostics have been applied to an experimental pulse combustor to elucidate the re-ignition, unsteady valve dynamics, mixing, and combustion processes. A simple model for combining the effects of fluid mixing time and ignition delay time (a property of the fuel used) has been developed and will be incorporated into a one-dimensional, nonlinear pulse combustor model. Valving dynamics, improved heat transfer estimates, inlet and exhaust decouplers, and a method of determining combustor resonant frequency were also incorporated in this model. In a complementary effort, the feasibility of using alternative fuels in pulse combustors has been established. A modified version of a Rijke pulse combustor has been successfully tested using a variety of liquid fuels including kerosene and No. 2 to No. 6 fuel oils. Combustion efficiencies of over 99 percent were obtained when burning fuel oil No. 6. This new understanding of pulse combustion processes will provide useful knowledge and design guidelines for the development of pulse combustion systems that may capture the inherent advantages of this technology.

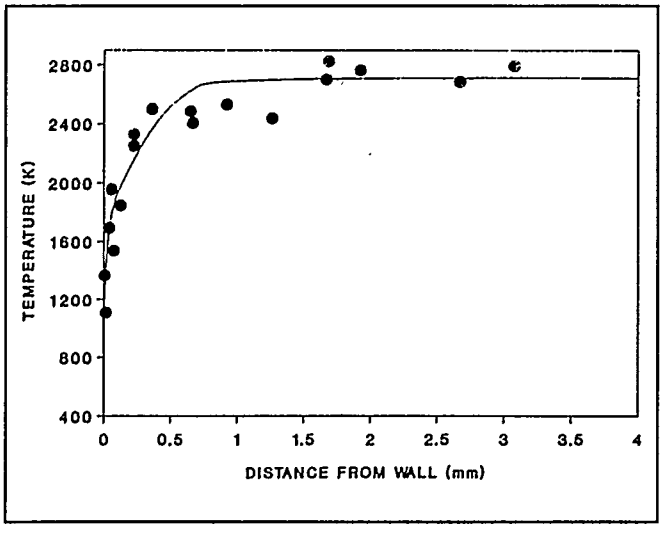
Ceramic Surface Modifications

Ceramic materials fail catastrophically through the growth and propagation of defects, particularly of cracks initiated at free surfaces. Surface modification techniques can reduce the size and number of defects and provide in the ceramic matrix a secondary phase that can absorb the crack propagation energy. DOE-funded research has established that ion and laser surface modifications are capable of arresting surface initiated crack propagation thereby significantly increasing the strength and reliability of ceramics. An increase of about 40 percent in the fracture toughness of silicon carbide has been achieved by laser treatment of nickel deposited on the ceramic surface. In partially stabilized zirconia (PSZ), implanting with aluminum ion (Al+) and annealing results in a 70 percent increase in fracture toughness and a 30 percent increase in microhardness. The development of tougher ceramic materials using these surface modification

techniques may permit the substitution of ceramics for metals in many end-use applications at elevated temperatures, high-stress levels, and in oxidizing environments.

Thermal Boundary Layer Measurements in Engines

Despite the importance of the thermal boundary layer in understanding engine combustion processes, there have been no previous quantitative measurements of the temperature profile near a wall in an operating internal combustion engine. In most engine combustion heat release computations, the thermal boundary layer is calculated theoretically because direct measurements are not possible. Nitric oxide emissions from an engine chamber are most sensitive to peak temperatures in the chamber, and these temperatures will be calculated incorrectly unless the thermal boundary layer is accurately modeled. Under DOE funding, researchers have been able to acquire the first detailed in-cylinder measurements of the thermal boundary layer evolution in an operating internal combustion (IC) engine. These techniques demonstrated excellent spatial resolution of better than 0.08 mm and were able to traverse to within 0.05 mm of the wall. Profiles were generated several times during the expansion stroke, showing the growth of the layer from fractions of a millimeter to nearly two. These measurements are a necessary first step in developing a complete picture of the combustion-wall interactions. Combined with wall heat transfer measurements being performed collaboratively with researchers from the General Motors Research Laboratory, the fundamental knowledge developed should lead to new engine designs that simultaneously optimize emissions control and fuel efficiency.



First detailed in-cylinder measurements of the temperature profile for the thermal boundary layer in an internal combustion engine.

Ceramic Joining

The potential of structural ceramics in advanced energy conservation applications has not been realized because little research has been conducted on the joining of ceramics. In 1982, DOE initiated long-term, generic applied research and development in the area of ceramic attachments for high-temperature applications. Subsequent research defined the current limits of room-temperature strengths of brazed ceramic-ceramic joints. Brazes were developed for silicon carbide (SiC-SiC) and alumina (Al_2O_3-Al_2O_3) with acceptable room temperature strengths and toughness. These brazes will allow ceramic components to be used economically in large operational systems such as high-temperature heat engines and heat exchangers, or in any other application requiring resistance to high temperatures, stresses, or oxidizing atmospheres. This project has been transferred from EUR to the Office of Transportation Systems for subsequent applications development. In a complementary effort, highly refined finite element mathematical models were developed to obtain an understanding of stresses and fracture mechanisms in ceramic-metal joints. These models were experimentally validated for rectangular and cylindrical joint geometries, and a three point flexure test geometry has been developed to experimentally validate adhesion models for zirconia-nodular cast iron braze joints. This research has been transferred to the DOE Ceramic Technology for Advanced Heat Engines Project for further applications development.

Magnetic Resonance Imaging for Advanced Ceramics

The steps in processing high-performance, high-temperature structural ceramics planned for use in advanced heat engines require much more understanding than has been achieved to date. Part of processing science is the development of practical nondestructive evaluation methods to identify problems at the earliest possible stages. One such method that has the potential to affect processing science is magnetic resonance imaging (MRI), a chemically sensitive, noncontacting, and nondestructive technique. DOE funded a project to study the potential of MRI to directly map the distribution of: (1) organic binders and plasticizers used in injection molding processes; and (2) porosity after the binder/plasticizer has been removed (i.e., dewaxed). Because the polymeric organic binder/plasticizer used contains a high concentration of protons, it was an excellent candidate for MRI. It was shown that MRI can be used to directly image distributions of organic binders/plasticizers as used in injection molding, and image porosity distribution if a carefully selected filler fluid is used with a proper infiltration procedure. Follow-on work with the technique is currently being undertaken by the DOE Ceramic Technology for Advanced Heat Engine Project.

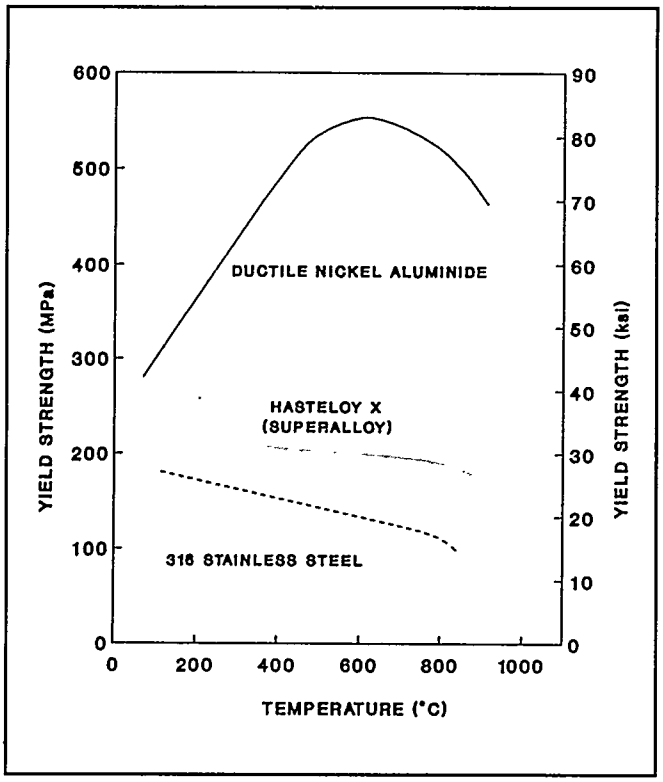
Recycling of Post-Consumer Plastic Scrap

It is projected that the energy embodied in plastics to be saved through recycling of post-consumer scrap can be as much as one percent of U.S. annual energy consumption. These savings would be in premium fuels, oil, and natural gas used as feedstock and fuels in plastics production. In addition, a major disposal problem would be alleviated by recovering and recycling plastics, since over 40 billion pounds of plastics are produced annually in the U.S. alone. The capability to recycle plastics from scrapped automobiles may make the use of plastics for major structural parts such as fenders and hoods more acceptable to automobile manufacturers and environmentalists. Under DOE funding, the Plastics Institute of America (PIA) at the Stevens Institute of Technology in a coordinated effort with Lowell University, Lehigh University, and the Polytechnic Institute of New York successfully showed the technical feasibility of recycling plastic scrap from shredded automobiles. These research studies were complemented by an industrial scale-up effort coordinated by the PIA and funded by the DOE Office of Industrial Programs. In June 1986, the Plastics Institute of America (PIA) held a technology exchange workshop on "Plastics Recycling as a Future Business Opportunity." This workshop, which was financially supported entirely by the PIA, was primarily aimed at entrepreneurs, representatives of local governments, and Congressional staffers. It was concluded that there is a potential constituency for plastics recycling in the private and local government sectors.

Ductile Ordered Alloys

The development of advanced energy conserving technologies is constrained by the lack of materials capable of withstanding high temperatures, high pressures and highly corrosive environments. Development of metallic materials of ordered crystal structure with high-temperature capabilities has provided an alternative to ceramics in overcoming material limitations. Intermetallic compounds offer potential advantages such as excellent high-temperature strength; good response to work hardening; superior creep properties; excellent oxidation and corrosion resistance for certain intermetallics (e.g., aluminides); and potential for reduced need for strategic materials. However, poor ductility and fabricality have been major problems with using aluminides as structural materials. Developed at Oak Ridge National Laboratory through research supported by the ECUT program, nickel aluminide is the first truly ductile ordered intermetallic alloy for withstanding high temperatures. The new high-temperature alloy is moving rapidly toward commercialization, with five

licensing agreements to date: with Cummins Engine Company, for use in large diesel engine applications; with Armco, Incorporated, one of the five largest steelmakers in the United States, for commercial mass production; with Armada Research Corporation for heating element uses for such applications as electric appliances and industrial furnaces; with Metallamics, for tool and die components; and with Valley-Todeco for aircraft fasteners.



Unlike conventional metals and alloys, nickel aluminide increases in strength at higher temperatures, making it suitable for energy-conserving, high-temperature applications.

Separation of Impurities from Molten Metals

The manufacture and fabrication of steel and other metallic materials is often complicated by the presence of nonmetallic particulates in the solidified metals. In the steel industry the movement toward thinner castings requires more stringent control of the particulate content of the metal. Earlier casting techniques that used large ingot molds and later, continuous casting required hot-rolling reductions, followed by cold rolling in order to produce sheet material. This large amount of energy-intensive mechanical working was sufficient to break up and disperse the particulates and make them relatively harmless. Newer, less energy intensive near-net-shape casting technologies do not require such substantial reductions; therefore, the particulates remain as originally formed, with possible deleterious effects to the metal's properties. To alleviate the problems associated with particulate contaminants in metals, DOE undertook the development of a magnetohydrodynamic (MHD) separator for use with liquid metals. Early work confirmed the usefulness of utilizing the molten metal as a current-carrying conductor passing through a magnetic field. This creates a body force on the metal so that it acts as if it had a higher density and causes the nonconducting particulates to flow quickly to a region where they can be skimmed or separated from the metal. Successful experiments have been performed using molten aluminum and either alumina (Al_2O_3) or silicon carbide (SiC) as the impurity particles. Two patent applications for the process have been filed, and industrial interest in the process is growing. Further technology development is being undertaken by the DOE Steel Initiative.

Genetic Engineering for Efficient Biochemical Processes

The application of genetic engineering techniques to certain microorganisms should lead to greatly reduced production costs for some organic chemicals. Microorganisms can be grown on relatively inexpensive feedstocks, such as biomass; production costs for some organic chemicals will be lower if genetically engineered processes can be scaled up. Before this potential can be realized in large-scale industrial processes, a method must be developed for stabilizing and retaining genetically engineered traits in large quantities (cultures) of microorganisms. DOE funded research developed and experimentally verified a new method of gene cloning

and amplification that will be far superior to the standard method in supplying stable strains of microorganisms useful in large-scale applications. In the new method, foreign genes or genes of interest carried on a plasmid are introduced directly into the main chromosome of the microorganism. A specific gene of interest has been inserted in the bacteriophage *E. coli* and has subsequently been observed to be amplified. This leads to improved stability and productivity of recombinant DNA microorganisms. These microorganisms can be produced in quantities required by large-scale industrial biocatalyzed processes. In addition to the potential for aiding in large-scale chemical production by biocatalysis, this research should also be applicable to the production of pharmaceuticals and biological materials.

Designing Biocatalysts for Energy-Efficient Chemicals Production

There are several technical barriers to the development and application of biocatalysts for the production of fuels and chemical feedstocks. The development of a molecular-level reaction model for enzyme systems is an initial scientific step in solving these problems. Over the past three years the California Institute of Technology, with DOE funding, has worked to develop software for computer-based graphic displays of three-dimensional structural models of molecules. The models permit the user to display and rotate a three-dimensional representation of the structure of any biological molecule of interest such as an enzyme or pharmaceutical. The interaction of the atoms in the molecule and any structural changes imposed by the user-specified conditions (e.g., increases in temperature, pressure, or the removal/substitution of any given atom) can be displayed. The models simulate real molecules by using a set of analytic force fields to describe the interactions among the atoms. When use of the models for predicting the molecular structure of the enzyme thermolysin as a function of temperature and inhibitors was undertaken, excellent agreement with crystallographically determined structures of thermolysin resulted. This tool is now being used to design new molecular structures for use in drugs, catalysis and for a wide variety of other applications. The simulation models may enable the design of supports for immobilizing enzymes without degradation of performance and enable the design of enzymes for selectivity and resistance to poisons.

Efficient Aerobic Fermentation

Biocatalysts have the ability to facilitate desired chemical reactions in one step by lowering the activiation energy barrier. Unfortunately, the availability of oxygen necessary for microorganisms is a major constraint in the growth and production of microorganisms within the bioreactor used in aerobic fermentation. Biochemical engineers have devised a variety of bioreactor geometry and stirrer configurations to minimize this problem. Under DOE sponsorship, a breakthrough technology with broad applications has been developed for aerobic fermentation using genetically engineered microorganisms. Professor James E. Bailey of the California Institute of Technology has shown that the oxygen limitation problem can be minimized by genetically inserting a hemoglobin gene into *E. coli* bacteria. It was clearly demonstrated that *E. coli* possessing plasmids containing hemoglobin, an oxygen carrier, grew more efficiently at a lower oxygen concentration (by a factor of two) than those without the hemoglobin gene. This method can dramatically improve the growth and productivity of genetically engineered aerobic microorganisms. The production of aerobically fermented products in the United States in 1987 was about 300 million pounds. Use of these genetically engineered microorganisms can help resolve critical barriers which currently impede the production technology of energy-efficient aerobic fermentation processes. Two broad-based patents covering the above technology have been filed by Professor Bailey.

High-Productivity Bioreactor

Batch fermentation processes using microorganisms suspended directly in the fermenting broth suffer from low product yields, accumulation of impurities which contaminate the desired product, and the loss of microorganisms from the batch when processing is completed. In order to increase productivity sufficiently for economically competitive industrial fermentation processes, it will be necessary to use more efficient continuous processing techniques. DOE research in continuous fermentation processes has increased ethanol productivity by greater than an order of magnitude in an advanced fluidized bed reactor system. The study of the kinetic properties of immobilized microorganism biocatalysts has led to a better understanding of the behavior and predictability of bioreactors. The A.E. Staley Company has expressed interest in the research and has provided raw corn dextrose slurry and corn light steep water (LSW) for laboratory tests. Experiments in a continuous stirred tank reactor using yeast extract as a nutrient source have been completed. The steady-state productivity was not changed when glucose was substituted for crude corn dextrose or when yeast extract was replaced with a 1:5 dilution of LSW. The only operational difficulty was some fouling because of the high lipid content of corn dextrose. During the 300-hour run, 25 grams/liter-hour of ethanol were produced at a 90 percent conversion rate. These results suggest that higher productivities for a fluidized-bed column at greater than 200 grams/liter-hour are possible when industrially acceptable feedstocks and media such as corn dextrose and LSW are used.

Base Oil Separation and Characterization

The American Society of Mechanical Engineers Research Committee on Lubrication has estimated that friction and wear losses in all mechanical systems account for up to 11 percent of total annual U.S. energy consumption. A wide variety of lubricants are currently required for mitigating energy losses from friction and wear in many important advanced energy conversion applications. To formulate better lubricants and establish lubricating base oil specifications and standards, an understanding of the influence of the molecular structure of the lubricant on its friction/wear characteristics needs to be developed. An extensive series of experiments on determining the tribological properties of base stock oils has been completed under DOE funding. Three lubricating base oils of various viscosity grades from Mideastern crudes were separated into various molecular compound classes using high-performance liquid chromatography (HPLC). Characterization of the fractions was made using infrared spectroscopy (IR), high-resolution mass spectroscopy (HRMS), nuclear magnetic resonance spectroscopy (NMR), Fourier Transform infrared spectroscopy (FTIR), and elemental analysis. Each compound class was subjected to microsample, four-ball wear testing for friction/wear characterization and free radical titration testing for oxidation stability. Results indicated that the organic acids subfraction of the polar fraction of the mideast 600 neutral base oil exhibited the lowest coefficient of friction. Having isolated and characterized the desirable components of base stock oils, researchers should now be able to further investigate and understand the relationship between the molecular structure and the lubricating qualities of base stock oils and, subsequently, to synthesize the "slipperiest" fraction for formulating superior energy-saving lubricants.

Intermediate and High-Temperature Lubricants

The development of laboratory techniques and procedures is necessary to enable lubrication engineers to characterize and evaluate candidate lubricants with a range of important properties for elevated-temperature and energy-conserving applications. Under DOE funding, a thermogravimetric analysis (TGA) method has been developed for screening candidate high-temperature lubricants. The procedure uses a pair of experiments to obtain measures

of volatility and oxidative stability, both of which are key parameters in the consideration of specifications on oxidation stability. The TGA method was successfully used to evaluate two phosphate esters, trixylyl phosphate (TXP) and diphenyl t-butylphenyl phosphate (DPBP). Although both materials exhibited good oxidative stability, DPBP appeared to be somewhat more resistant to oxidation than TXP. At temperatures above 280 C, TXP showed an oxidation induced high molecular weight residue, while DPBP showed only normal (nonoxidative) evaporation. As new candidate intermediate and high-temperature lubricants are evaluated by this technique, in concert with other tribological tests, an extensive data base will be developed which will be invaluable to lubrication engineers for improving the tribological performance of mechanical components and systems that operate at elevated temperatures.

Lubrication at Elevated Temperatures

Advanced designs of low heat rejection engines present two significant tribological challenges, namely, lubrication at elevated temperatures and lubrication of ceramic materials. Anticipated peak temperatures for these engines are of the order of 600 C in the near future and 1200 C in the more distant future, which far exceed the performance limits (about 250 C) of all currently marketed lubricants. DOE has conducted research into a novel method of attaining effective lubrication at elevated temperatures by depositing lubricating films from the gas phase. Completed studies show that bearing lubrication may be continued to temperatures well above the stability of the liquid lubricant by delivery to the high-temperature bearings in a vapor state. Experimental data indicates that a wide variety of conventional liquid lubricants can be used in a homogeneous gas phase diluted with an inert carrier gas such as nitrogen or mixtures of nitrogen and oxygen to produce a friction-polymer-like film on metal-bearing surfaces at high temperatures. Studies have been successfully carried out at temperatures as low as 200 C and as high as 1600 C. It is believed that this technology will be useful in high-temperature lubrication of adiabatic or low heat rejection engines as well as in high-temperature metal forming operations. Further research on gas phase lubricant delivery to ceramic surfaces will also impact on the development of ceramic parts for new, more efficient advanced engine designs.

Coatings for High-Speed Cutting Tools

Improved tooling systems for automated machining operations have the potential to increase production rate, reduce tool replacement time, and improve energy utilization. These new tooling systems for high-speed machining can be developed based on improved understanding of tool wear mechanisms. A cooperative effort funded by DOE has developed processes for depositing hard coatings and a theoretical understanding of the wear behavior of hard coatings that explains the differences in performance of one coating over another in cutting operations. The two commercially viable processes are the high-rate reactive sputtering (HRRS) and the activated reactive evaporation (ARE) processes. Cutting performance tests have indicated that HRRS coatings outperform uncoated tool inserts by factors of between 3 and 10, depending on coating composition. ARE coatings were found to outperform uncoated inserts by a factor of 3. Two patent applications have been filed covering the HRRS processes, and two licensing negotiations are underway. The theoretical model that was developed includes, in addition to the effects of mechanical wear, the effects of chemical dissolution of the tool into the workpiece. The theory has been confirmed for high-speed steel (T-15) cutting tool inserts coated with carbides and nitrides of titanium (Ti) and zirconium (Zr). Cutting test results on titanium nitride (TiN) and zirconium nitride (ZrN) coatings on T-15 showed an increased wear resistance by about a factor of 3 for ZrN as compared to TiN, verifying predictions made using the theoretical model. This research has advanced tool wear understanding to

a point where it is feasible to employ computer searches of a data base on thermodynamic and mechanical properties with the objective of identifying the best coating compositions for wear resistance. As a result, industry should be able to systematically implant less expensive substrate materials with coatings that have low friction and wear properties.

ENERGY-RELATED INVENTIONS PROGRAM

Packaging and Shipping Fresh Produce without Refrigeration

With the support of a DOE grant for laboratory studies and field testing, an inventor has developed a packaging technology that makes interstate shipment of fruits and vegetables possible without refrigeration. To date, this system has been used to penetrate the fresh tomato market in 39 states. The tomatoes are packed in a shrink-wrap plastic-covered box with a filter enclosed that allows them to ripen in a controlled environment with a temperature that ranges from 68 to 72 F. The purifier effectively regulates the levels of carbon dioxide, oxygen and the relative humidity surrounding the tomatoes in shipment, slowing down the ripening process and eliminating the need for refrigeration. Because of different environmental temperatures, some heating or refrigeration may still be required, but the amount of energy consumed will be substantially reduced. Marketed under the trade name of "TomAHtoes," 751,000 25-pound boxes were shipped in 1987, with $35 million in retail sales. With its potential for use with other fresh fruits and vegetables, this innovative packaging can provide significant national energy savings.

Aluminum Chip Roofing System

With the support of a DOE grant, a small company was able to use a product it was already manufacturing, aluminum chips, to develop new energy-

Packaging technology developed through the Energy-Related Inventions Program allows tomatoes to ripen slowly when shipped at room temperature.

saving roofing products. The grant allowed the company to test and optimize the size, shape, and composition of a reflective aluminum chip roofing system. Tests showed that building energy use was reduced by 30 to 40 percent in the summer due to the high reflective quality of the chips (70 percent reflective) and 10 percent in the winter due to low emissivity when aluminum chips were used in conjunction with a traditional industrial flat roof. Because the chips are opaque to the sun's ultraviolet rays, they also protect the roofing substrate and double the life of the roofing product.

Steam Turbine Packing Ring

Assisted by DOE funding, an inventor developed a new packing ring that can improve the heat rate efficiency of steam turbines by more than 1 percent. The rings reduce wear and allow a tighter seal during normal steam turbine operations, minimizing leakage between stages. The packing rings can replace existing rings with little modification during regular overhaul of steam turbines. In turbines using coal or oil for fuel, payback for replacing an entire set of existing rings would be less then two months. If the rings are adopted as an industry standard, investor-owned electric utilities alone could save up to $200 million annually in generating costs. If the rings are use in municipally-owned and industrial generators, the total savings would increase dramatically. After a successful full-scale test of the rings at a Maryland generating plant, the inventor entered into an exclusive worldwide licensing agreement for manufacturing and marketing the packing rings in 1987.

Alter-Break

After building and testing an advanced prototype with the help of DOE funding, an inventor has licensed his fuel-saving, automotive alternator and battery-charging system to a startup company which projects production capacity of a million units per month starting in calendar year 1989. In the Alter-Break system, the alternator is automatically disengaged during acceleration -- the engine's least efficient mode -- so that all electric power is taken directly from the vehicle battery and no alternator load is placed on the engine. At cruising speed, the alternator is automatically re-engaged and made to deliver about 90 percent of the rated output. Removing the alternator load in this way achieves a 10 to 20 percent increase in fuel efficiency, with a payback period between 3 and 6 months. Expected to sell for around $60, the 3-ounce, solid-state device can be easily connected in just a few minutes. Due to its simplicity and effectiveness in saving gas, the Alter-Break has opened the door for additional innovation in automotive design, pointing the way to new approaches for improving fuel efficiency.

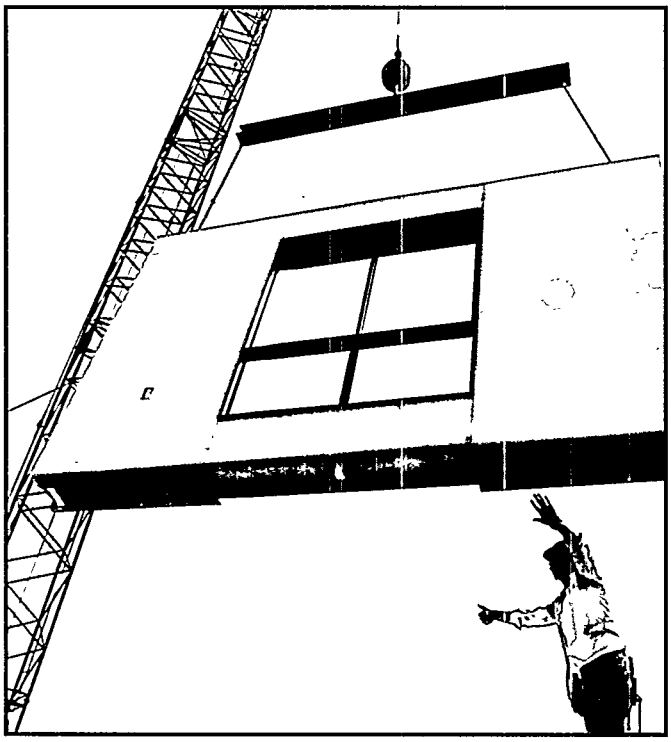
Composite-Reinforced Cylinders and Pipelines

With financial assistance from DOE for prototype development, an inventor has successfully commercialized a composite reinforcement technology using glass filament winding in several applications. Because the filament winding permits thinner metal walls, the reinforced pipe is about 20 percent less costly per foot than steel pipe and requires about 40 percent less energy in its manufacture. The technique has been used to produce strong but lightweight aluminum cylinders for transporting compressed natural gas and for fuel tanks for natural gas-powered vehicles which are virtually pollution free. Numerous natural gas fleets of cars, school buses, and small service trucks are using this technology throughout the country, profiting from operating costs that are 50 percent lower than those for traditional gasoline vehicles. The cylinders for bulk transportation of natural gas may make feasible the development of small, isolated gas fields where pipeline connection is currently impractical. The method is also being used to produce pipe for high-pressure transmission of gases or liquids. The process may also permit American manufacturers to produce composite-reinforced, large-diameter high-pressure pipe which exceeds the specifications of the steel pipe currently imported from Japan and Ger-

many. Other applications being developed include crack arresters for pipeline retrofit and reinforcement of steel pipe.

Exfoliated Graphite Fibers

Conventional high-strength graphite fibers are very brittle and require extreme handling care, in fabrication as well as in application. Through research funded by the DOE, a less brittle graphite fiber has been developed. This exfoliated graphite can be bent to a radius of curvature as small as 5mm without breaking. Composites which could exhibit lower density, improved ductility, and higher electrical conductivity can be fabricated from the exfoliated graphite. Because the exfoliation process for making these fibers can be conducted at low temperatures, manufacturing costs may also be lower than current high-cost methods of producing high-strength fibers using graphite. A strong, lightweight composite material such as this could find ready application in airplane and auto bodies, where weight reduction could result in vast gasoline savings.



In construction with integrated concrete technology, prefabricated panels are lowered into place and then connected by a poured-in-place structural concrete grid to improve energy efficiency by 40-50%.

Photo credit: LENS-ART PHOTO

Integrated Concrete Technology

A DOE grant was used to test the performance claims of an innovative building technology, which has since been incorporated in more than a dozen large building projects in the United States and abroad. The construction process uses a poured-in-place structural concrete grid to connect prefabricated, highly insulated permanent walls. The wall components have a very low heat transfer coefficient of R=30 or better. Because the two-step operation accomplishes seven construction processes at the same time, buildings can be constructed much more efficiently. Construction time for multistoried buildings can be cut by 30 percent, and the building's energy consumption will be 40-50 percent less than a traditional structure. Buildings using Integrated Concrete Technology are 60 percent lighter than comparable structures and use heating systems that are half as large as those used in buildings of equal size.

Compressor Control Systems

With support by a DOE grant, an inventor completed development of a microprocessor-based control system for regulating centrifugal and reciprocating equipment used in natural gas compressor stations. The invention achieves significant energy savings in plants using multiple compressors, maintaining optimum efficiency for as many compressors as possible when operating conditions extend beyond their optimum range. The control system can be introduced at low cost with nominal interference in normal operation for retrofit purposes, and with little effort for new installations. Energy savings sufficient to give a product payback in weeks are achieved by matching compressor load to energy requirements for engine startup. Although the savings

of between 1 and 5 percent may be small compared to the total energy used in pipeline pumping, the total national energy savings can be substantial. Many other compressor applications are envisioned. This technology was the basis for a new business that has grown to be a multimillion-dollar firm; its president was named 1986 Innovator of the Year by the Small Business Administration. A product line suitable for smaller compressors has already been developed.

High-Efficiency Water Heater

In 1977, an inventor was awarded a DOE grant to install his direct-contact, gas-fired hot water heater in a new 210-unit apartment building and measure the system characteristics, efficiency and reliability. The high-efficiency water heater is designed for commercial and industrial use and employs a unique design which blows a natural gas flame directly into a "rain of water." Because the temperature of exhaust gases is equal to ambient temperatures, there are no stack losses and a hot stack is not required, reducing installation costs. The efficiency of the unit exceeds 98 percent. After the performance claims had been established, the inventor was able to license his technology, and multimillion-dollar sales were achieved in 1987. A stack economizer spin-off technology is also being marketed with increasing sales.