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Electric Steelmaking

Also in this issue • Biological Carbon Sequestration • Advanced Combustion Turbines • DSM Survey

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Cover: Advances in electric steelmaking technology have steadily reduced the amount of energy required to make a ton of steel, leading to pronounced changes in the U.S. steel industry.

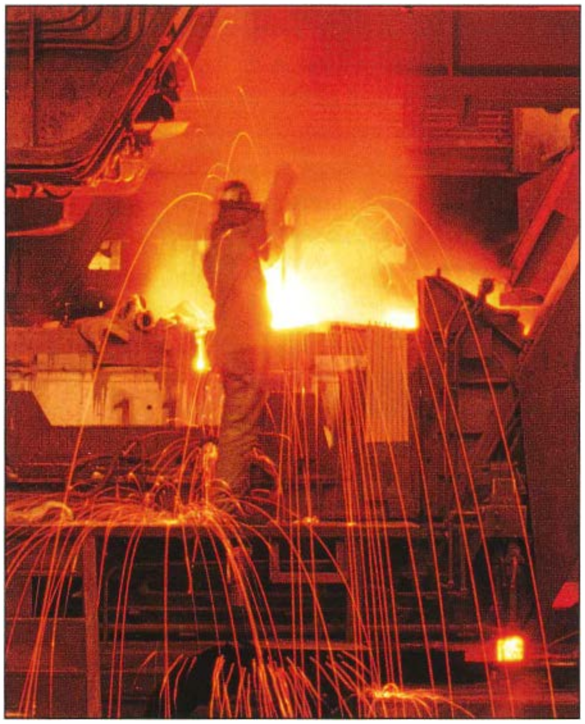
EPRI JOURNAL

Volume 18, Number 7 October/November 1993

COVER STORY

6 **New Technologies for Electric Steelmaking**

Advances in efficiency, product quality, finishing, and waste management promise to tip the balance yet further in favor of electricity-based steel production.



6 Electric steelmaking

FEATURES

16 **A Rich Harvest From Halophytes**
Highly salt-resistant plants known as halophytes promise a wealth of potential uses and benefits, including the ability to store atmospheric carbon dioxide for long periods.

24 **Advanced Combustion Turbines Set for Takeoff**
Performance enhancements in the latest high-thrust fan-jet aircraft engines are fueling a growing interest in compact aeroderivative turbines for utility use.

DEPARTMENTS

2 **Products**

4 **Discovery**

33 **Contributors**

34 **Project Startups**

36 **In the Field**

RESEARCH UPDATES

38 **Utility DSM Activities: 1992 Survey**

40 **Ultramax Methodology for Continuous Process Improvement**

43 **Power Plant Cycles Featuring Air Humidification**

47 **GLOCO: Modeling the Global Carbon Cycle**

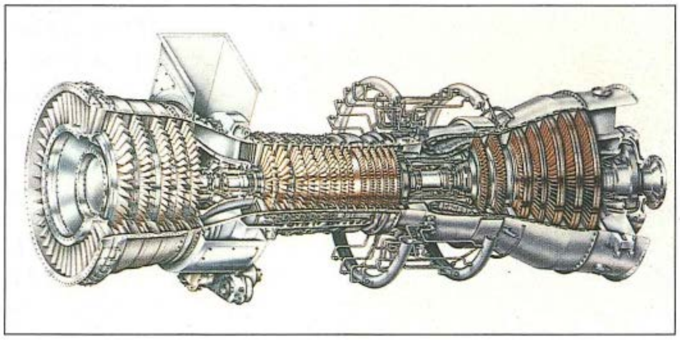
LISTINGS

51 **New Contracts**

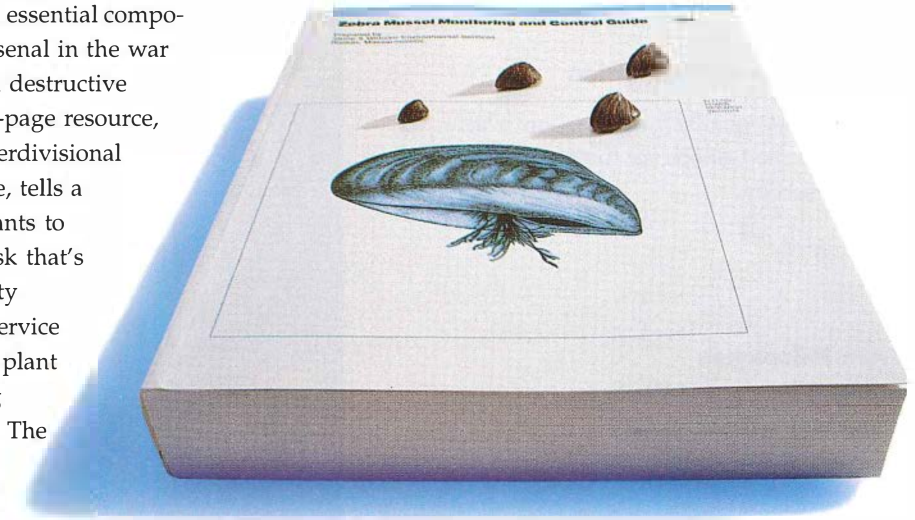
53 **Events**

16 Halophytes

24 Advanced turbines



Bible of Zebra Mussel Control



EPRI's *Zebra Mussel Monitoring and Control Guide* (TR-101782) is an essential component of any utility's arsenal in the war against the prolific and destructive zebra mussel. This 700-page resource, a product of EPRI's interdivisional zebra mussel task force, tells a utility everything it wants to know about the mollusk that's been plugging up utility condensers, clogging service water lines, increasing plant heat rates, and causing power plant deratings. The guide offers a comprehensive compilation of current U.S. and European control measures, including thermal treatment, chemical methods, physical removal processes, and special coatings for intake system components. In addition, the guide covers innovative techniques still under study. *For more information, contact Bob Edwards, (415) 855-8974. To order, call the EPRI Distribution Center, (510) 934-4212.*

Clean Air Technology Workstation

This software tool is a utility's direct route to developing and updating least-cost strategies for complying with the 1990 Clean Air Act Amendments. Whether a utility is evaluating emissions control technologies and power plants individually or systemwide, the Clean Air Technology (CAT) Workstation™ crunches the numbers swiftly, accounting for a range of variables—including capacity factors, emissions constraints, and the value of emissions allowances and other economic considerations. The program automatically ranks technology-fuel combinations by cost over specified time periods. It also recommends the number of sulfur dioxide emissions allowances to buy or sell in a given period. For a more comprehensive analysis, the CAT Workstation can incorporate direct output from several related EPRI software programs, such as those dealing with sulfur dioxide reduction, continuous emissions monitoring, and fuel costs.
For more information, contact Richard Rhudy, (415) 855-2421. To order, call the Electric Power Software Center, (214) 655-8883.

DSManager

Considered to be the new industry standard for demand-side planning, DSManager 2.0 provides a quick way to design demand-side management programs and evaluate their cost-effectiveness. This software can compare the costs of various DSM program options and predict a program's potential impact on a utility's peak demand. It also provides a useful means of managing the multitude of data required for DSM programs. Its combination of analytical capabilities and user-friendly features is unmatched by any other demand-side planning software available today, making it the tool of choice for utility planners across the country. The new features of Version 2.0 include its ability to exchange data with other EPRI and non-EPRI software. Version 2.0 is more than 10 times faster than Version 1.0, and its database occupies less than 20% of the disk space previously required.

For more information, contact Perry Sioshansi, (415) 855-2329. To order, call the Electric Power Software Center, (214) 655-8883.

Smart Ground Multimeter

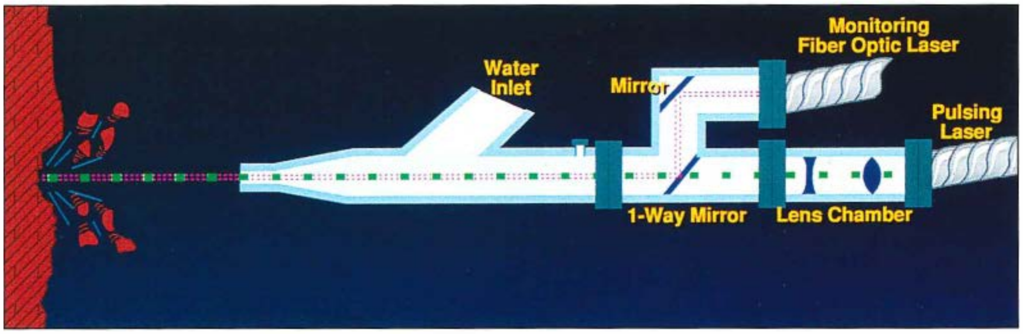
Proper grounding is essential to ensuring the safety of utility transmission and distribution systems. Yet the conventional methods of measuring and monitoring grounding at utility substations are time-consuming and labor-intensive and yield unreliable results. They also require disconnecting the transmission or distribution system from the substation. EPRI's new Smart Ground Multimeter employs novel current-injection techniques and digital signal processing to overcome these drawbacks. The personal-computer-based meter is able to filter out the electrical disturbances that commonly hinder conventional measurement processes. It also can make field measurements in energized as well as de-energized substations.

For more information, contact Gilbert Addis, (415) 855-2286. To order, call Lyn Cosby at Hood-Patterson & Dewar, (404) 296-5990.

Mining Rock With Light

Imagine a laser beam piercing through darkness and striking the wall of a gold mine. Almost instantaneously, a portion of the wall shatters and falls in a heap on the ground.

If EPRI has its way, this could be the future of hard-rock mining. Through a project that began about one year ago, researchers are working to develop laser technology for the mining of hard minerals, such as precious metals, as well as for underground excavation, such as that required for certain construction projects. As Gene Eckhart, manager of the project, explains, the laser does not perform a slicing function as it does in surgical practice. Rather, the frequency of the beam is tuned to the rock's natural vibrational frequency. This causes the rock to vibrate and fracture.



The researchers have already demonstrated the feasibility of the concept through laboratory tests. They have also learned that the use of water is critical to the process. Not only does a jet of water provide a clear path from the laser source to the rock surface, but it also increases the pressure against the rock, imparting miniature shock waves that function much like traditional explosives, causing the rock to crumble. "This type of equipment represents the wave of the future for rock mining," says Eckhart. "It's an idea that we could never have pulled off 20 years ago."

Conventional methods of hard-rock mining involve the use of explosives to break off chunks of rock varying from pebble-sized pieces to boulders bigger than a pickup truck. To break down the large boulders, miners use special hammers powered by compressed air, which is typically supplied by underground diesel generators.

The laser technique offers several advantages over conventional methods. For one thing, it is faster and quieter, since it does not involve the use of explosives. Also, because the resulting debris consists of similarly sized, relatively small chunks that do not require further breakdown, the technique offers the potential for significantly increased productivity. It also eliminates the need for underground generators and the fumes they create.

The researchers' next step is to build a demonstration tool to offer to equipment suppliers who may be interested in demonstrating the technology on a pilot scale.

■ *For more information, contact Gene Eckhart, (202) 293-7517.*

Electrochemistry Brings Chemical Production On-site

Producing industrial chemicals in exact quantities on-site, as needed, can have a number of practical advantages. Based on electrochemical synthesis rather than heat-intensive processes, the on-site approach can increase energy efficiency, eliminate the creation of hazardous by-products, and avoid difficulties and restrictions related to transportation. Since electrochemical reactions take place without the need for combustion or intermediary reagents, often they can be used at near-ambient temperature with little wasted heat.

The possibilities for widespread on-site chemical production are being boosted by recent advances in electrochemical cells. Some of these advances—including rugged ion-exchange membranes, improved electrode materials, and novel cell designs—are also being researched and refined in the development of advanced fuel cells, which use many of the same basic components. Both cells work by transferring electrons or ions through an electrolyte to stimulate chemical reactions at opposite electrodes. In a fuel cell, chemical energy is converted to electricity; in an electrochemical cell, electric energy is used to produce desired chemicals, such as chlorine or ozone.

The advantages of on-site synthesis can already be seen for these two chemicals. Chlorine for water purification, for example, is now produced from the off-gas at large chlor-alkali plants and trucked to consumers. At least one state, however, has banned the transportation of chlorine through populated areas; an attractive alternative is to produce concentrated chlorine on-site with small electrochemical cells fitted with special membranes. For other applications, such as preventing biofouling of power plant cooling systems, an undivided (membraneless) cell with advanced electrode materials can be used to produce dilute chlorine directly in the cooling water.

Similar progress has been made recently in the production of ozone using an electrochemical cell with an ion-exchange membrane, a solid polymer electrolyte, and a porous electrode. This process is more efficient and potentially much less expensive than making ozone by means of corona discharge.

A study sponsored by EPRI and conducted by Dextra Associates has identified several R&D opportunities to promote electrochemical synthesis. The study also explored possibilities for using electrochemistry to strip toxic materials from contaminated water or surface soils.

■ *For more information, contact Ammi Amarnath, (415) 855-2548.*

Low-Dose Radiation May Stimulate Immune System

Several environmental agents, such as sunlight and vitamins, have qualitatively different effects on organisms at high doses and at low doses. The enhancement of a desirable biological process by the administration of low doses of an otherwise toxic agent is called hormesis, and a considerable body of evidence indicates that low-dose radiation (LDR) may have hormetic effects.

This evidence is not widely known and remains poorly understood. Some early reports suggesting hormetic effects were dismissed as statistical flukes. Recently, however, experiments have indicated two possible mechanisms for radiation hormesis: the enhancement of cellular DNA repair and the stimulation of the body's immune system. EPRI has sponsored research on the latter mechanism at the Department of Veterans Affairs Medical Center at the University of California, Los Angeles (UCLA).

An important component of the immune system is the family of white blood cells (lymphocytes) called T cells, produced by the thymus gland. The main function of these cells is to destroy "foreign invaders," such as bacteria, cancer cells, and transplanted tissues. They also appear to be involved in autoimmune diseases, in which the body attacks its own healthy tissue.

The initial research at UCLA demonstrated that LDR appears to encourage the proliferation of T cells in normal mice, while in autoimmune mice it decreases the production of the abnormal T cells responsible for the autoimmune reaction. More recently, experiments have focused on the effect of LDR on mouse mammary tumors. In these experiments, although LDR exposure alone did not affect tumor growth, a combination of LDR and the restriction of calories in the diet did suppress growth, sometimes leading to dramatic tumor regression. LDR was also found to reduce the swelling of lymph tissue in a strain of mice that spontaneously develop a disease resembling human autoimmune disorders.

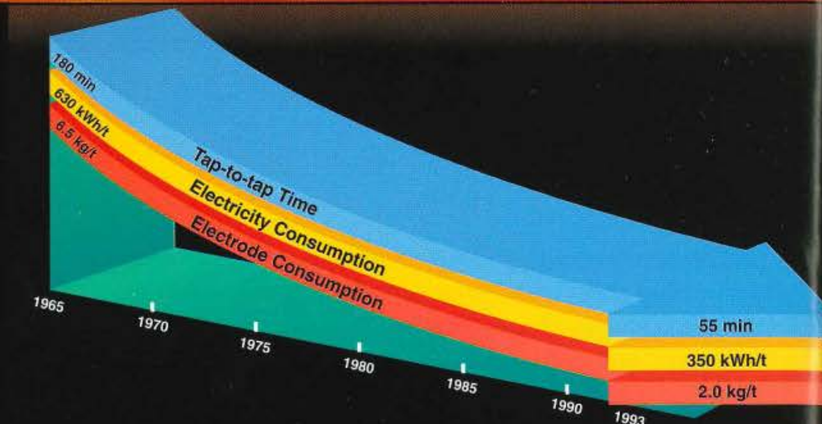
"The existence of hormesis does not necessarily mean that the destructive effects of radiation just disappear at low doses," says senior medical scientist Leonard Sagan. "Rather, there are probably competing processes in which LDR may damage some cells while stimulating others to enhance T-cell production."

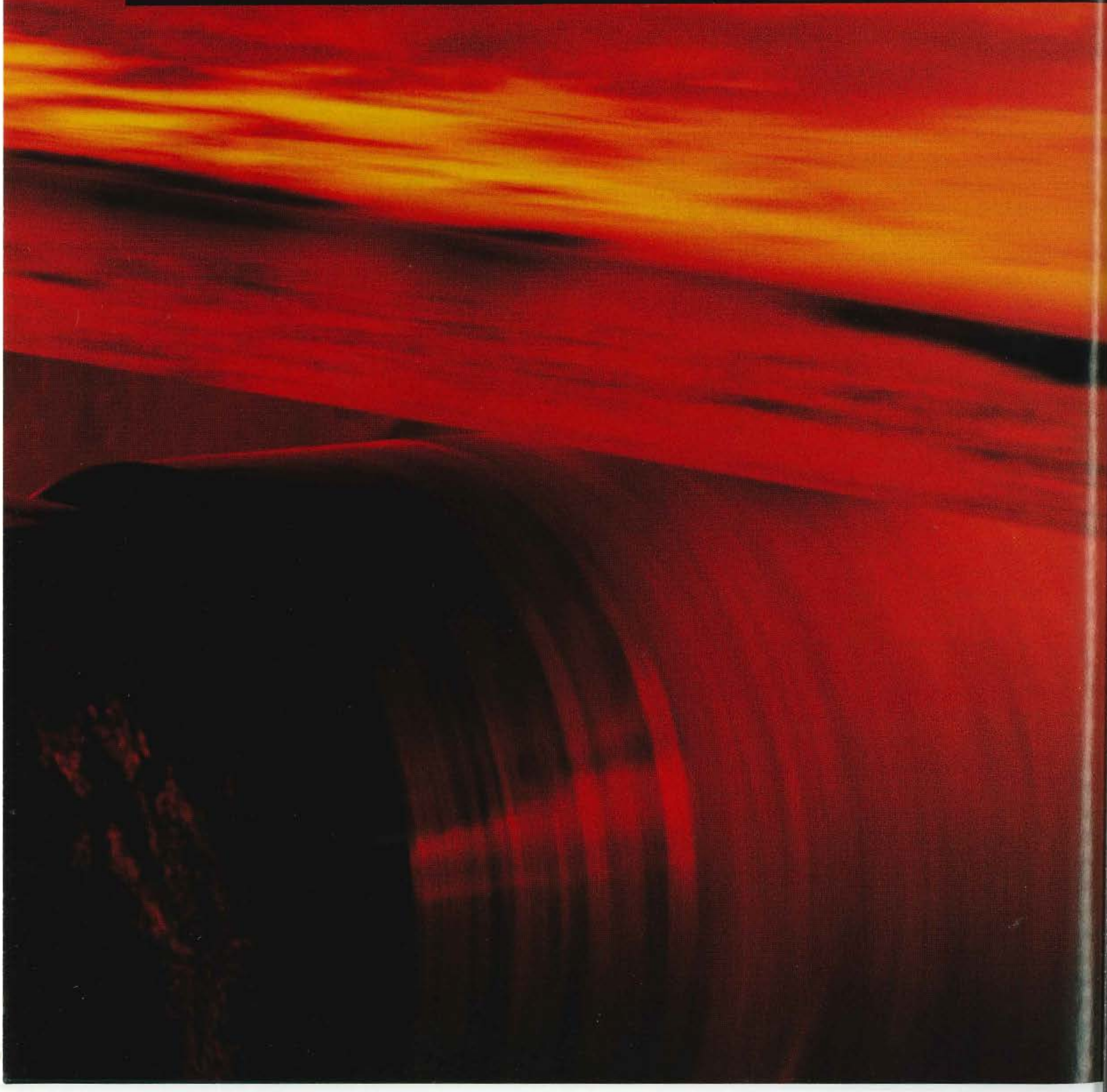
EPRI, along with federal agencies and other industry groups, supports a new organization called BELLE (Biological Effects of Low-Level Exposures), which publishes a newsletter and sponsors an annual conference on the subject.

■ *For more information, contact Leonard Sagan, (415) 855-2585.*

IMPROVEMENTS IN SPEED AND EFFICIENCY

Major changes have taken place in electric arc furnace steelmaking over the past three decades, cutting furnace time per charge by two-thirds and sharply reducing power requirements and electrode consumption per ton of steel. Innovations include computer control, oxy-fuel burners to increase melt rate, and ladle refining, which lowers overall power consumption and improves product quality.





NEW TECHNOLOGIES FOR ELECTRIC STEELMAKING

by John Douglas

THE STORY IN BRIEF

Technological advances such as thin-slab casting have promoted the steady rise of electric steelmaking processes. And refinements in such areas as nitrogen content reduction are expected to soon allow steel from electric arc furnaces to compete in the very desirable market for high-ductility sheet steel. EPRI's Center for Materials Production has been working closely with researchers and the steel industry on these and other developments, including advanced finishing techniques, efficiency and productivity improvements, and environmental and waste issues. In its most recent initiative, CMP is forming a new collaborative partnership with the Steel Manufacturers Association to further such research and to identify key technical issues and opportunities for electric steel producers.

The steel industry is going through a wrenching transition. Large, integrated producers—who make steel from iron ore with blast furnaces and basic oxygen furnaces—are faced with excess capacity, lower profit margins, stiff environmental regulations, and loss of market share. Meanwhile, electric steel producers—who use arc furnaces to make steel primarily from scrap—have seen their share of U.S. raw steel production rise to nearly 40% as they have steadily lowered costs and penetrated new markets. As a result of the advantages of technical change, even the well-established integrated producers are planning to shift more of their production to electric steelmaking.

Now a variety of new technologies promise to tip the balance even further. The most important of these innovations, thin-slab casting, is opening the sheet steel market to electric arc furnace (EAF) steelmakers for the first time. Other technologies are enabling them to make higher-quality products, reduce environmental impacts, and increase overall efficiency.

Electric utilities have a major stake in all this. Steelmaking as a whole accounts for about 4.5% of all industrial power sales by utilities, or some 20 billion kWh. And while the total amount of energy needed to make a ton of steel has steadily declined over recent years, the portion of energy supplied in the form of electricity continues to rise. By fostering the development and transfer of advanced, electricity-based technologies, utilities can help sustain important industrial customers in their increasingly competitive global markets.

Since 1984, EPRI's Center for Materials Production (CMP) has been a focal point for research and development related to the use of electricity in steelmaking. Located at the Carnegie Mellon Research Institute of Carnegie Mellon University in Pittsburgh, CMP has worked closely with both integrated and electric steel producers on a wide range of technologies. The center is now seeking ways to collaborate even more closely with individual steel companies as the pace of technological innovation accelerates.

"The opportunities ahead are tremendous," declares Gene Eckhart, manager of materials production and fabrication in EPRI's Industrial Program. "As competition heats up and technological advantage becomes even more important, CMP's value and influence will continue to increase. We are already working on a broad portfolio of research that can make electric steelmakers more productive and help the whole steel industry address critical environmental issues. We are also looking for new ways to cooperate with key industry players on projects of particular interest to them."

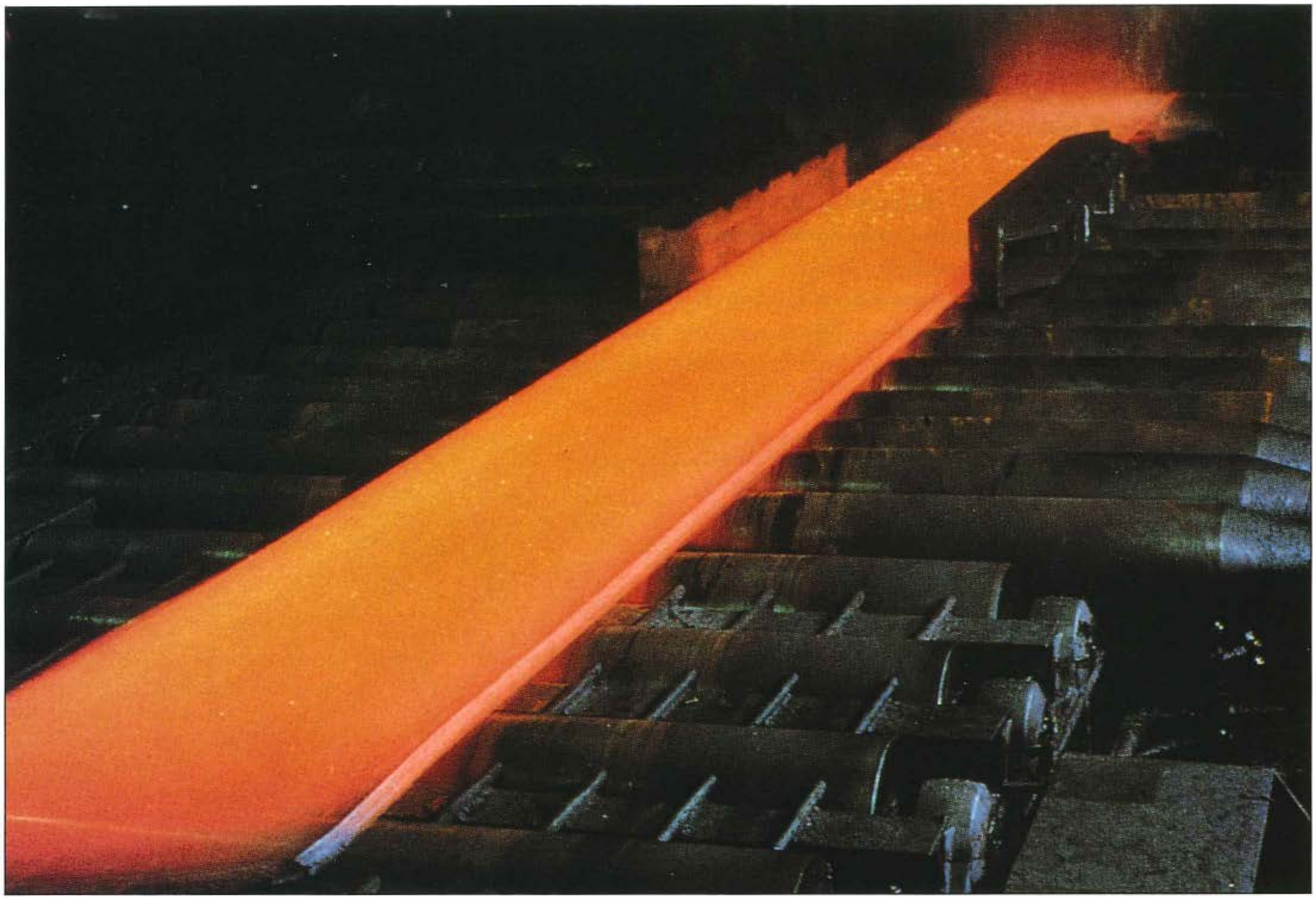
The thin-slab revolution

Until about 20 years ago, most steel was produced in integrated, ore-based facilities, where it was generally cast into ingots after leaving the furnace. These ingots then had to be reheated before they could be shaped into semifinished products, such as billets or slabs. The development of continuous casting—producing billets or slabs of steel directly from the furnace—eliminated the need to cast and reheat ingots. But continuous casting did more than reduce the energy loss and material handling costs associated with ingots; it also enabled small scrap-melting shops to compete with the integrated mills in producing steel bar and rod products for use in construction.

As casting technology continued to improve, EAF steelmakers also began to compete successfully in the production of structural steel, such as I beams for steel-frame buildings. The most recent casting technology development is the thin-slab caster, which produces slabs about 2 inches thick instead of the usual 9–10 inches. In 1989 Nucor Corporation began producing sheet steel from a thin-slab caster at its Crawfordsville, Indiana, plant. In 1992 the company opened a second thin-slab facility in Hickman, Arkansas.

The effect was immediate. By substantially reducing the amount of hot rolling required to produce sheet steel (about 0.1 inch thick), thin-slab casting enabled EAF steelmakers to compete in the hot-rolled-sheet market. Sheet steel currently accounts for about half of the domestic steel market. With the introduction of thin-slab technology, the price of hot-rolled sheet dropped from about $400 per ton to less than $300. Even greater price reductions are expected to result when direct casting of sheet steel eliminates the need for hot rolling altogether. Commercialization of such direct strip-casting technology is ex-

THE NEXT CHALLENGE: HIGHER DUCTILITY **Steel from standard electric arc furnaces has a high nitrogen content, which reduces its ductility and results in cracking when the steel is pressed deeply over dies. Research has revealed a number of steps that steelmakers can take to reduce nitrogen uptake by the steel and thus render it suitable for deep forming.**



pected within the next 2–5 years for stainless steel sheet and within 8–10 years for carbon steel sheet.

"So far, EAF steelmakers are competing mainly for the commodity end of the sheet market—things like bands for strapping and structural materials for use in culverts or building construction," points out Robert Schmitt, CMP's associate director. "The product quality still isn't high enough for applications where good ductility is required—press-formed automobile panels, for example. To achieve that level of formability, we'll need to reduce the nitrogen content and achieve greater control of other residual elements in steel produced by electric arc furnaces." Controlling nitrogen levels in EAF steel is one of the initiatives CMP has recently undertaken.

THIN-SLAB CASTING **A recent technological breakthrough in steelmaking is the development of thin-slab casting. Producing slabs that are about 2 inches thick instead of the previous 9–10 inches substantially reduces the amount of hot rolling required to make sheet steel. The thin-slab approach has enabled electric mills to compete in the market for hot-rolled sheet, reducing the price of this product by more than 25%.**

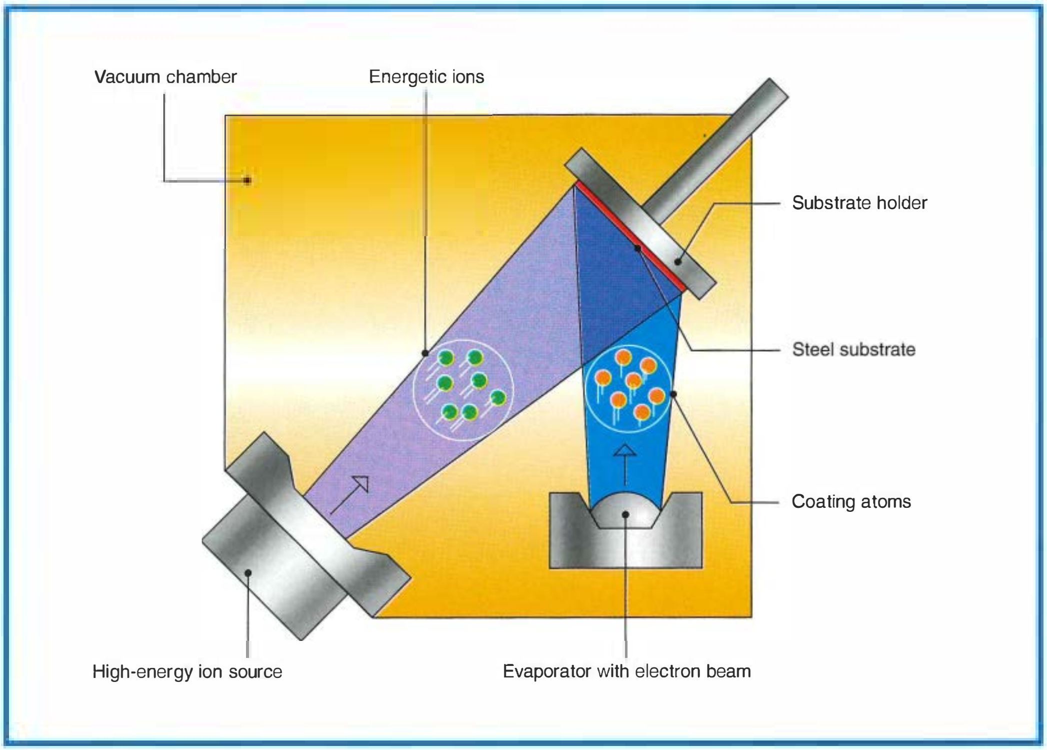
Lower nitrogen

During arc heating in an electric furnace, molecular nitrogen from the atmosphere tends to dissociate into its atomic form, which is readily absorbed into the molten steel. The typical nitrogen content of arc furnace steel is about 70–120 parts per million, compared with only 10–40 ppm for steel from a basic oxygen furnace. A high nitrogen content reduces the formability of steel, thus making it unusable for applications requiring a high degree of ductility. In order for electric arc furnaces to produce steel that can be deeply pressed over dies, nitrogen levels must be reduced to about 30–50 ppm.

To determine how best to lower the nitrogen content of EAF steel, CMP organized a collaborative research project involving about a dozen steel companies as cosponsors. The North Star Steel plant in Monroe, Michigan, was selected as the project site, where five steelmaking practices related to melting and refining were studied experimentally. In addition, historical data provided by North Star enabled researchers to investigate how other, subsequent processes—including ladle refining and casting—affect the nitrogen content.

The results confirmed that the largest amount of nitrogen is absorbed by the steel during initial melting and that nitrogen levels are reduced when oxygen is injected into the liquid steel to react with carbon. Specifically, the carbon monoxide formed during this reaction tends to flush out the nitrogen. Also, the presence of a foamy slag covering the molten metal reduces the chance for more nitrogen to be absorbed. The foam is produced when carbon dioxide gases from the steel bath form small bubbles within the slag; it has approximately the consistency of the foam that forms on top of a carbonated beverage. Controlling nitrogen absorption from the atmosphere is important during later stages of steelmaking too, including ladle refining and casting. The researchers concluded that conventional EAF steelmaking equipment can probably achieve low enough nitrogen levels to produce sheet steels suitable for deep forming.

ION BEAMS IMPROVE SURFACE TREATMENT **Ion-beam-assisted deposition (IBAD) is a process for applying coatings to specialty steels without producing the chemical residues associated with hot dipping and electroplating. Ion bombardment both cleans the substrate and accelerates atoms from the evaporator to provide a better-quality coating.**



Preventing nitrogen absorption from the atmosphere is one factor in reducing the level of nitrogen in finished steel. But the level of nitrogen and other elements in the steel also depends on the type of raw materials used—specifically, the quality of scrap and the amount of direct-reduced iron (DRI) in the initial charge. Hence the availability of high-quality raw materials at competitive prices is another key to the continued growth of EAF steelmaking. CMP is investigating projects to upgrade steel scrap and to reduce the cost of making DRI.

Greater productivity and quality

Competitiveness in the international steel market is ultimately a matter of making a cost-competitive product that meets the quality needs of the customer. For some years, one of the techniques EAF steelmakers in Europe and Japan have used to increase productivity has been inert gas injection, or bottom stirring, which reduces melt time, saves energy, and increases yield. Interest in this practice is beginning to grow among EAF steelmakers in the United States.

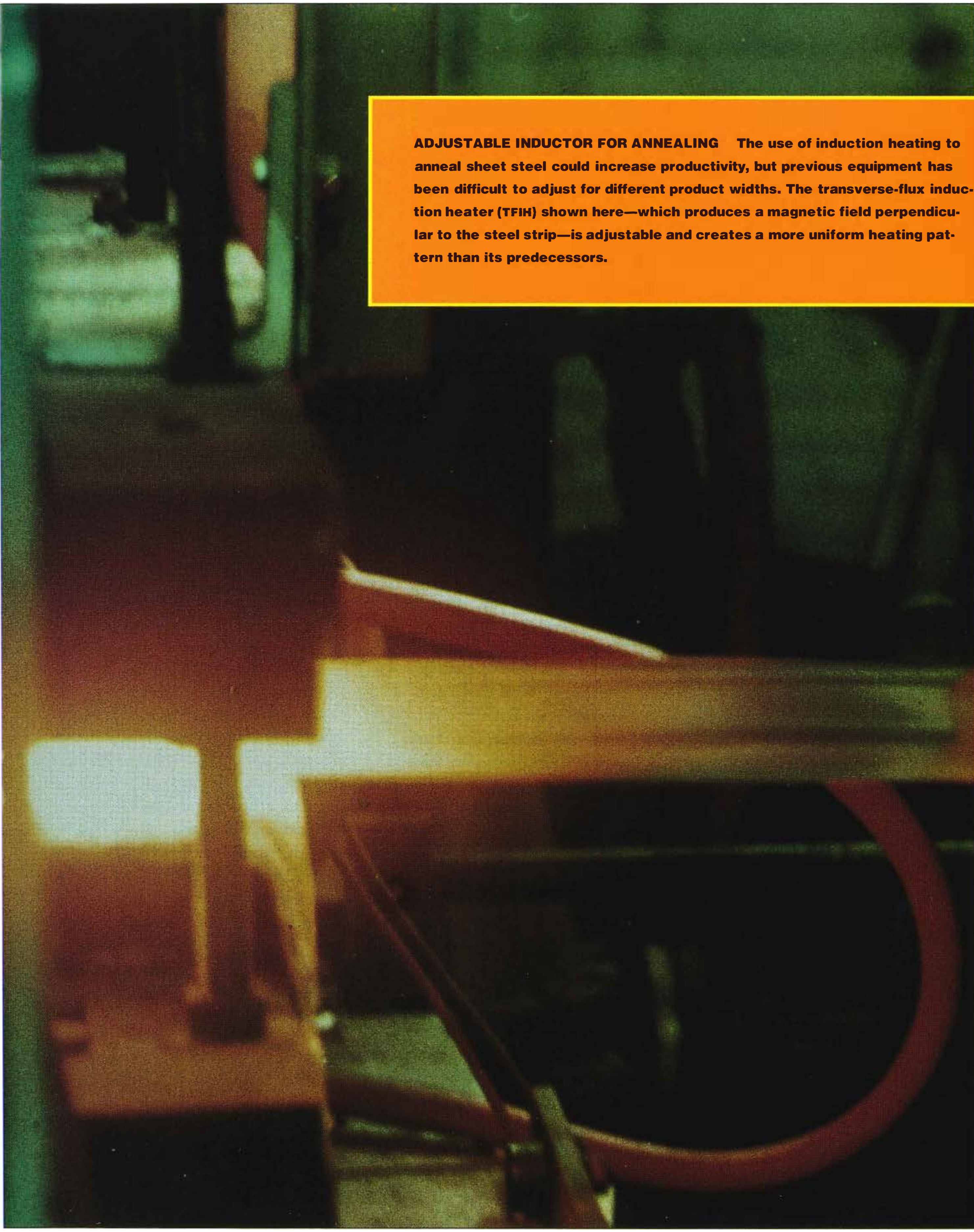
To investigate the potential benefits, CMP sponsored a demonstration project at Lukens Steel Company, Coatesville, Pennsylvania, in which bottom stirring was used in the company's 165-ton arc furnace. Porous plugs were installed at the bottom of the 22-foot-diameter furnace for the injection of argon gas in a series of carefully controlled heats considered typical of regular carbon steel production.

Increased circulation of the bath did decrease the process time because of more-uniform melting of the scrap. Productivity increased by 10 tons per hour, while electricity consumption decreased by 10–20 kWh per ton. Also, slag formation influenced by gas injection removed phosphorus and sulfur from the steel more effectively. Although there had been some concern that increased agitation would cause greater electrode consumption and refractory wear, these did not occur to any significant extent.

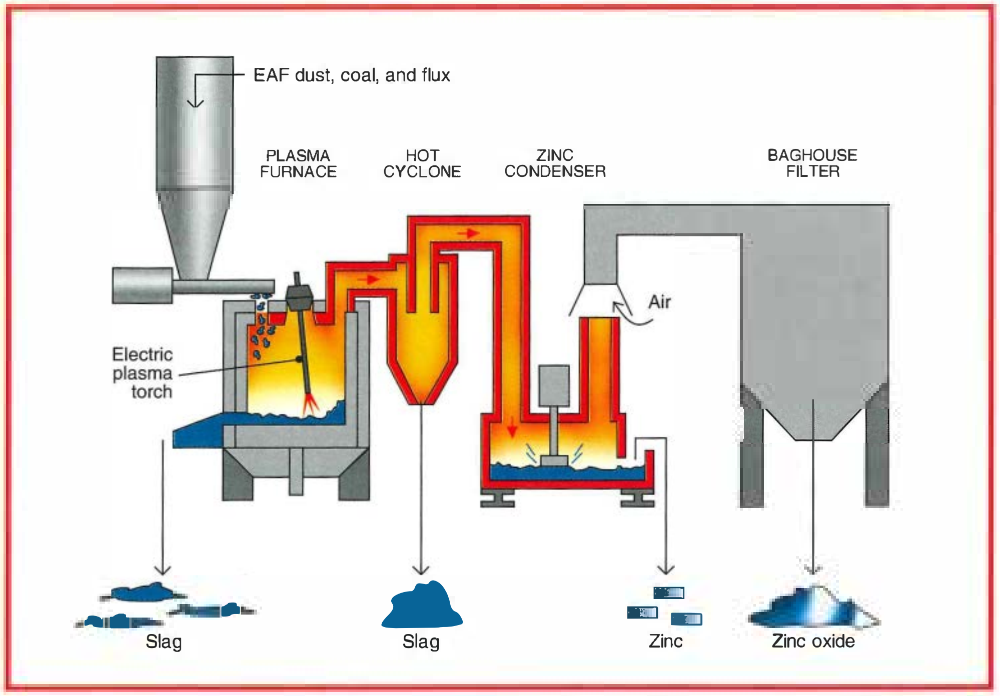
Heat for rolling

Another opportunity to adopt advanced technology occurs just after casting. Before the thin slab produced by a continuous caster enters a rolling mill, it requires additional heating. The caster discharges a slab at a speed of about 18 feet per minute, and the slab must then be accelerated to 45–60 feet per minute for entry into the mill. By the time a 150-foot slab is ready for rolling, its leading edge may have been cooling for some 10 minutes. Additional heating of about 100–120°C is thus usually required before the slab is ready to be rolled. This heating step should also reduce temperature differences across the slab to less than 20°C.

Research sponsored by CMP has investigated the use of electric induction heating to adjust the temperature of thin slabs



ADJUSTABLE INDUCTOR FOR ANNEALING The use of induction heating to anneal sheet steel could increase productivity, but previous equipment has been difficult to adjust for different product widths. The transverse-flux induction heater (TFIH) shown here—which produces a magnetic field perpendicular to the steel strip—is adjustable and creates a more uniform heating pattern than its predecessors.



PLASMA TREATMENT FOR ARC FURNACE DUST A critical environmental problem facing electric arc furnace steelmakers is how to treat the dust produced by the vaporization of hazardous metals during scrap melting. Treating the dust with a plasma torch facilitates the separation of a nonhazardous slag and the condensation of commercial-grade metallic zinc, lead, and cadmium.

before casting and rolling. Such heating takes place when magnetic coils near a steel slab induce currents in it, raising the temperature because of the inherent resistance of the metal. EPRI studied two types of induction heating for this application.

Transverse-flux heaters create a magnetic field perpendicular to the wide surface of the slab, which promotes high power densities in the metal and results in a relatively short heating time. The researchers found, however, that the transverse-flux method was not effective in this application because temperature uniformity across the slab was not adequate.

Axial-flux heating, the second option studied, uses coils wound around the slab to produce a uniform magnetic field in the longitudinal direction of the slab. Experiments showed that, for 1000-Hz alternating current in the coils, the axial-flux heater produced a good temperature profile in the slab (variations of less than 10°C), with an overall operating efficiency of about 75%.

In spite of this efficiency, the study concluded, induction heating alone would be too expensive for use with thin-slab steel. The researchers recommended a system that would use fossil fuels for most of the heating and apply the electric induction technique to fine-tune the temperature just before rolling. Such a hybrid system would require less space than an all-fossil-fuel system and provide greater operating flexibility.

New finishing technologies

Before being incorporated into final products, the 0.1-inch sheet steel is usually cold-rolled to a thickness of roughly 0.01–0.06 inch. Typically, the strip is then heated to a high temperature in order to restore ductility, permitting fabrication into a finished product. New electrotechnologies can help make these finishing steps more productive and less costly.

Heat treating, or annealing, requires the use of furnaces in which the steel reaches temperatures of more than 1000°F. Both gas-fired and electric resistance furnaces are currently used for this purpose. Electric induction heating could, however, offer several advantages, including compactness of equipment, ease of automation and maintenance, increased productivity, and improvement of yield.

In the past, induction heating was not used commercially to anneal sheet steel because of the difficulty of making adjustments for the sheet width. Previous attempts at induction heating also tended to make the edges of a strip hotter than the center, resulting in edge distortion and cracking. Recently, however, Ajax Magnethermic Corporation of Warren, Ohio, received a patent on a system for transverse-flux induction heating (TFIH) that is both adjustable and more uniform in its heating. While, as mentioned earlier, this technology is not an effective option for slab heating, it appears to be particularly well suited for thin-strip heating. CMP, in collaboration with Ajax and Allegheny Ludlum Steel Corporation, built a pilot TFIH line at Allegheny's plant in Vandergrift, Pennsylvania, to demonstrate the concept.

Tests on the pilot line showed that the TFIH system could reduce annealing costs by about 28%, compared with conventional processing. Temperature variation across the width of the steel was kept within 5% of the mean. In addition, only about one-third the usual amount of oxide scale built up on the steel surface during annealing, making removal easier and eliminating the need for acid pickling. CMP is now identifying opportunities to commercialize TFIH annealing for both stainless and carbon strip steel.

To impart corrosion resistance to carbon sheet steel, a layer of zinc is often applied, usually through electroplating or hot dipping. The cost of these conventional treatments is rising, however, because of new environmental requirements regarding the treatment of the waste solution from electroplating and the confinement of fumes from hot zinc baths. A new electricity-based coating process, which is environmentally contained and uses only directly recyclable materials, is now being explored by CMP.

Known as ion-beam-assisted deposition (IBAD), this process has been used to apply metal coatings to electronic and medical equipment. For treating sheet steel, IBAD offers several potential benefits, including a lack of chemical residues, the flexibility to handle a more varied product line, high yields, and improved coating quality.

Spire Corporation, which makes IBAD equipment, conducted a study on the process for CMP, with the assistance of an advisory group provided by the American Iron and Steel Institute. Work included experiments in which the IBAD process was used to apply a zinc coating to samples of automotive sheet steel. The experiments found the mechanical and corrosion performance of all IBAD-coated samples to compare favorably with that of the corresponding commercially produced samples. CMP is currently considering a collaborative project with steelmakers to construct a pilot IBAD line.

Addressing environmental concerns

One of the most important areas of collaborative research organized by CMP addresses generic environmental issues that have major impacts throughout the steelmaking industry. Two recent accomplishments illustrate the important role that the EPRI center can play in helping resolve these issues.

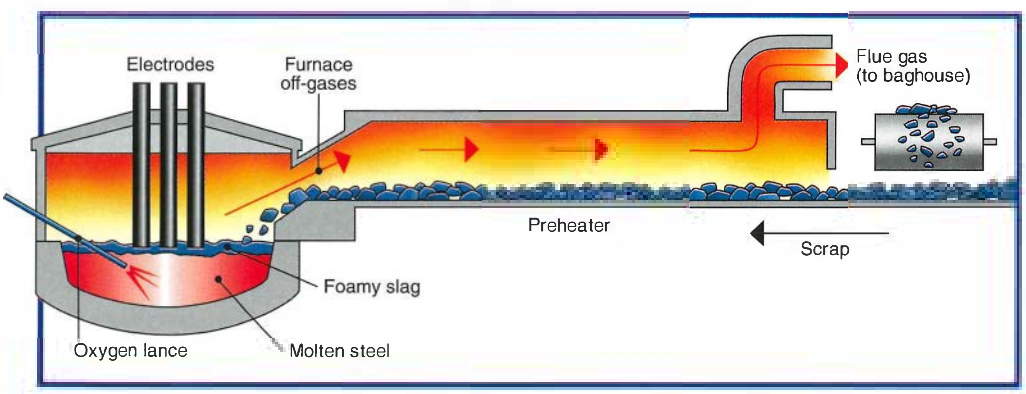
The first concern arose rather suddenly in the mid-1980s, when, under provisions of the Resource Conservation and Recovery Act, the U.S. Environmental Protection Agency listed electric arc furnace dust as a hazardous waste because of its toxic metal content. When scrap is melted by an electric arc, highly volatile metals—such as zinc, lead, and cadmium—vaporize and react with oxygen to form a fine (0.1–10-micrometer) dust. Each year, EAF steelmakers in the United States and Canada must dispose of about half a million tons of this dust.

In 1986 CMP led an industry group comprising 22 companies in selecting two dust treatment technologies for demonstration projects. Both technologies are based on the concept of offsetting treatment costs by recovering and selling zinc from the dust. The flame reactor process uses oxygen-enriched air and fossil fuel to chemically reduce and volatilize the metallic dust particles, eventually collecting the zinc oxide product in a baghouse. The plasma furnace process uses a plasma torch to heat the dust to a much higher temperature, vaporizing zinc and lead; the vapor is then condensed to obtain commercial-grade metallic zinc.

The demonstration results (published in 1988) indicated that both treatment processes could render arc furnace dust nonhazardous, but that the flame reactor product would contain less than the minimum acceptable level of zinc for resale to a smelter. The plasma furnace process, however, had zinc recovery rates of about 75%, and economic analysis showed that sale of the zinc should produce a net gain of about $63 per ton of treated dust, excluding the slag disposal cost. As a result, two commercial plasma-based treatment plants are now operating. The plasma technology, developed by Tetronics R&D Company, was scaled up by International Mill Service for on-line use at the Jackson, Tennessee, plant of Florida Steel Company (8000 tons of dust per year) and at the Blytheville, Arkansas, plant of Nucor-Yamato Steel Company (12,000 tons per year).

Another important environmental problem affecting both electric and integrated steel mills is what to do with the oily metallic emulsions and sludges produced by the cooling water used in the hot rolling of steel. In volume, typical sludge consists of about equal portions of water, oil, and iron oxide particles. One hot-strip-rolling mill can generate more than 50 tons of such sludge a day, which currently requires several hours to separate by means of such conventional processes as gravity settling or heating and decanting.

Responding to the need for a better approach, CMP has completed laboratory tests of a process that uses microwave energy to separate sludge into its constituents. In this effort, researchers at Carne-



CONSTEEL SCRAP PREHEATING Heating scrap before it is melted in an electric arc furnace saves energy and increases productivity. The new CONSTEEL process, which uses recovered furnace off-gases to preheat scrap, was recently demonstrated at a steel mill in North Carolina.

DC ARC FURNACE For new installations, a direct-current arc furnace with a single electrode may have advantages over the traditional three-electrode ac furnace. Reported benefits include higher efficiency and lower electrode consumption. (Photo courtesy of ABB Metallurgy, Inc.)

gie Mellon Research Institute modified a microwave emulsion cracking process patented by Conoco, Inc. Test results showed that after a magnet was used to concentrate the oily metallic particles, microwaves could separate sludge into clear water, clean oil, and clean metal in 10 minutes or less. The costs for operation and disposal at commercial scale for the new process are estimated to be only 10% of the current costs. CMP is now working to establish a collaborative project with the steel industry to demonstrate a scaled-up version of the microwave separation technology.

The drive for efficiency

The drive for greater energy efficiency is an important factor in keeping electric steelmaking competitive. Over the years, CMP has pursued several initiatives in this area, including the recent publication of a wide-ranging study of arc furnace efficiency (see reading list). Two field demonstrations of efficiency-enhancing technologies illustrate some of the benefits that can be achieved.

About 25% of the total energy used in electric steelmaking almost literally goes up in smoke—in waste gases, to be exact. Recovering the thermal energy from furnace gases to preheat scrap before melting has several potential benefits, including greater productivity and lower cost. To explore this potential, CMP organized a consortium of six steel industry companies and two utilities to sponsor a demonstration of the CONSTEEL process for scrap preheating at the Charlotte, North Carolina, plant of Florida Steel.

In the CONSTEEL process, hot exhaust gases pass through a side opening in the furnace into a refractory-lined tunnel about 80 feet long. As a conveyor moves scrap toward the furnace through this tunnel, the scrap is preheated by thermal energy from the waste gases. In the demonstration at the Florida Steel plant, this heat-recycling arrangement improved steel production from 33 to 44 tons per hour and lowered the tap-to-tap melting time from 83 to 60 minutes. Electrode consumption was also reduced by about 30%. Although energy efficiency per se did not increase as much as expected, the productivity improvements reduced direct operating costs from about $23.30 to $21.52 per ton—indicating a payback period of approximately two years for investment in the CONSTEEL process. And Florida Steel reports that improvements undertaken in the process since the demonstration have boosted energy efficiency.

Another major energy consumer in the steelmaking process—requiring up to about 10% of the electric energy input—is the air pollution control system. Many of these systems were designed to operate constantly at maximum air evacuation levels, with little regard for energy consumption or effect on product yield. Yet such high flow may be needed for only 15–25% of the total melt cycle. CMP has investigated the potential benefits of using adjustable-speed drives on fan motors to reduce energy consumption.

The study involved tests at the electric steelmaking plant of Structural Metals, Inc., at Seguin, Texas. Walli Engineering was the principal investigator for the study, with CRS Sirrine Engineers providing data analysis. The test results showed that using adjustable-speed drives could substantially improve the energy efficiency of the air pollution control system, probably repaying an investment in two and a half years.

Toward closer collaboration

After more than a decade of collaborative effort, CMP is seeking ways to work even more closely with electric steel producers. To accomplish this objective, CMP is forming—in collaboration with the Steel Manufacturers Association (SMA)—an electric steelmaking technology committee to sponsor development and demonstration projects. The organizational meeting was held on October 13 in Chicago, in conjunction with the annual meeting of SMA, which is composed primarily of electric steelmaking companies.

EPRI's Gene Eckhart, who facilitated the formation of the collaborative EPRI/CMP/SMA partnership with the assistance of Paul Stewart of EPRI's Customer Systems Division, outlines the strategy: "Our purpose is to identify key technical issues and opportunities for electric steel producers that can be addressed collaboratively by CMP and SMA. The membership fee to join will be modest. We will look to the SMA members to join in sponsoring specific projects, along with CMP and EPRI member utilities." According to CMP's director, Joe Goodwill, the center will develop and manage selected projects for the partnership.

"Many electric mills are lean outfits with only small technical staffs," notes Bob Jeffress, manager of EPRI's Industrial Program. "That makes it difficult for them to study and keep up with the latest international technological developments. Collaboration between SMA and EPRI/CMP will provide opportunities for our members to work more closely with electric steel producers on jointly sponsored projects that will help them retain global competitiveness." ■

Further reading

Electric Arc Furnace Efficiency. December 1992. CMP (Center for Materials Production) report 92-10.

Nitrogen Control in Electric Arc Furnace Steelmaking Final report for RP2787-1. December 1992. EPRI TR-101600.

Ion-Beam-Assisted Deposition of Coatings on Carbon Steel. November 1992. CMP report 92-9.

Continuous TFIH Annealing of Stainless Steels. August 1992. CMF (Center for Materials Fabrication) report 92-4.

Application of Microwaves to the Separation of Oil-Water Sludges. July 1992. CMP report 92-6.

Adjustable-Speed Drives for Electric Arc Furnace Air Pollution Control Systems. December 1991. CMP report 91-10.

The CONSTEEL Scrap Preheating Process. May 1991. CMP report 91-9.

Bottom Stirring in an Electric Arc Furnace. February 1991. CMP report 91-5.

Electrotechnologies for Reheating Thin Slabs Prior to Rolling. March 1990. CMP report 90-5.

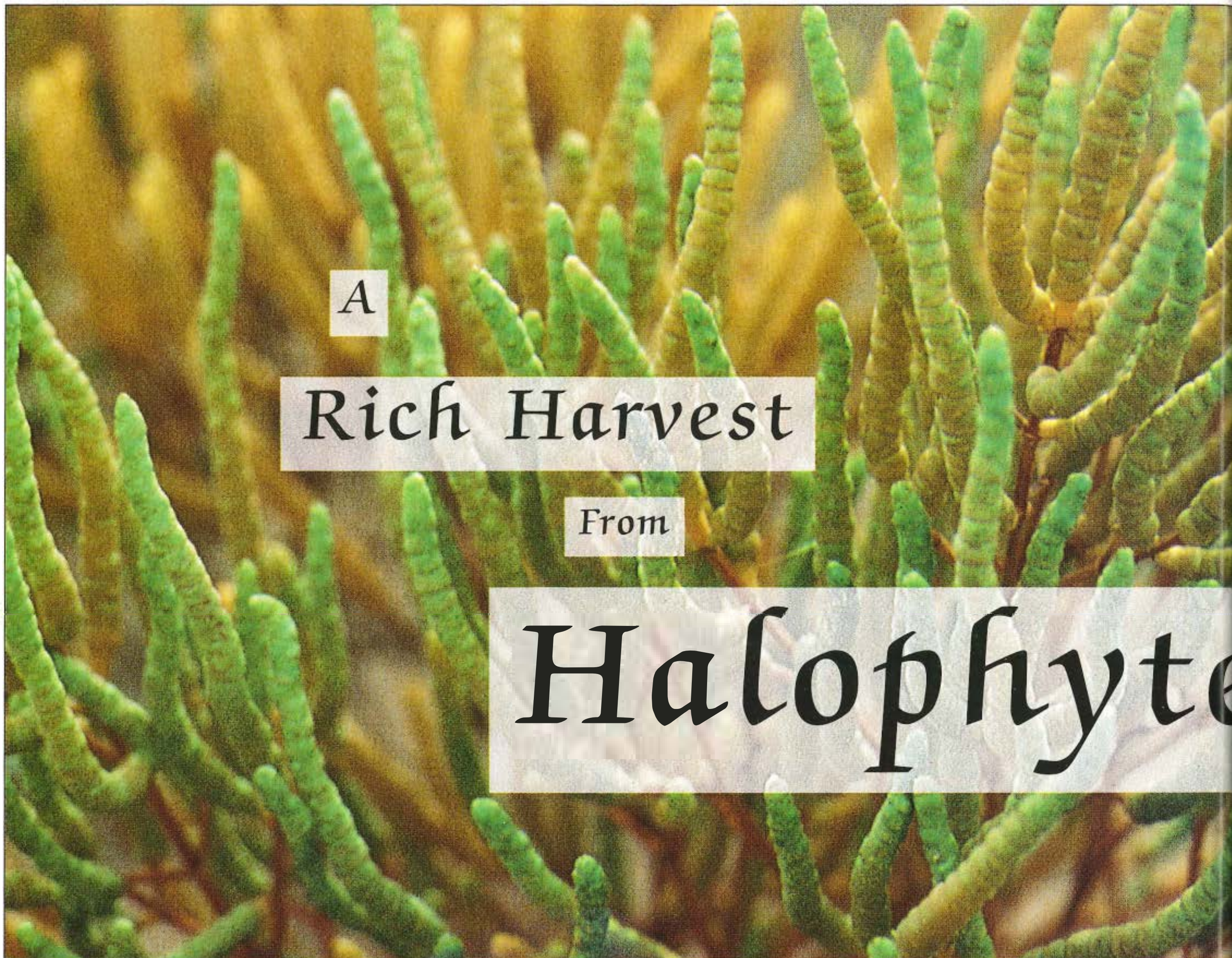
Advanced Process Control for Electric Arc Furnaces. December 1989. CMP report 89-3.

Plasma Furnace Treatment of Electric Arc Furnace Dust as Demonstrated by Bethlehem-Tetronics. November 1988. CMP report 88-2.

Flame Reactor Process for Electric Arc Furnace Dust. August 1988. CMP report 88-1.

Electric Arc Furnace Dust: Disposal, Recycle, and Recovery. May 1985. CMP report 85-2.

Background information for this article was provided by Gene Eckhart and Robert Jeffress of EPRI's Customer Systems Division and Robert Schmitt of the Center for Materials Production.

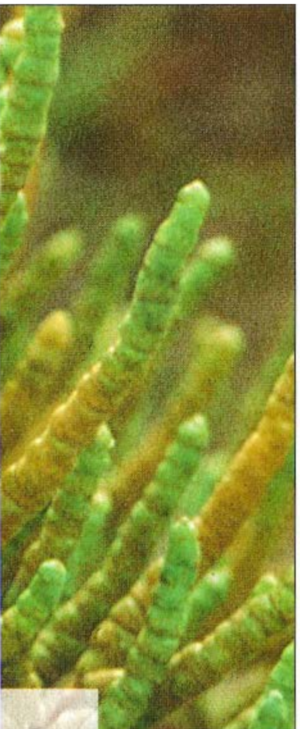


A Rich Harvest From Halophyte

The widening search for solutions to global environmental and social problems is leading to some surprising discoveries about underutilized natural resources. Take halophytes, for example, a group of only distantly related plants that have in common one special ability—salt tolerance. Ranging from shrubs and succulents to certain kinds of turf grass, halophytes are commonly found along seacoasts, in salt marshes, and across inland alkali deserts. Some halophytes, such as *Salicornia bigelovii*, can even be grown as food crops—producing seeds that compare favorably with soybeans in oil and protein content—using seawater for irrigation.

Some of the advantages of increasing the use of halophytes worldwide are obvious: they can grow where other plants can't; they don't need fresh water for irrigation and, in fact, can help reclaim salinized desert areas; and, as crops, they can increase global agricultural productivity without deforestation. Less obvious are the potential benefits for electric utilities. The subject of ongoing EPRI research, these benefits include sequestering carbon dioxide, removing salt and heavy metals from power plant wastewater, providing a new nonfossil biofuel, and reducing the salinity of drainage water in major irrigation districts.

"The original purpose of our work in this area was to examine the potential of halophytes to remove carbon dioxide from the atmosphere as an offset for emissions from fossil fuels," says Sy Alpert of the Office of Exploratory & Applied Research. "But then we began to see many other opportunities that could involve utilities directly or indirectly. I believe, for instance, that an important emerging issue is the increasing shortage of potable water as populations grow around the world. The development of crops that can be irrigated with seawater could help ease this shortage. On a smaller scale, salt-tolerant plants could be used in bioremediation for a variety of water contamination problems. Utility involvement in halophyte research for such applications represents a win-win situation both globally and locally."



THE STORY IN BRIEF **Halophytes—a diverse group of salt-tolerant plants ranging from succulents to sea grass—appear to be something of a wonder crop. They can thrive in environments that will not support conventional plant life, and some can actually be irrigated with seawater. Researchers estimate that more than 320 million acres of desert and salt-degraded cropland worldwide could be used to grow halophytes, with a wealth of potential benefits. Several species of the hardy plants are being investigated as both a food crop and a new nonfossil biofuel, and strategically placed plantings can also assist with land reclamation and the removal of salts and heavy metals from power plant wastewater. Perhaps most important, halophytes offer a new biological alternative for removing and storing atmospheric carbon dioxide.**

by John Douglas

Using halophytes

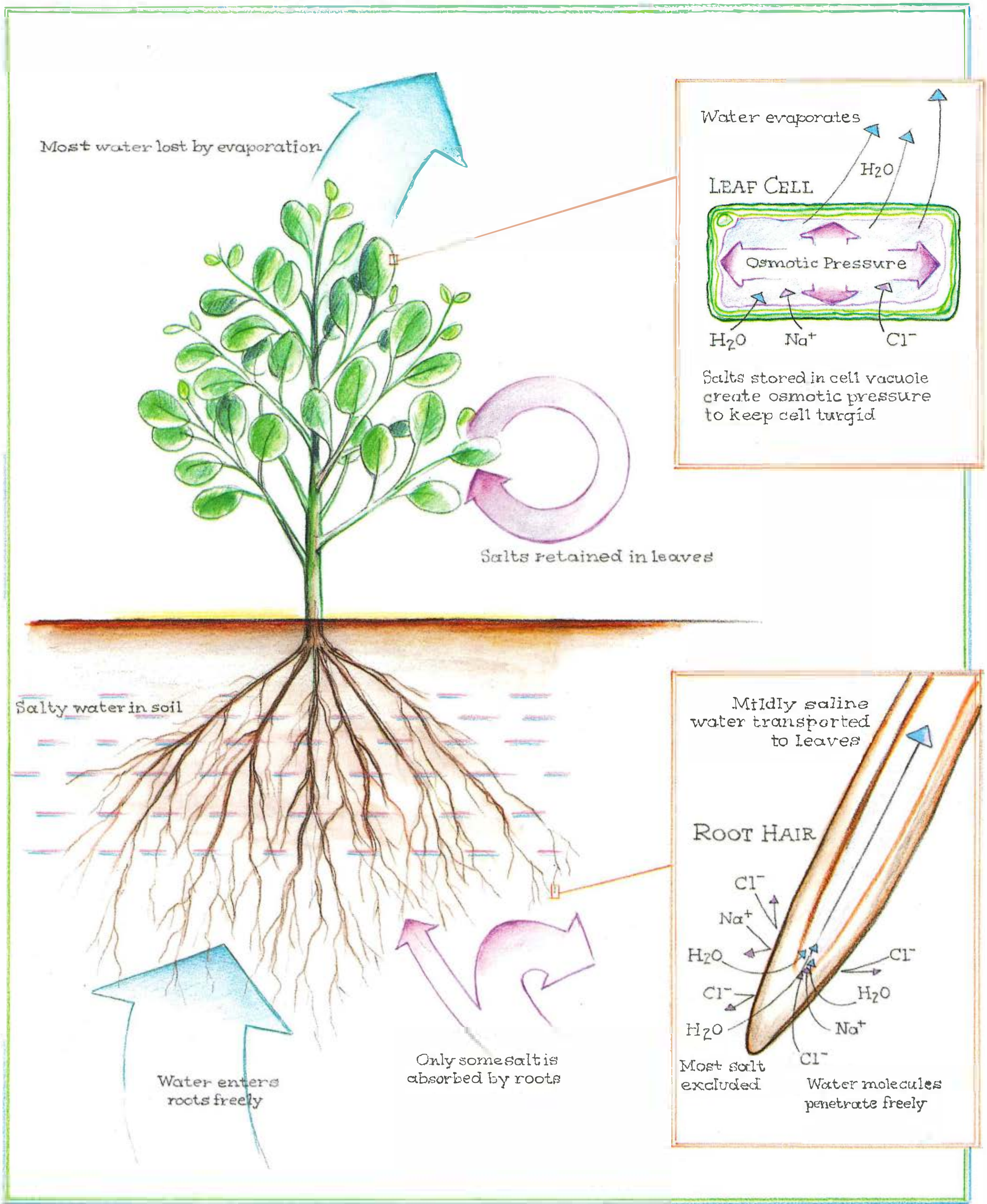
Ordinary salt, sodium chloride, is essential for life, but maintaining a proper balance of it in various cells can be a challenge for plants and animals alike. The cells of plant leaves, for example, concentrate salt in storage spaces called vacuoles, which become distended as water flows into the cells under osmotic pressure. This pressure keeps the leaves turgid; without it, the leaves wilt. If groundwater contains too much salt, however, the osmotic flow of water can actually be reversed, draining and killing the plant.

Halophytes solve this problem by expending energy to accumulate salts in their vacuoles to levels that are higher than those in the soil solution, ensuring a net movement of water into rather than out of the plant. Like other plants, halophytes use large protein molecules (enzymes) in the cell membranes of roots to regulate salt intake. Called proton pumps, these enzymes exchange sodium ions for hydrogen ions and thus reduce the plant's salt uptake. There is evidence that these pumps operate more efficiently in halophytes than in nonhalophytes at high external salt levels.

Whatever the mechanism, halophytes are able to accumulate salt to more than 6% in their cell vacuoles, more than enough to offset the osmotic pressure generated even by pure seawater (3.2% salt) in the external solution. Halophyte seeds, however, do not accumulate salt, so they can be used for food and fodder without further processing, provided they can be harvested conveniently. Historically, at least two halophyte grains were major food sources for the Native Americans inhabiting the coastal desert regions along the northern part of the Gulf of California.

But the ecological benefits of halophyte cultivation may be of far greater importance than the plants' food potential. The global circulation of the atmosphere has created a band of dry air at about 30° latitude in each hemisphere, producing some of the world's great deserts and other drylands, which will not support conventional plant life. These areas include some 720 million hectares (1 hectare equals 2.471 acres) of coastal deserts and inland saline deserts. In addition, about 43 mil-

HIGH SALT TOLERANCE **Most plants cannot survive in saltwater areas. But halophytes can because they accumulate salts in their leaves to levels higher than those in the soil. This ensures a net movement of water into—rather than out of—the plant. Like other plants, halophytes use large protein molecules in the cell membranes of their roots to regulate salt intake.**



lion hectares of irrigated cropland have been degraded by salinization.

An estimated 130 million hectares of these salt-affected drylands could be used to grow halophytes, according to research conducted by the Environmental Research Laboratory (ERL) of the University of Arizona, under cosponsorship by EPRI and the Salt River Project. This estimate assumes that coastal regions would be irrigated with seawater; inland saline basins would use water from brackish aquifers too salty for conventional agriculture; and desert irrigation districts would use saline drainwater from existing fields.

An important reason to consider the cultivation of halophytes on a large scale is their potential for removing carbon from the atmosphere. This approach promises several advantages over some of the alternatives that have been suggested previously. Creating tree plantations for carbon sequestration, for example, may displace existing cropland, which could lead to forest clearing elsewhere. Indeed, over the next 75 years, some 200 million hectares of new cropland may be needed to support the projected doubling of the population in the tropics alone.

By contrast, halophyte plantations on salinized drylands would not compete with other agricultural uses or tap scarce freshwater resources. Such plantations either could be used to sequester atmospheric carbon dioxide directly, through the long-term storage of the resulting biomass, or could contribute indirectly by increasing the world's net total of cropland, saving existing forests to sequester carbon. One hectare of *Salicornia bigelovii*, for instance, could replace 1 hectare of soybeans or multiple hectares of pasture—the principal crops for which much of the Brazilian forest is being cleared. There is even a chance that increasing the plant mass on large areas of drylands could help change local climate conditions and increase rainfall.

Halophytes are also a potential source of renewable fuel for electric power generation or transportation. Although the heat content of halophyte biomass varies by species, it generally falls in the same range as that of lignite coal. ERL research indicates that using a 2-to-1 ratio of coal to halophyte biomass in a 500-MW power plant would produce about 10% less heat per unit weight than coal alone but would result in 25% less carbon being contributed to the atmosphere (because of the recycling of carbon back to the biomass). It is also possible that refined halophyte oil could be blended with diesel fuel to power vehicles.

Questions of feasibility

Before halophyte cultivation is greatly expanded for any of the purposes just described, however, much more needs to be known about its long-term feasibility and cost-effectiveness. The most recent research by ERL scientists has focused on four important questions: What are the yields of various halophyte species under seawater irrigation? What are their irrigation requirements? How quickly do halophytes decompose under various circumstances, releasing their stored carbon to the atmosphere again? And how expensive would it be to sequester carbon using halophytes? This research, also sponsored by EPRI and the Salt River Project, was conducted at a site on a farm on the Sonoran coast of the Gulf of California. The farm is owned by Genesis, Inc., a Mexican company that grows halophytes commercially and that is acting as a subcontractor for ongoing ERL research.

Yields of 14 halophyte species were measured over two growing seasons at the Mexican farm, using seawater for irrigation. (Rainfall in the area is less than 4 inches per year.) Even under these harsh conditions, the five most productive species had annual dry biomass yields in a range from about 17 to 34 metric tons per hectare—about the same as for conventional crops irrigated with fresh water. Using a conservative estimate of 25% carbon content for the halophytes (compared with about 36–40% carbon content for wood), the yields translate into an annual carbon uptake of about 4–8 metric tons per hectare—within the range of high-yielding tree plantations.

Measurements of water consumption showed that halophytes require 1–3 cubic meters of seawater per square meter of soil each year, depending on the species and the growing season. This range is about the same as that for cotton and alfalfa irrigated with fresh water under similar desert conditions. Some of this water is used by the plants, while the rest is needed to leach salts downward to prevent their accumulation in the surface soil. The relatively high water transpiration rates of halophytes mean that they could provide a more efficient alternative to the solar evaporation ponds that some utilities use for disposing of wastewater.

Irrigation costs, primarily for pumping seawater, are the most significant expense in growing halophytes. In addition, the "carbon cost" of using fossil fuels in planting, irrigating, and harvesting halophytes equals about 25% of the carbon content of the biomass yield. These initial findings were based on experiments conducted on plants grown in lysimeters, 10-gallon containers designed to monitor water consumption; further data taken under field conditions will be needed to confirm and refine the results.

Decomposition of the halophyte biomass, which releases carbon into the atmosphere, is very slow when the harvested plants are removed and buried in dry desert soil. Alternatively, the harvested biomass can be plowed back into the ground (which will be irrigated and reused to grow more halophytes), saving transportation costs. Small-scale experiments indicate that the decomposition rate of halophyte biomass in seawater is about half that in fresh water but that it differs sharply by species. With or without irrigation, the decomposition rate is low enough that there is a net accumulation of organic carbon in the soil—a potential first step toward rehabilitating some desert areas for raising other kinds of crops. Although such decomposition experiments indicate that about 30–50% of the carbon taken up by halophytes might enter long-term storage, the ultimate magnitude and duration of storage has not yet been determined.

Under the conditions just described, the direct cost of raising halophytes is approximately $44–$53 per metric ton, compared with $30–$45 for conventional biomass crops. This cost includes the energy input of diesel fuel for irrigation and tilling but does not include payments to farmers. Growing halophytes just to store carbon would thus be relatively expensive, but the net cost could be significantly reduced if the seeds were cultivated as a source of food or animal fodder, leaving a carbon-rich by-product for storage.

"I expect that halophytes will be grown for multiple purposes," says Edward Glenn, a senior research scientist at ERL. "*Salicornia,* for example, is very easy to harvest. It looks like green, jointed pencils with seed spikes on the top third of the plant. Harvesting the oilseeds would leave straw, containing about 90% of the total carbon, available for sequestration. In the case of woody halophytes grown for forage, the stem and roots, containing about 75% of the carbon, would remain."

Glenn and his associates, Mary Olsen and Robert Frye, calculate that if such crop residues were plowed under and if only one-third of the buried carbon entered long-term storage, the net marginal cost of sequestration would be only $12 per ton of carbon. "That would be an attractive cost for carbon sequestration if further research supports these estimates," says EPRI's Sy Alpert.

The next stage of ERL's research in Mexico, again sponsored by EPRI and the Salt River Project, will be to address some of the remaining issues related to the feasibility of using halophytes for sequestering carbon. The major question is, what happens to the carbon once it enters the soil? Does it leach and drain away into rivers? Is it released to the atmosphere by bacterial decomposition? Or does it remain sequestered?

The first objective of the new research will be to determine the fate of dissolved organic carbon leached from the halophyte production system. Another objective will be to measure the effects that residue burial and subsequent nitrogen fertilization have on biomass production from the next crop and on decomposition of the residues. From these and other experiments, researchers eventually want to develop a predictive model of the carbon-storing potential of halophyte crops.

"Previous research has helped create worldwide interest in growing halophytes

THE NEXT REVOLUTION IN AGRICULTURE? **EPRI and the Salt River Project sponsored research on 14 halophyte species at a northern Mexico farm located on the Gulf of California. With only seawater for irrigation, the five most productive species had an annual dry biomass yield comparable to that of conventional crops irrigated with fresh water. The carbon sequestration potential of these plants was also judged to be excellent.**

on salt-affected drylands," says Louis Pitelka, a research manager in EPRI's Environment Division. "The United Nations' environment program, for example, has endorsed the use of halophytes on salinized soils to help arrest desertification in developing countries. Some people believe that this could even be the beginning of the next revolution in agriculture. In any case, more research will be needed to find out how widely applicable some of these concepts may be."

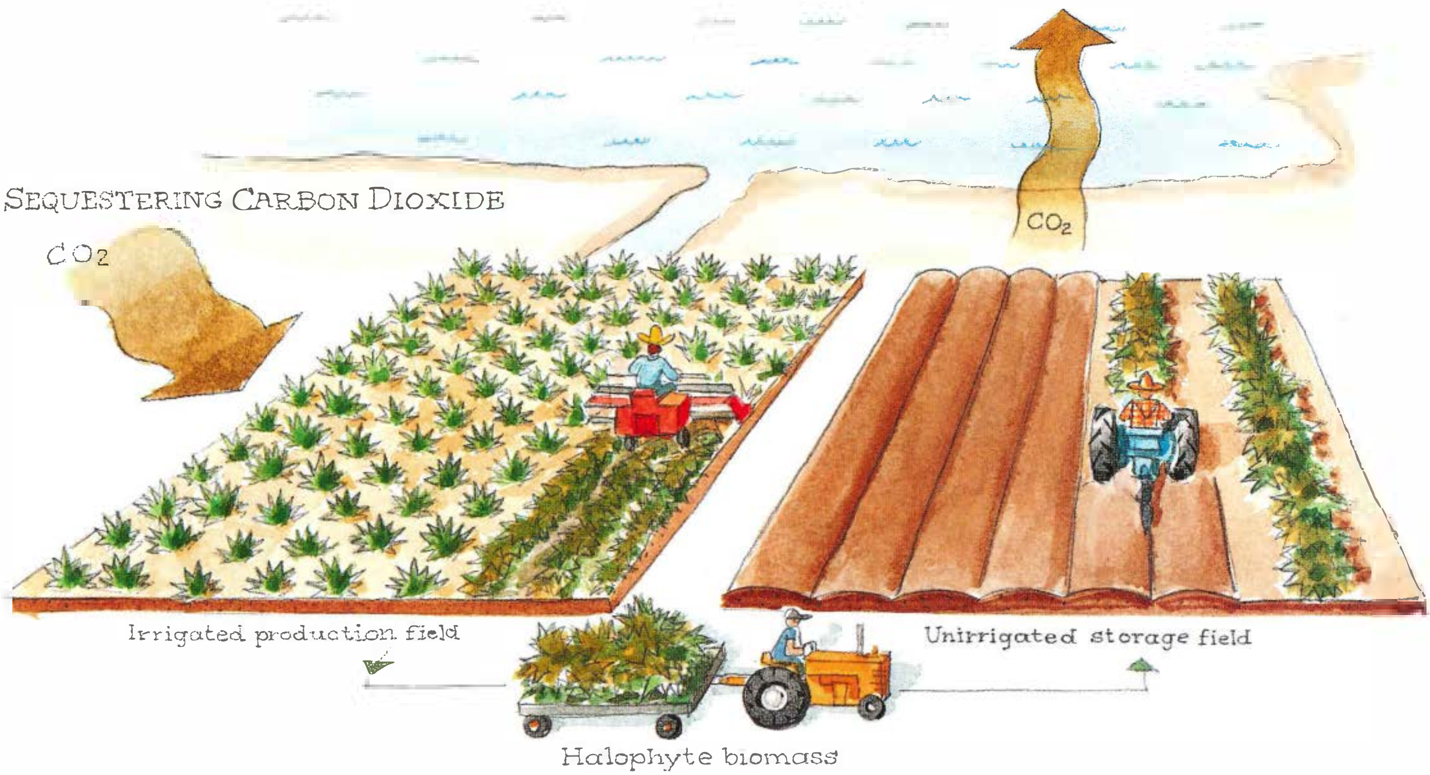
Utility applications

Already, some utilities are beginning to consider halophytes for specific applications in their own facilities or service territories. Arizona Public Service Company, for example, is cofunding a project with EPRI to study the use of halophytes to improve the quality of wastewater at two coal-fired power plants and to dispose of contaminated water.

At the Ocotillo plant in Tempe, Arizona, the aim is to use moderately saline blowdown water (0.4–0.5% salt) for growing halophytes as lawn and shrub landscaping, rather than discharging the water to a sewer system. Such discharge is a potential hazard for crops downstream, and it is hoped that using halophytes can help the plant meet regulatory guidelines for wastewater disposal with zero discharge off-site. Several plastic-lined basins will be constructed in trenches near the plant for a two-year experiment to develop an optimal planting and irrigation scenario, with minimum leaching of salt into the aquifer below. Three plant types will be investigated: *Atriplex nummularia,* a shrub suitable for landscaping; *Paspalum vaginatum,* a halophyte turf grass; and *Sesuvium portulacasstrum,* a flowering ground cover. If all goes well, recommendations will be made for planting halophytes on 25–50 acres of the site to accept an annual discharge of some 76 million gallons of water from the plant.

At the Four Corners plant in Farmington, New Mexico, deep-rooted halophytes will be used to intercept the underground flow of saline seeps from tailings and evaporation ponds. *Atriplex* root systems, for example, can penetrate 20 feet or more

UTILITY BENEFITS **EPRI researchers are examining the potential benefits the utility industry could draw from halophyte production. Among these are the reduction of carbon dioxide levels in the air, the removal of salts and heavy metals from power plant wastewater, and the creation of a new nonfossil biofuel.**



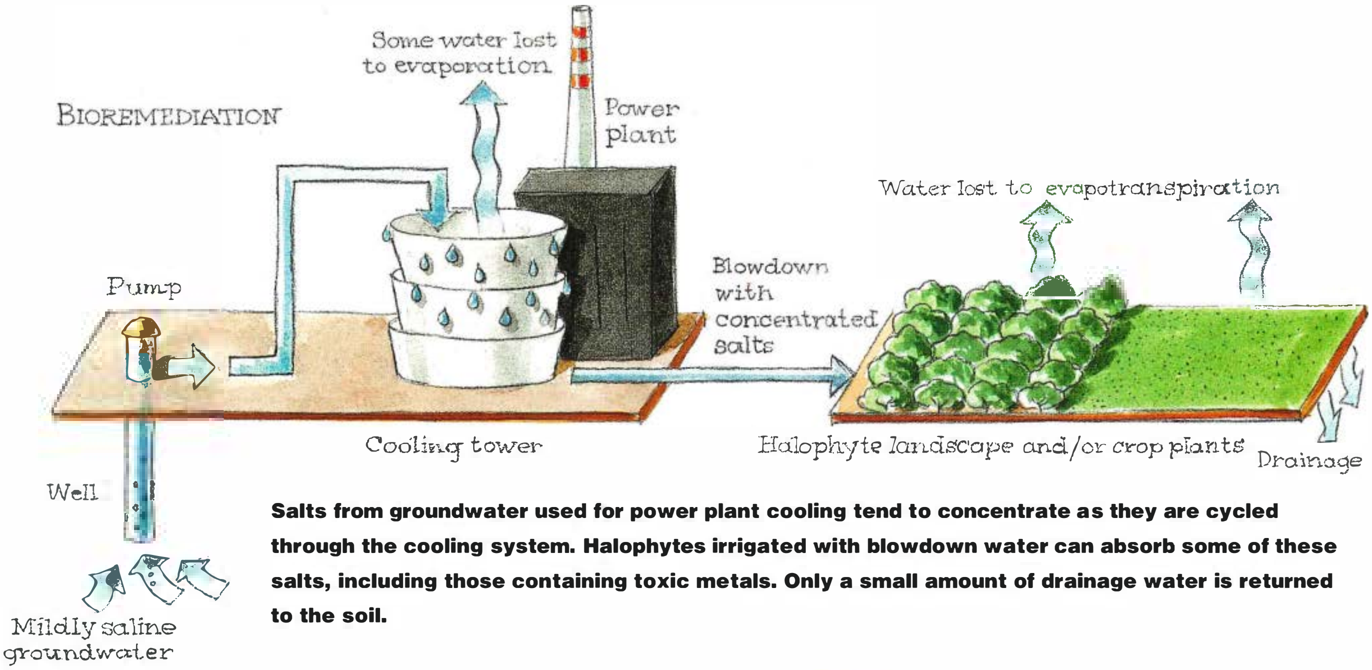
When plants die, most of their carbon quickly returns to the atmosphere as they decompose. But experiments indicate that harvested halophyte biomass, when removed and buried in dry desert soil (as shown here), may be able to retain 30–50% of its carbon for a long time. Simply plowing the crop under where it grows also sequesters some carbon, though less than at an unirrigated site. Researchers are working to determine the actual rate of release of carbon dioxide from the buried halophytes to the atmosphere.

into the ground and have been used to lower the saline water table under some agricultural fields. Research now getting under way at the plant will determine whether halophyte trees and shrubs can be used in a similar way to reduce the percolation of saline discharge water toward the underlying water table. Experiments will focus on the evaluation of local halophyte species for their ability to reduce the volume of standing water in large lysimeter pots with an artificially imposed water table.

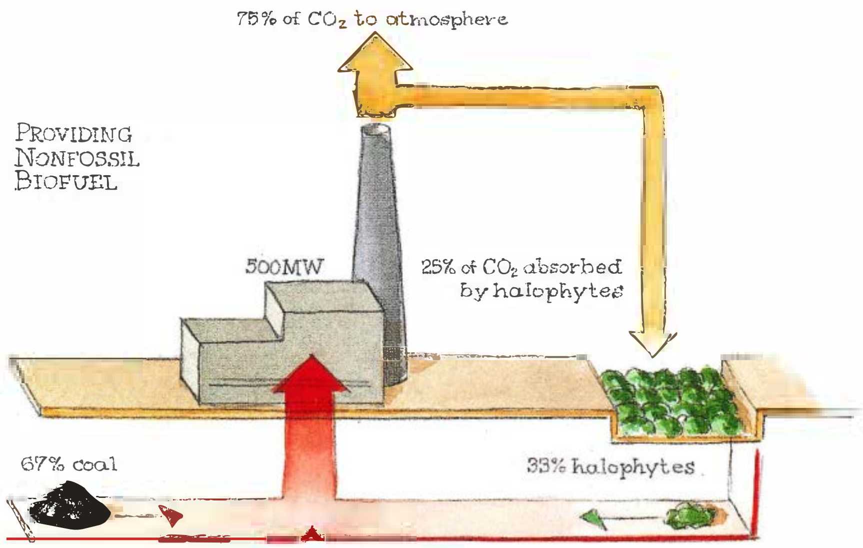
Related laboratory work sponsored by Arizona Public Service and EPRI will be conducted in Tucson, Arizona, with special attention to metal uptake by various halophyte species. Toxic metals—such as cadmium, chromium, selenium, and arsenic—are sometimes present in potentially hazardous concentrations in agricultural drainage water or in power plant discharges in the western states. Halophytes have a unique ability to concentrate these metals, which are not normally absorbed by ordinary plants. These experiments on metal uptake will provide basic data on how halophytes could be used in bioremediation for a variety of contamination problems, both inside and outside the utility industry.

EPRI is hoping to expand this work by testing the ability of halophytes to capture and sequester selenium from evaporation ponds that catch drainage water from irrigated agricultural fields. Although selenium is an essential element for life, in large concentrations it can be toxic, and the buildup of selenium in evaporation ponds is seen as a potential threat to indigenous wildlife. The proposed research would use halophytes to remove selenium and other heavy metals from the drainage water, while reducing the volume of water by 90–95%.

This proposed project is based on previous research conducted by Carolyn Watson of ERL, in cooperation with the Tulare Lake Drainage District, which currently has about 100 acres of halophyte test plantings in the area. In the project, ERL would plant halophytes in cascades along the drainage route. Near the agricultural fields, where the water flows under-



Salts from groundwater used for power plant cooling tend to concentrate as they are cycled through the cooling system. Halophytes irrigated with blowdown water can absorb some of these salts, including those containing toxic metals. Only a small amount of drainage water is returned to the soil.



Some halophyte species can be burned as fuel, since they have a heat content roughly equal to that of lignite. Cofiring of coal and halophyte biomass (in a 2-to-1 ratio) is particularly attractive from a carbon dioxide standpoint because much of the carbon released from the stack is recycled into a new biomass crop.

ground, trees would be planted so that their roots could absorb the drainage water where salts are least concentrated. Farther along, as the water moves through surface drainage ditches and becomes more saline, fields of plants that are more salt-resistant would be used. The feasibility of using some of the woody halophytes as biofuel would also be considered.

Many unknowns

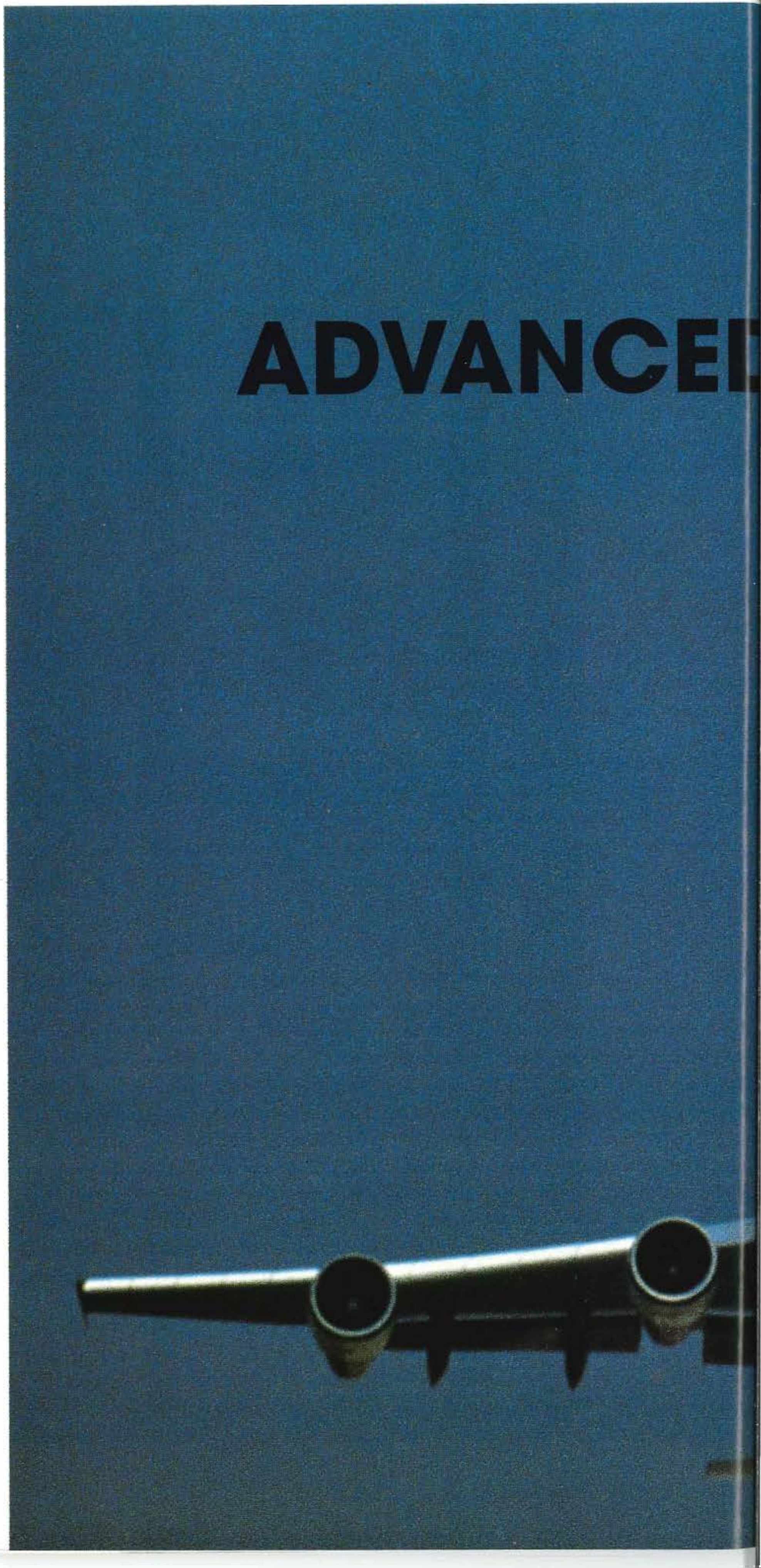
"Halophyte cultivation using seawater or contaminated brackish water offers great promise for helping us address a number of environmental problems and opens up new agricultural opportunities," concludes Sy Alpert. "Some specific applications will obviously benefit some western utilities directly, but we're not ready to go large-scale yet. Many unknowns remain."

Louis Pitelka underscores this point: "More research is needed to determine the long-term effects of planting halophytes. There are a host of issues that need to be resolved whenever wild species are brought under cultivation. In this case, for example, will prolonged irrigation with seawater raise salt levels in the ground too high? What proportion of buried carbon remains sequestered? Also, how large a contribution might halophytes make to reducing carbon dioxide in the atmosphere for long periods?"

The value of continuing such research can be explained in terms of a "no regrets" policy toward carbon sequestration, according to Edward Glenn. "There's a great deal of uncertainty about greenhouse gases and climate change, but we can do things that would make sense anyway. Then, if global warming doesn't occur, we can still look back on what we've done without regret. I believe that the halophyte option makes sense in this context. Besides taking up carbon dioxide, halophytes can help provide a new food source and contribute to land restoration, while saving forests and not tapping scarce freshwater resources—not a bad combination." ■

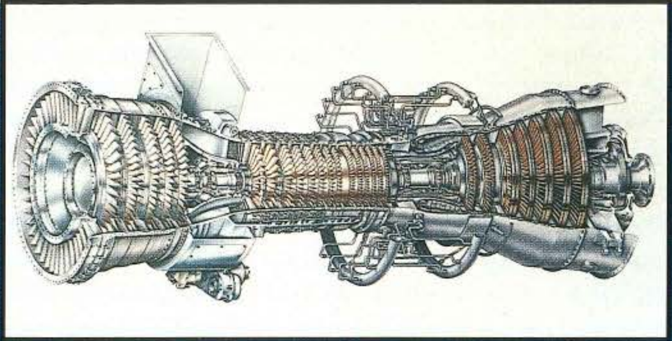
Background information for this article was provided by Sy Alpert, Office of Exploratory & Applied Research, and Louis Pitelka, Environment Division.

THE STORY IN BRIEF With the stage set for a major increase in gas-fired generation, the world market for combustion turbines—already one of the most competitive among current plant options—is becoming even hotter. The efficiency and performance of advanced heavy-frame turbines are increasing as equipment suppliers continue to raise firing temperatures and unit capacities. And performance advances in the latest high-thrust fanjets that power large jetliners are now fueling a growing interest in compact aeroderivative turbines, developed directly from aircraft engines. Promising efficiencies that equal or surpass those of conventional combined-cycle plants, advanced aeroderivatives will have the added advantage of smaller, more attractive capacity increments. EPRI is leading an international consortium to accelerate the commercialization of advanced combustion turbines that could become the core of a variety of innovative power plant cycles.



ITTC Productions/Image Bank

General Electric's LM6000 aeroderivative turbine



COMBUSTION TURBINES

SET FOR

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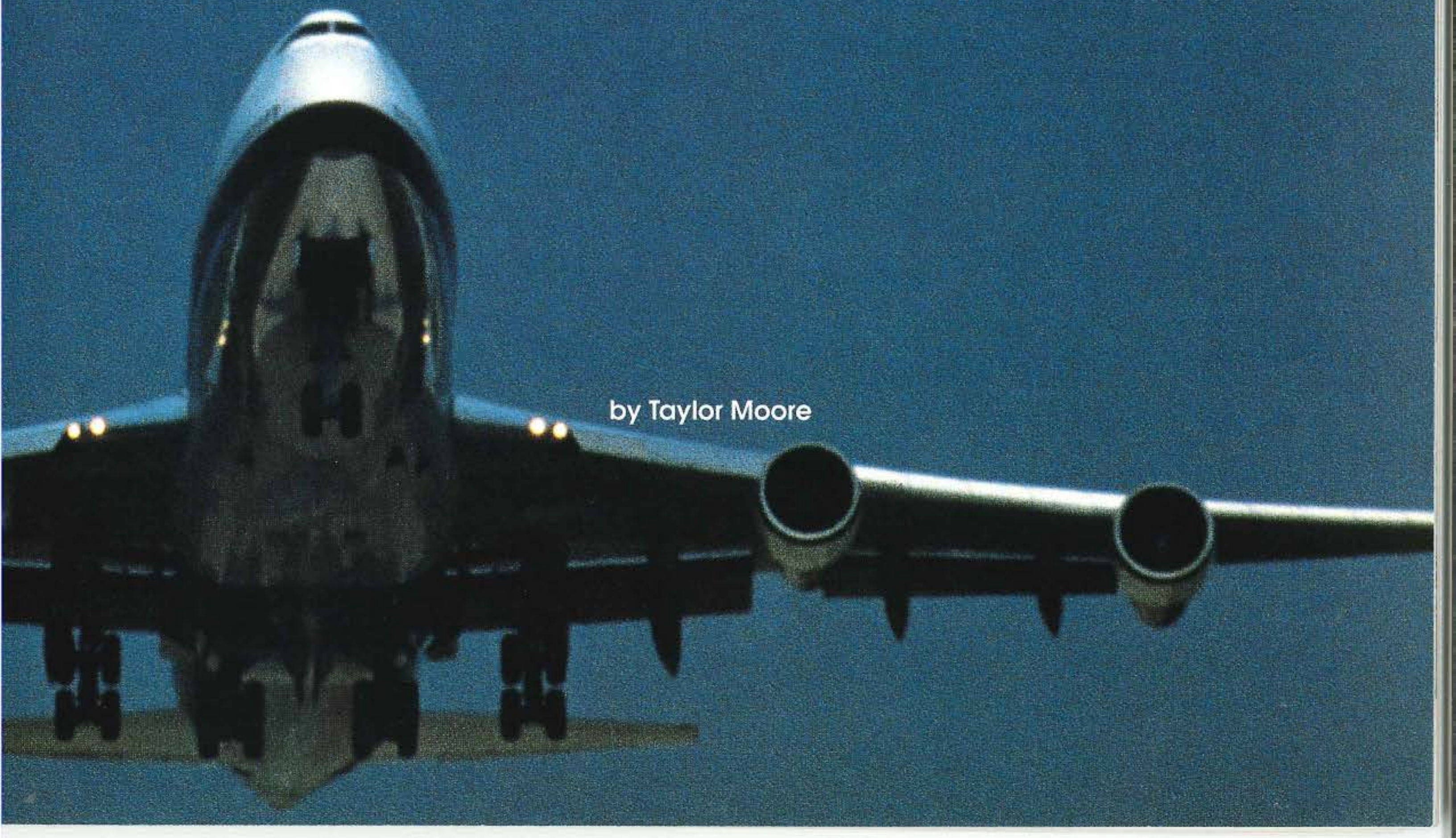
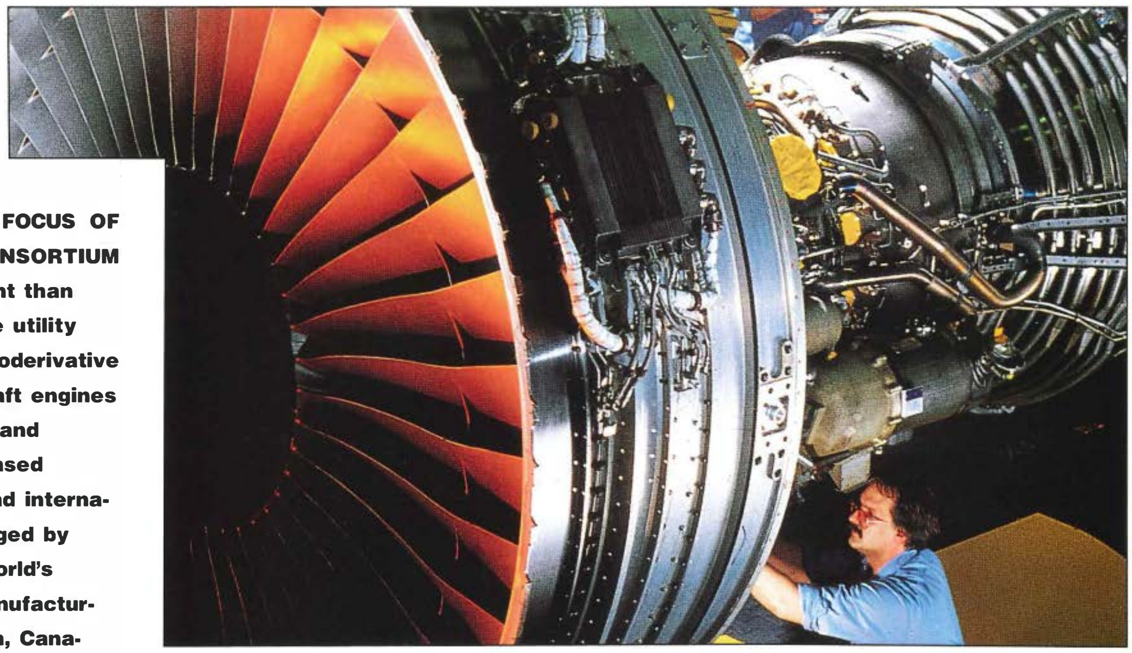


by Taylor Moore

The growing popularity of natural gas as the fuel of choice for most new electric generating capacity is turning up the spotlight on combustion turbines, a rising star among plant options in an expanding worldwide power generation market. Long regarded as a poor relation in the family of generating-plant options, to be used mainly for peaking power, combustion turbines are moving to center stage both internationally and even in the slower-growing U.S. generation market. They are now cast in a leading role in evolving strategies for capacity expansion and for repowering existing steam generating capacity.

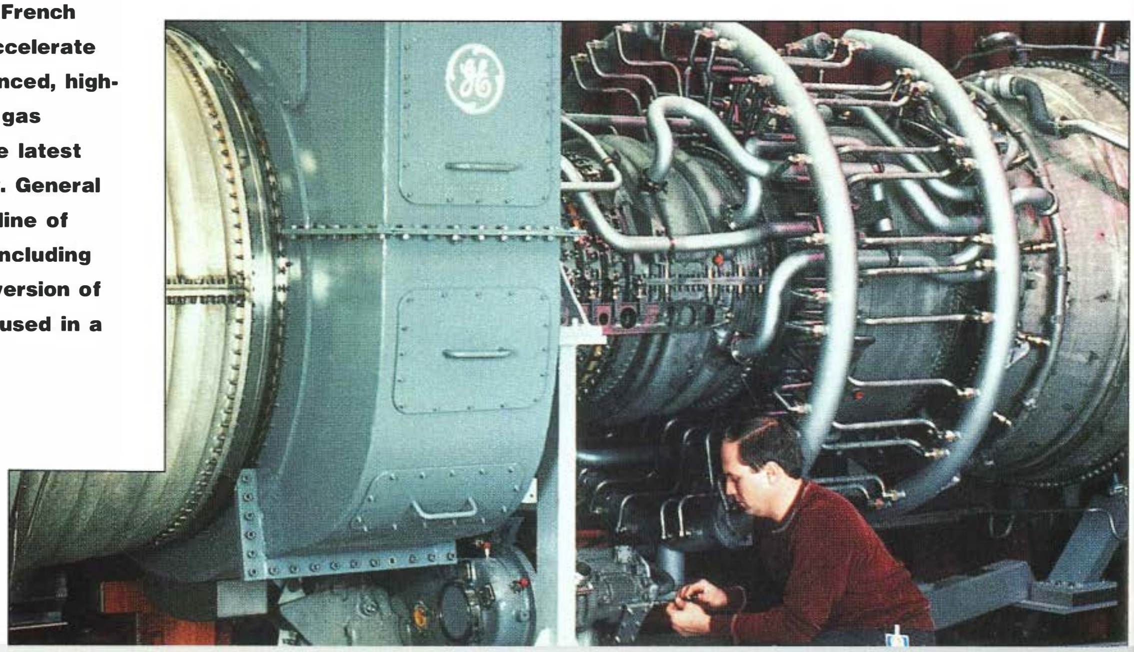
In the United States in particular, many utilities, spurred by increasingly tighter emissions limits set out in recent amendments to the Clean Air Act, are making plans to use natural gas—the cleanest fossil fuel—to the maximum extent practical, as have many independent producers. With the price of gas still near its lowest levels of the past decade, natural-gas-fired generation continues to offer some of the least expensive electricity currently available from new plants. Even companies that have chosen to build flue gas scrubbers or to switch to lower-sulfur coal for existing steam plants are eyeing gas-fired turbines for future growth because of their comparatively low capital cost, inherently low emissions, short lead time for installation, and flexibility for repowering.

No longer are combustion turbines the stepchild of the power generation business, mainly limited to peaking service. Thanks to their close technological kinship to jet aircraft engines, combustion turbines have benefited from the successive technology advances developed initially for high-performance military jets over the past 15 years. These include hotter firing temperatures, improved blade-cooling designs and blade coatings, higher compression ratios for greater power, and electronic controls. The incorporation of such advances into the engines powering commercial jet aircraft contributed directly to current state-of-the-art fan-jets, which allow a wide-body airliner to make nonstop flights of more than 8500 miles.



Pratt & Whitney's PW4000 fan-jet engine

AERODERIVATIVES ARE FOCUS OF ADVANCED TURBINE CONSORTIUM
Smaller and more efficient than conventional heavy-frame utility combustion turbines, aeroderivative turbines are fan-jet aircraft engines that have been modified and repackaged for ground-based power generation. A broad international consortium—managed by EPRI and including the world's major aircraft engine manufacturers and American, British, Canadian, Danish, Dutch, and French utilities—is working to accelerate the development of advanced, high-efficiency aeroderivative gas turbines incorporating the latest fan-jet engine technology. General Electric already offers a line of aeroderivative turbines, including the LM6000, a modified version of the GE CF6-80C2 engine used in a wide range of jetliners.



GE LM6000 aeroderivative turbine

Many of the fundamental improvements in jet engine technology have found their way into the newer models of heavy-frame industrial and utility combustion turbines produced by the traditional power equipment manufacturers. In 60-Hz versions, these heavy-frame machines have now reached over 150 MW in rated capacity. At the same time, jet engine makers—facing a decline in aircraft orders due to a glut of jetliner capacity—are showing renewed interest in the power generation market. They're packaging their current models as compact, aeroderivative turbines that offer 35-45 MW of capacity and efficiencies of up to 40% in simple-cycle operation—although usually at a higher capital cost per kilowatt than for heavy-frame machines, which are less expensive to engineer and build. The smaller, aeroderivative turbines have found favor with both small and large utilities, although many larger utilities, or those experienced at operating larger generating units, tend to prefer heavy-frame machines.

Today, both aeroderivative and heavy-frame turbines are available across a wide range of modular capacity increments and can generate economically competitive electricity at partial as well as full load. Engineered for high reliability, like their aircraft-powering relatives, the new combustion turbines can be operated continuously as baseload generators or cycled as peaking units. And when the hot exhaust from one or two of these turbines is channeled to a heat recovery steam generator to make even more power with a steam turbine in a combined-cycle configuration, the units can be the most-efficient performers in a utility's entire cast of generators; the thermal efficiencies of the most recent examples range from 53% to 55%.

Even without a steam bottoming cycle, the combustion turbine's main power cycle of gas compression and expansion has untapped potential for efficiency improvement through the application of such advanced concepts as intercooling and innovative exhaust heat recovery schemes. In contrast, the conventional Rankine cycle, which is the basis of all fossil-fired steam generation, appears to have a practical efficiency ceiling of 40–45%. Major advances in materials and design would be needed to exceed current steam temperatures.

Growing competition and new strategic alliances among the manufacturers of the two principal types of combustion turbine provide ample evidence that, in more ways than one, these turbines are hot and getting hotter. The new machines are bigger and literally run hotter than ever before—some have a firing temperature of over 2300°F (1260°C). And manufacturers acknowledge the potential for further performance improvement in both turbine types. For heavy-frame machines, they anticipate firing temperatures of 2500–2600°F (1371–1427°C) and combined-cycle efficiencies of 58–61% by the end of the decade. With an accelerated development effort, it may be possible to obtain similar performance from aeroderivative-turbine-based plants, but in more-cost-competitive versions and in smaller capacity increments than are typical of combined-cycle plants using heavy-frame turbines.

Building on a collaborative initiative

Low natural gas prices, the inherently low emissions possible with gas-fired generation (for example, half the carbon dioxide, per unit of electricity output, that is produced by burning coal), and the high cost of environmental compliance for other fossil fuel options are converging to make gas and gas-fired capacity attractive options for utilities. EPRI is hoping to leverage this convergence of opportunities to its members' benefit through new collaborations and development efforts aimed at leapfrogging to the next generation of advanced combustion turbines in just a few years.

"It's not hard to predict the future of combustion turbine power generation—to know what the electric utility technology will be like in 10 years, you just look at what is flying around in jet airplanes today," says George Preston, EPRI vice president for generation and storage. "Recent developments have put EPRI, the equipment suppliers, and their clients in a position to shorten the time for transferring advanced jet engine technology into advanced turbine technology to perhaps five years or less."

EPRI has assumed overall management responsibility for the Collaborative Advanced Gas Turbine Project (known as CAGT), an international consortium originally organized by Pacific Gas and Electric Company. CAGT is aimed at catalyzing the early introduction of advanced gas turbine plants that use machines incorporating the latest fan-jet engine technology. In addition to EPRI and PG&E, sponsors include EPRI member utilities San Diego Gas & Electric Company and Southern California Edison Company. Other CAGT sponsors include the Gas Research Institute, the Sacramento Municipal Utility District, and Southern California Gas Company. The California Energy Commission and the U.S. Department of Energy (DOE) support CAGT through funding grants.

The effort has also attracted strong international support, testifying to the broad appeal that smaller-capacity, low-capital-cost, high-efficiency modular gas turbine units have for companies in the generating business around the world. Non-U.S.-based sponsors of CAGT include British Gas, the Canadian Electrical Association, Electricité de France, Elkraft Power Company of Denmark, KEMA of the Netherlands, National Power of Britain, and TransAlta Utilities of Alberta, Canada.

All three of the western world's fan-jet engine manufacturers are also involved with CAGT: Britain's Rolls-Royce and, from this country, General Electric Company and the Pratt & Whitney Division of United Technologies Corporation (UTC). Pratt & Whitney is represented by UTC's Turbo Power & Marine Systems Division, which develops and markets aeroderivative turbines based on Pratt & Whitney engines.

In the CAGT program, the first phase of which is nearing completion, each of the engine makers is teamed with a power plant engineering firm—either Fluor Daniel or Bechtel—to develop initial design concepts for high-efficiency aeroderivative-turbine-based plants that would incorporate the latest-model superfan engines. The three-phase CAGT program is expected to extend into the next decade and result in actual field demonstrations of advanced designs, although Phase 1 is the only part currently funded.

The CAGT members are coordinating their evolving collaborative program with DOE's Advanced Turbine Systems (ATS) Program, an eight-year, $700 million effort authorized by Congress in the Energy Policy Act of 1992. This program is aimed specifically at the development of advanced, high-efficiency utility and industrial turbines for post-2000 commercial availability. For utility combustion turbines, the ATS effort is aiming for a machine that is 60% efficient in combined-cycle operation, that will have nitrogen oxides (NO_x) emissions 10% lower than today's lowest levels, and that will generate electricity 10% more cheaply than today's best systems. In addition to pursuing common objectives, the CAGT sponsors hope to stimulate the much larger DOE program, and the equipment vendors participating in it, to demonstrate advanced turbine concepts and systems for the power generation industry somewhat earlier and with somewhat lower efficiencies than were initially targeted.

"We want to encourage involvement by the entire community of stakeholders in the growing market for natural gas in electric power generation," says Ron Wolk, director of the Advanced Fossil Power Systems Department in EPRI's Generation & Storage Division. "The vision is that, collectively, we can form the right combination of market pull and technology push to give us a substantial leap forward to lower-cost gas-fired power plants and advanced power cycles that are both highly efficient and highly reliable. Such a leap forward would make the new turbines even more flexible as both dispersed and central station power plants."

As originally conceived, CAGT was aimed at exploiting the significant opportunity represented by the high-efficiency fan-jet engines entering service in commercial aircraft. PG&E determined that it could use advanced aeroderivative turbines to repower much of its aging 7000 MW of fossil fuel steam-generating capacity. The California utility anticipates replacing much of this capacity beginning around 2000, but, like many other utilities, it faces low load growth and limited access to new power plant sites near load centers.

According to Arthur Cohn, who manages EPRI projects on advanced-cycle power plants, the majority of the earliest utility gas turbine generating units, installed in the 1960s, were aeroderivatives based on Pratt & Whitney engines. These were the engines used in such aircraft as the F-105 fighter and early jetliners, including the Boeing 707. Many utilities could afford to install dozens of these engines as ground-based units for peaking duty; the machines would be needed only a few hundred hours a year.

"Aircraft engines are designed and engineered to a different standard of reliability and dependability than conventional combustion turbines, which translates into very high development and testing costs. Fortunately, these costs for aeroderivatives have already been covered, which is why you can even consider using them in power plants," explains Cohn. "So the great thing about aeroderivatives is that you get the high-cost features—such as the high-temperature components—for free, in a sense. But if you want the manufacturers to change anything in the design or the specifications, it can get very expensive, because in their way of doing things, nothing comes cheap."

Early in the program definition for CAGT, the results of EPRI's more than 15 years of research in advanced power cycles and gas-turbine-based power systems provided a planning focus. The EPRI studies identified and analyzed a variety of innovative approaches with potentially very attractive efficiencies—some approaching 60%—and very low emissions. Without requiring a bottoming cycle, some advanced cycles promise capacity ratings and efficiencies approaching those of combined-cycle plants based on lower-cost, heavy-frame combustion turbines.

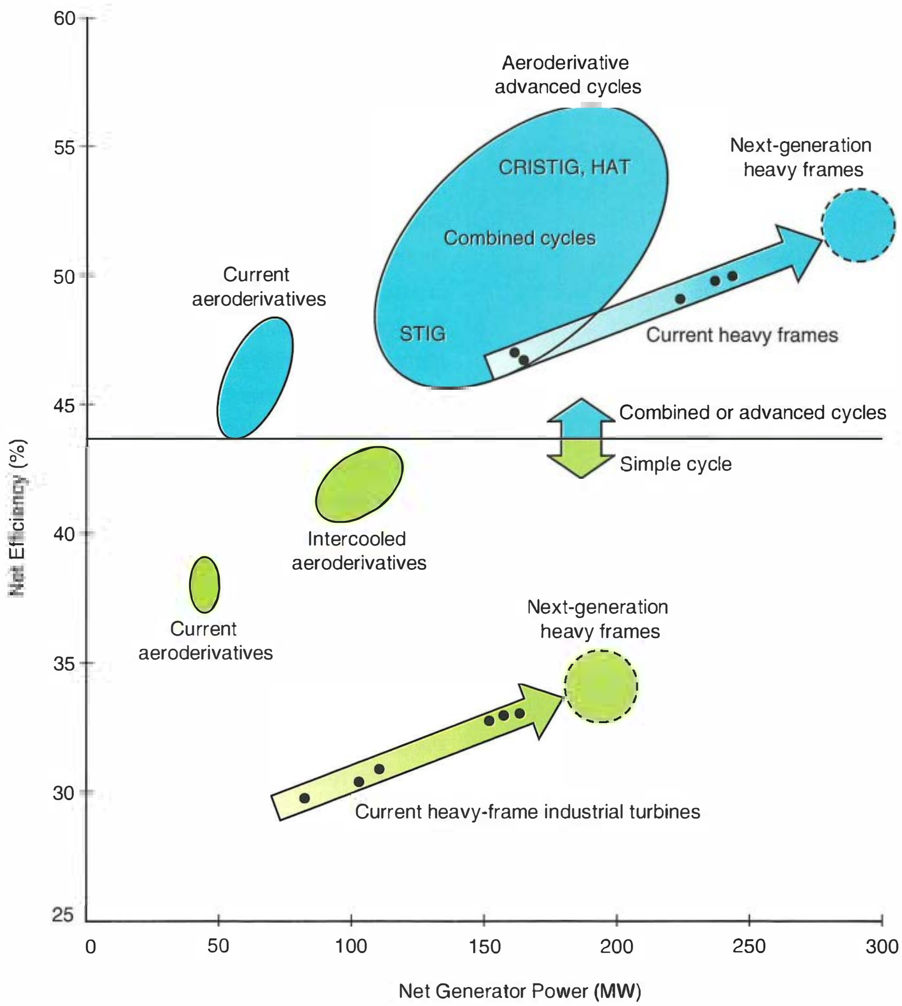
For heavy-frame machines, the addition of a bottoming steam cycle to make a combined-cycle plant almost doubles the installed capital cost per unit of generating capacity, explains Cohn. Innovative advanced cycles making use of a series of already available advanced gas turbines that would not require full-scale development and demonstration could be a less expensive option. Such units would likely, but not necessarily, be based on aeroderivative turbines.

ADVANCED CYCLES COULD PROPEL AERODERIVATIVES TO HIGHER PLANE OF EFFICIENCY In this graph, the potential progression in performance of high-thrust aeroderivative gas turbines is compared with the performance of heavy-frame industrial machines in both simple-cycle and combined-cycle applications. Innovations such as intercooling and advanced cycles could make aeroderivatives available in attractively sized modular units with efficiencies that would rival those of current or even next-generation heavy-frame machines in combined-cycle plants involving larger capacity increments. Advanced cycles of interest for aeroderivatives include the STIG (steam-injected gas turbine), CRISTIG (chemically recuperated, intercooled steam-injected gas turbine), and HAT (humid-air turbine) cycles.

High performance and reliability would make these generating units appropriate for baseload and intermediate duty, as well as for complete or partial station repowering and for green-field plants. With a relatively small overall footprint, these modular, lightweight units could also be used as portable power plants for temporary siting at dispersed load centers or transmission substations.

CAGT's three-phase development program

The CAGT consortium has awarded contracts for conceptual design studies totaling $2.5 million to the manufacturer-engineering teams of General Electric and Stewart & Stevenson Services with Bechtel; Rolls-Royce with a second Bechtel team; and UTC's Turbo Power & Marine Systems with Fluor Daniel. Each of the aircraft engine makers offers turbofan engines that provide 50,000 to 80,000 or 90,000 pounds of thrust. These machines are used in virtually all wide-body, long-



haul jetliners in service today or scheduled to enter service soon, such as the Boeing 777. General Electric recently began testing an even more advanced fan-jet—the GE-90—that is expected to deliver up to 100,000 pounds of thrust.

The vendor teams' engineering and economic evaluations of various power plant designs and configurations incorporating turbines based on these advanced aircraft engines are expected to be completed by the second quarter of 1994. The teams will conduct a comprehensive screening of options to identify preferred designs that can be readily commercialized. Also as part of Phase 1, the teams are developing proposals detailing the technical, business, and financial requirements for demonstrating a preferred-concept machine. Early commercial plant designs from 50 MW to 200 MW in capacity could be on the market by 1998. During the first phase, the CAGT members are trying to catalyze early market interest and establish initial market pull, represented by potential customer orders.

The next phase envisions early commercialization of the leading designs for generating systems based on advanced aeroderivative turbines, with one or more units to be built by each manufacturer for risk-sharing, pioneering owner-operators. CAGT members would have priority on orders for the new machines and would perhaps share in royalties. In this second phase, which is expected to run from 1994 through about 1998, substantial user feedback on the new machines' initial operating experience will help confirm and validate the development strategy.

The process is also expected to identify what will be needed during the project's third phase for the development of the preferred turbine designs and their application to advanced, innovative power cycles. Specific points of current technical focus include various applications of compressor intercooling as a means of increasing turbine efficiency and power output. Intercooling looks attractive to the CAGT sponsors both as a short-term enhancement to existing high-thrust aeroderivative designs and as part of longer-term advances in combined and more-complex power cycle applications (such as the use of intercooling in combination with steam injection and with reheat combined cycles).

There is also interest in high-efficiency combustion turbine designs that would combine components of aeroderivative turbines and heavy-frame machines. Intercooling, for example, has implications for redesigning the first compressor spool of an aeroderivative machine or replacing it with a lower-cost compressor designed to industrial turbine standards.

Another advanced-cycle concept under investigation involves chemical recuperation of waste heat combined with intercooling and steam injection. Still another is the humid-air turbine (HAT) cycle—an intercooled, regenerative cycle with a saturator that adds moisture to the compressor discharge air.

As part of a recent study jointly funded by EPRI, Fluor Daniel, Texaco, and UTC, Turbo Power & Marine Systems designed a HAT cycle that uses an aeroderivative turbine based on the current top-of-the-line Pratt & Whitney engine (the PW4000). A saturator is used to add about 20–40% water vapor to the compressor discharge air, increasing the turbine mass flow and therefore the power output while also helping to limit NO_x emissions. Such a HAT cycle could be expected to boost the turbine's power output to 157 MW, compared with 42 MW in a simple cycle, while increasing plant efficiency to 55.5%, compared with 52.6% for a comparable heavy-frame-based combined-cycle unit. Further modifications have been identified that could raise the power output to 199 MW. (For more information on the HAT cycle, see the research update article on page 43 of this issue.)

CAGT is taking a fresh look at all the advanced-power-cycle possibilities. An interim report on the most promising ones in view of CAGT's accelerated development plan should be available by April of next year. EPRI managers stress that the overall aim is actual power plant designs that provide the best combination of capital cost, development cost and schedule, efficiency, and low emissions. (Of particular concern are NO_x emissions, which increase as the flame temperature in a gas turbine increases.) Minimizing the consumption of water, whether for boosting power and efficiency or for limiting NO_x emissions, is also a criterion for some of the advanced cycles. Some trade-offs may be necessary between the cost and performance of advanced designs and the risks of certain development paths.

Catching up with industrial turbines?

As EPRI's Arthur Cohn explains, CAGT's first-phase comparative analyses of the efficiency and capacity potential of advanced aeroderivative-turbine-based plants suggest that the near-term incorporation of such innovations as intercooling and the longer-term incorporation of advanced cycles could propel high-thrust aeroderivatives to new heights of power and performance.

"Intercooling could boost simple-cycle efficiency over the best current aeroderivative turbines by about 5 percentage points—for an overall heat rate that is 15–20% better than the best current heavy-frame machines—while more than doubling the power output and substantially reducing the capital cost per kilowatt of generating capacity," says Cohn. Meanwhile, advanced cycles incorporating high-thrust aeroderivative turbines could achieve efficiencies as high as, or possibly even higher than, those anticipated with the next generation of industrial turbines in combined-cycle operation—while offering smaller capacity increments.

But if developers are hoping that aeroderivative-based gas turbine plants can someday claim the high ground in efficiency and performance over the heavier-frame models, they will have to aim at a moving target. Despite the recent interest in advanced aeroderivatives, the worldwide expansion in the market for gas turbine power plants today is focused mainly on heavy-frame machines. There, competition between the four principal manufacturers—ABB Asea Brown Boveri, General Electric, Siemens, and Westinghouse—is heating up. In addition, the three of these four that do not also make aircraft engines are pursuing strategic alliances with other firms that do, forming teams that may spark even fiercer competition on the aeroderivative front.

General Electric dominates much of the world market for heavy-frame combustion turbines. It also commands a significant share of the aeroderivative market, in part through its link with power plant packagers, such as Stewart & Stevenson Services. GE was the first to introduce a 2300°F combustion turbine with its Frame 7F series, which was initiated in the late 1980s with a prototype at Virginia Power's Chesterfield station. In a recent article in *Business Week*, the company acknowledged the commercial success of the F-technology turbines as a major contributor to improved earnings in recent years. GE has licensed the technology for production in Europe by a consortium known as European Gas Turbines and, more recently, for production in Japan by Hitachi. The company has now introduced the 2350°F (1288°C) 7FA turbine, the first four of which are expected to enter U.S. utility service late this year.

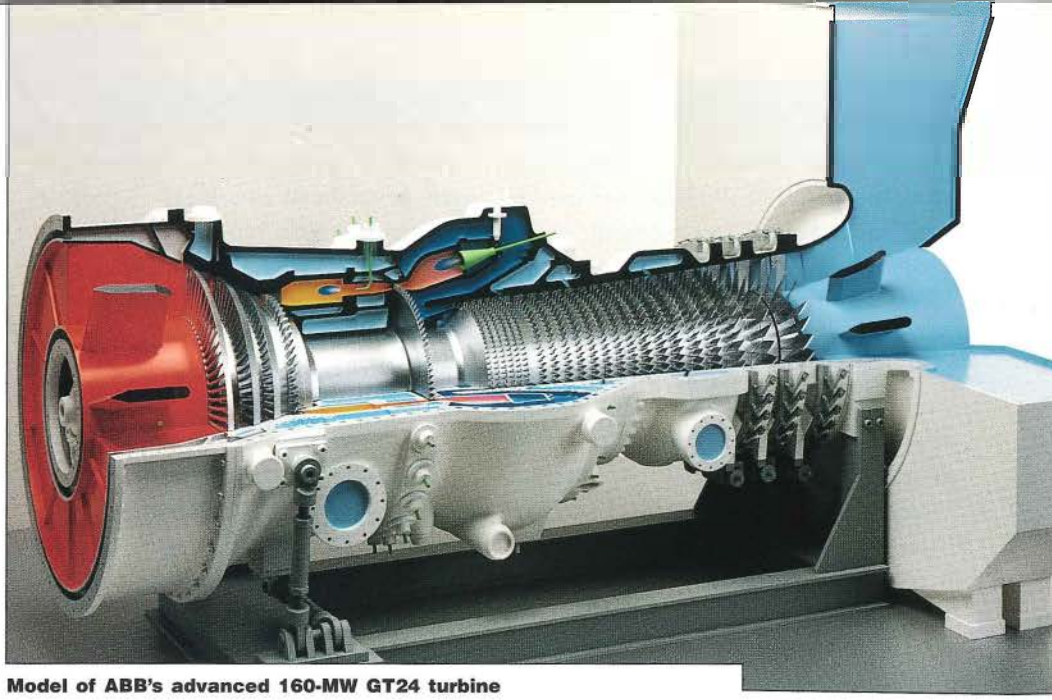
Tokyo Electric Power recently named the GE-Hitachi combine as the turbine supplier for an eight-unit, 2800-MW combined-cycle plant—the world's largest—planned for completion by the mid-1990s in Yokohama, Japan. The plant will use 9FA turbines, which are new, more powerful (226-MW), 50-Hz versions of GE's 7FA machine.

The other three principal worldwide suppliers of utility turbines have also either introduced or announced plans to introduce 2300°F machines. Westinghouse, which resumed manufacturing large combustion turbines in this country two years ago after ceding much of the work to licensee Mitsubishi Heavy Industries, formed a joint venture with Mitsubishi to supply 2300°F machines for what will be Europe's largest combined-cycle station—the 1875-MW Teesside plant in England, built by Enron Power.

GE and Westinghouse together can claim about two-thirds of the U.S. installed gas turbine market, but their two main European rivals, Siemens and ABB—which have long edged them out of the steam turbine business on the continent—are now competing with them head-on for the gas turbine business both here and abroad. Siemens, the engineering and electrical giant based in Germany, has a presence in the U.S. market with a line of combustion turbines based on a design developed several years ago in a now-ended joint effort with UTC's Turbo Power & Marine Systems. Siemens has gas turbine manufacturing facilities in Wisconsin and has completed testing in Germany of a 152-MW (60-Hz), 2350°F machine. It has announced that Metropolitan Edison Company will install the prototype next year at its Portland, Pennsylvania, station.

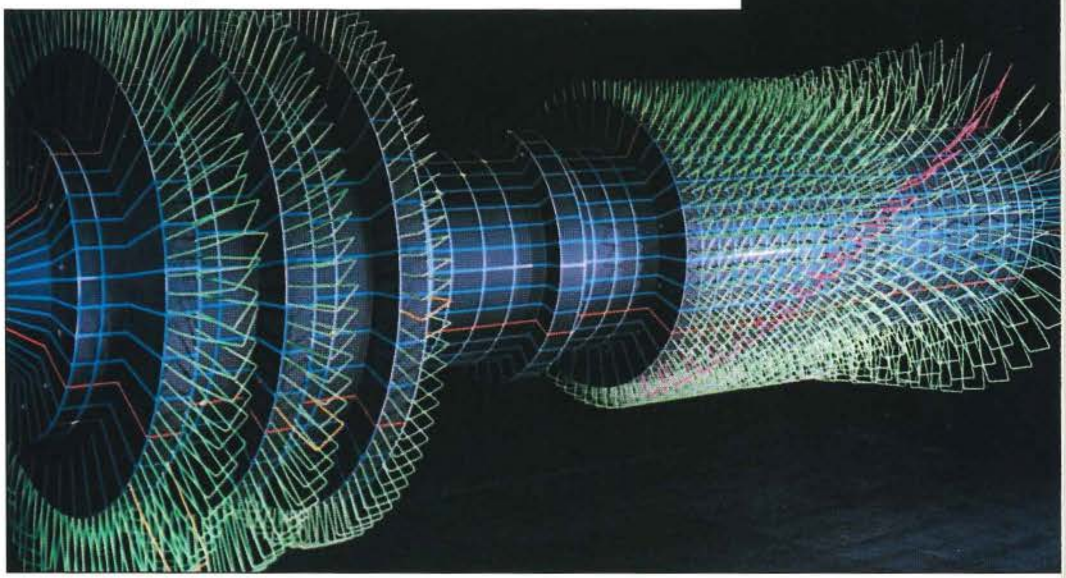
The Zurich-based multinational conglomerate ABB includes the corporate suc-

COMPETITION IN HEAVY-FRAME TURBINES CONTINUES TO HEAT UP The new interest in advanced aeroderivative turbines notwithstanding, most of the recent growth in the worldwide market for combustion turbines has involved the larger-capacity heavy-frame machines produced by the major power generation equipment suppliers. General Electric was the first to offer heavy frames with a 2300°F (1260°C) firing temperature—the 7F series, introduced in the late 1980s (and since surpassed by the 7FA machine). Westinghouse, Siemens, and ABB Asea Brown Boveri followed suit, introducing competitive high-efficiency gas turbines in similar unit capacities. Next-generation heavy frames in 60-Hz models could approach 200 MW of generating capacity in simple-cycle operation.

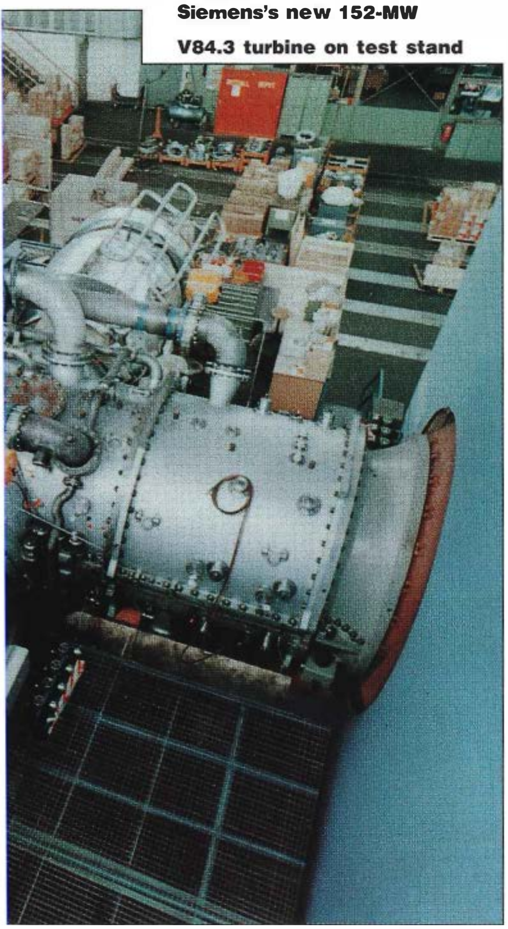


Model of ABB's advanced 160-MW GT24 turbine

GE 7FA rotor design



Siemens's new 152-MW V84.3 turbine on test stand



General Electric's 159-MW 7FA turbine

cessor to the Swiss firm that introduced the first gas turbine in a power generation application in 1939. ABB has installed 80-MW-class and 100-MW-class turbines in the United States, most recently six at Cincinnati Gas & Electric Company's Woodsdale plant. It is expanding domestic manufacturing facilities for gas turbines in Virginia. In September, ABB announced the commercial availability of advanced, 160-MW-class (60-Hz) and 240-MW-class (50-Hz) high-efficiency gas turbines, with an order for the first 60-Hz machine in hand from Jersey Central Power & Light Company for an expected 1996 in-service date. ABB says that the turbine will achieve a combined-cycle efficiency of 58%.

The heavy-frame gas turbine manufacturers are moving to cover all the bases of the fast-evolving international market. Siemens and ABB are pursuing alliances with Russian turbine and aircraft engine manufacturing enterprises, hoping both to gain entry into the repowering and new-plant markets of the former Soviet Union and to tap the highly regarded technical expertise of Russian engine designers.

Recently, Westinghouse announced an agreement with Rolls-Royce that reportedly could result in the use of the British aircraft engine manufacturer's aeroderivative turbine technology in Westinghouse's next generation of large gas turbines. Rolls-Royce, in turn, which is developing a high-efficiency aeroderivative turbine based on its Trent series of aircraft engines, will gain access to Westinghouse heavy-frame technology and machines for its product line.

Heavy-frame turbine manufacturers are already planning next-generation machines that observers expect will incorporate the technology for 2500–2600°F firing temperatures—believed to be the temperature range of the latest advanced aircraft engine designs. If the heavy-frame models can do this, they may be able to offer combined-cycle power plant unit capacities approaching 300 MW with efficiencies of 58–61%.

A comprehensive R&D response

EPRI's participation in the CAGT effort to accelerate the incorporation of advanced aeroderivative technology into gas turbine power plants is only the latest development in a broad ongoing Institute program in combustion turbines—a program that provides technical support and information to a diverse community of users of the existing turbine fleet. Support capabilities include the Combustion Turbine Center in Charlotte, North Carolina, whose technical staff can provide telephone consultation and on-site assistance.

"The differences between the current aeroderivative and heavy-frame fleets translate mainly into how they are maintained," says George Touchton, EPRI program manager for combustion turbines. "From the point of view of aerodynamics, mass flows, temperatures, and the resulting stresses and strains, you've got the same issues all around."

EPRI's ongoing durability surveillance monitoring program supports utilities' growing use of combustion turbines. The program focuses on the early users of the latest high-capacity heavy-frame turbines. The effort began in 1989 when EPRI outfitted an early GE 7F turbine—installed initially for peaking duty at Potomac Electric Power Company's (PEPCO's) Station H at Dickerson, Maryland—with numerous sensors and other monitoring equipment. Over 200 data points are monitored in real time, with remote data links to EPRI, GE, and other participants. Similar systems have been installed on four GE 7FA (2350°F) machines scheduled for startup as baseload combined-cycle units late this year at Florida Power & Light Company's Martin plant. The program also intends to monitor other manufacturers' advanced machines as they are installed at utility sites.

Clark Dohner, the EPRI project manager, says that durability surveillance of the advanced heavy-frame machines can identify significant problems and find solutions early in a new turbine model's debut period, confirm operating-life predictions for key components, and provide feedback to the manufacturers for improvements in design or operation. Maintenance costs and performance are being documented as well. Each machine is to be monitored for about three years.

Monitoring gear installed on the GE turbines to date includes EPRI-developed optical pyrometers that measure the actual operating temperatures of individual turbine blades and buckets through small holes in the turbine casing. Dohner says that a significant success was realized only a short time after initial operation. The collaborative efforts of PEPCO, GE, and EPRI resulted in a change to the first-stage blade that will benefit future buyers of F-technology turbines.

Much of the information collected during the monitoring program, which will run at least through 1995, will be added to EPRI's databases on combustion turbine operations and maintenance. Along with technical support, these databases and related software for analyzing turbine performance and reliability are available through EPRI's Combustion Turbine Center. The center's services include rapid-response technical assistance and consultation. Another resource is EPRI's Data Applications Center in New York, which provides access to five reliability databases that can help utilities save money on plant design, modification, and purchase decisions.

The R&D payoff

"What we have today is a rare convergence of near-term economic, political, and regulatory forces and technological development with longer-term environmental choices and capacity-planning decisions," concludes EPRI Vice President George Preston. "This business climate drives the power generation market both here and abroad toward higher-efficiency conversion technologies that will permit greater and more economical use of natural gas as a fuel for power generation. Advanced aeroderivative gas turbine power plants represent a high-payoff opportunity for collaborative research, development, and demonstration aimed at achieving this goal." ■

Background information for this article was provided by Arthur Cohn, Clark Dohner, George Touchton, and Ron Wolk, Generation & Storage Division.

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New Technologies for Electric Steelmaking (page 6) was written by science writer John Douglas with background information from two members of EPRI's Customer Systems Division.

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Gene Eckhart, who works out of EPRI's Washington Office, is manager of the Institute's materials processing and fabrication research. Before joining EPRI in 1992, he spent six years as program manager in the Department of Energy's Office of Industrial Technologies, developing programs to benefit the domestic primary metals industry. From 1972 to 1985, Eckhart held engineering positions in both research and product development with the Specialty Steel Division of Armco, Inc. He holds a BS in metallurgical engineering from Drexel University and an MBA from Loyola College in Maryland. ■

A Rich Harvest From Halophytes (page 16) was written by John Douglas, science writer, with assistance from two EPRI staff members.

Seymour Alpert, Research Fellow, is an executive scientist in the Office of Exploratory & Applied Research. Since joining EPRI in 1973, he has served as technical director for the development of a number of systems, including renewable resource, energy storage, and advanced coal-based power systems. Earlier he worked for industrial and consulting organizations in the petroleum and chemical industries. He is a graduate of the Polytechnic Institute of New York and Rutgers University.

Louis Pitelka, manager of ecological studies in the Environment Division, has overseen a wide range of projects concerning the effects of air pollution and climate change on terrestrial ecosystems. Before coming to EPRI in 1984, he was director of the National Science Foundation's program on population biology and physiological ecology. He previously taught biology at Bates College in Maine for nine years and also served as chairman of the Biology Department for part of that time. Pitelka received a BS in zoology from the University of California at Davis and a PhD in biological sciences from Stanford University. ■

Advanced Combustion Turbines Set for Takeoff (page 24) was written by Taylor Moore, *Journal* senior feature writer, with principal assistance from two members of EPRI's Generation & Storage Division.

Arthur Cohn manages research on advanced power plant cycles in the Gasification Power Plants Program. He has also managed work in fusion and coal gasification since joining the Institute in 1974. Previously Cohn worked for Cambridge Research Laboratory, Avco-Everett Research Laboratory, and Pratt & Whitney Aircraft Company. He earned SB and SM degrees from the Massachusetts Institute of Technology and a PhD in electrical engineering from Rensselaer Polytechnic Institute.

Clark Dohner manages research in the Combustion Turbines Program, as well as the international Collaborative Advanced Gas Turbine (CAGT) Project. He joined the Institute in 1982 after 20 years with General Electric Company, where he held various gas turbine engineering positions. Earlier he worked for Westinghouse Electric Corporation. Dohner holds two degrees in mechanical engineering—a BS from Johns Hopkins University and an MS from the University of Pittsburgh. ■

Expert System Software

EPRI Develops Tools for Power Restoration

As many control room operators can tell you, restoring electric power after a blackout can be like trying to find a flashlight in the dark. Although sophisticated systems exist for monitoring daily operations—automatically dispatching generators according to fluctuations in supply and demand—there is no system to guide utility operators through the delicate process of complete power system restoration.

"The power system is tremendously complicated, and after a blackout it must be brought back up piece by piece in an order that ensures the safety of personnel and equipment," says Gerry Cauley, EPRI's manager of control center technology. "It's not always obvious to the operator which units should be brought on and at what point." One possible consequence is that a utility trying to restore power to a region may bring it back to customers, only to have it fail once, twice, or even several times more. Not only can that be annoying and inconvenient for customers trying to resume normal operations, but it also can be dangerous. As Cauley points out, a lifeless downed wire that is presumed safe could be reenergized at any moment.

"Power system restoration needs to be accomplished in a controlled, methodical manner so that there's a logical sequence in bringing everything back on-line," says Cauley. "There are a thousand areas in which a mistake could be made."

That has inspired EPRI to initiate a project to develop an expert system consisting of a collection of software tools that will walk control room operators step by step through the process of power restoration. When completed, the expert system will have the capacity to suggest a reliable restoration strategy based on the state of the utility's various generation, transmission, and distribution facilities. The system will recommend what actions the operator should take and how to take them, including detailed instructions for restoring individual lines.

Contractors working on the project have already developed a prototype of the central piece of the system, and it has been successfully demonstrated at Philadelphia Electric. This part of the system is now being enhanced and modified for production-grade release.

When the entire system is completed, probably in about a year, it will be beta-tested by the Salt River Project and the Western Area Power Administration. At the moment, those utilities are helping to refine the design. According to Cauley, the system not only can provide expert advice during an actual power restoration but can help utilities develop restoration plans in advance and can be used to train operators in power system restoration.

■ *For more information, contact Gerry Cauley, (415) 855-2832.*

Tube Inspection

Sound Wave May Yield Better Results Faster

The use of eddy currents for inspecting power plant tubing is a technique that's been widely employed in the industry for more than 20 years. But there are several drawbacks to this method: it is time-consuming and can require multiple inspections; it requires the insertion of a probe into every tube inspected; and the resulting data can indicate only the location of flaws, not their size.

Researchers at Pennsylvania State University may have found a better method for tube inspection. Initial laboratory experiments indicate that the use of the lamb wave, a type of sound wave that can be generated in thin materials, can provide more-detailed information on damage to heat exchanger tubing. Lamb waves also offer the potential for quicker results.

Created by an electrical impulse, lamb waves travel the length of a tube or a pipe at the speed of sound. (By contrast, the eddy-current technique involves the use of a probe that must travel the full length of a tube—typically 60 feet—at speeds of 12 to 24 inches per second.) As they flow through the tube material, the lamb waves are modified by it. The resulting wave characteristics hold the key to details not only about the location of tube damage but also about its nature and extent. The speedier lamb-wave technique offers the potential for significant savings. It also could be used as a screening device to select tubes that require further testing.

To a limited extent, other types of sound waves—shear and longitudinal waves—can be used for tube inspection by inserting a probe similar to that used in the eddy-current technique. But these waves are not useful for inspecting thin-walled tubing from one end because they get absorbed by the material before they are able to travel back to the end where they originated. Lamb waves can travel back and forth through tubing without significant attenuation.

So far, the Pennsylvania State University researchers have developed a device to generate lamb waves in power plant tubing and a mathematical model that can decipher the wave signals from relatively thin walled material as they are instantaneously relayed to a computer. EPRI hopes that the researchers will be able to demonstrate the feasibility of using lamb waves for inspecting thicker materials such as piping.

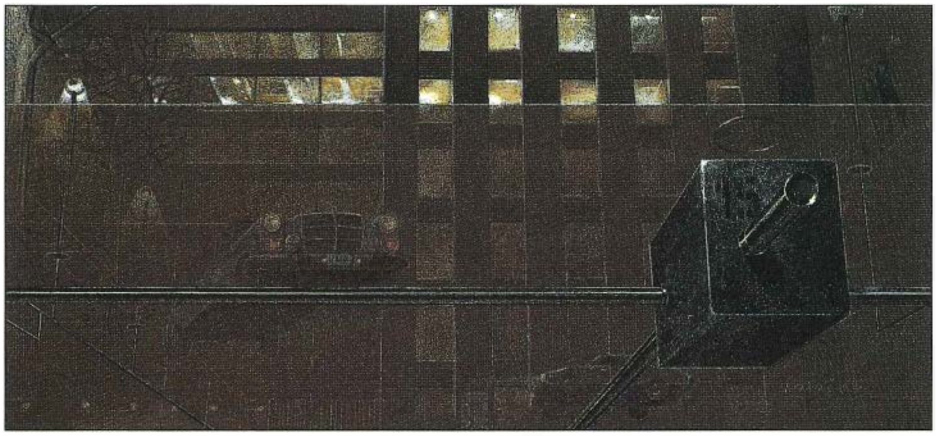
"The initial research results are promising, suggesting that lamb-wave inspection may have the potential to expand into the analysis of erosion/corrosion in thicker-walled piping," says project manager Jack Spanner. If additional laboratory tests scheduled for 1994 are successful, the technique will be demonstrated at EPRI's Nondestructive Evaluation Center in Charlotte, North Carolina. After that, it would be tried at the plant of an EPRI member utility.

■ *For more information, contact Jack Spanner, (704) 547-6065.*

Underground Cables

Prototype Development Begins on Fault Finder

An EPRI contractor has begun developing prototypes of EPRI's Fast Fault Finder—a compact sensor that is expected to locate damaged sections of underground cables more swiftly than available methods can. The Fast Fault Finder senses irregularities in current and voltage that result from a given fault and extracts information from those transients to determine the fault's location. In laboratory tests of the device, it has demonstrated an accuracy of ±2% of the circuit's length.



According to Harry Ng, manager of the project, the Fast Fault Finder will be significantly faster than conventional methods for fault location. The most common conventional method is what Ng refers to as the divide-and-conquer technique. This involves dividing a problem circuit in half by tripping a fuse near the middle of the circuit to determine which section contains the fault. The relevant section is repeatedly divided in this manner until the precise location of the damage is determined.

A second conventional method involves the use of a fault indicator, which senses the magnetic fields generated by the current resulting from faults. The drawback to this method is that fault indicators must be installed at every transformer. The result is that much time is spent opening up transformer cabinets, which contain the indicators, to obtain readings.

By contrast, only one Fast Fault Finder is required for a given circuit. Measuring approximately 6 by 4 by 2 inches, the device can be installed either as a temporary locating device after a fault has occurred or as a permanent monitoring instrument that will automatically indicate the location of a fault as it occurs.

The development of Fast Fault Finder prototypes is part of a longer-term project that began a few years ago with the conceptualization of the device by EPRI contractor BDM International. The Institute's present contractor, Edison Control Corporation, began developing prototypes this fall. By early next year, 75 prototype devices are expected to be ready for testing by member utilities. After the utilities offer feedback to Edison Control, the device will be modified for commercial release, which is projected for mid-1994. Ng says that the Fast Fault Finder will cost under $800 per unit.

■ *For more information, contact Harry Ng, (415) 855-2973.*

Adapting Wireless Networks for Monitoring Building Performance

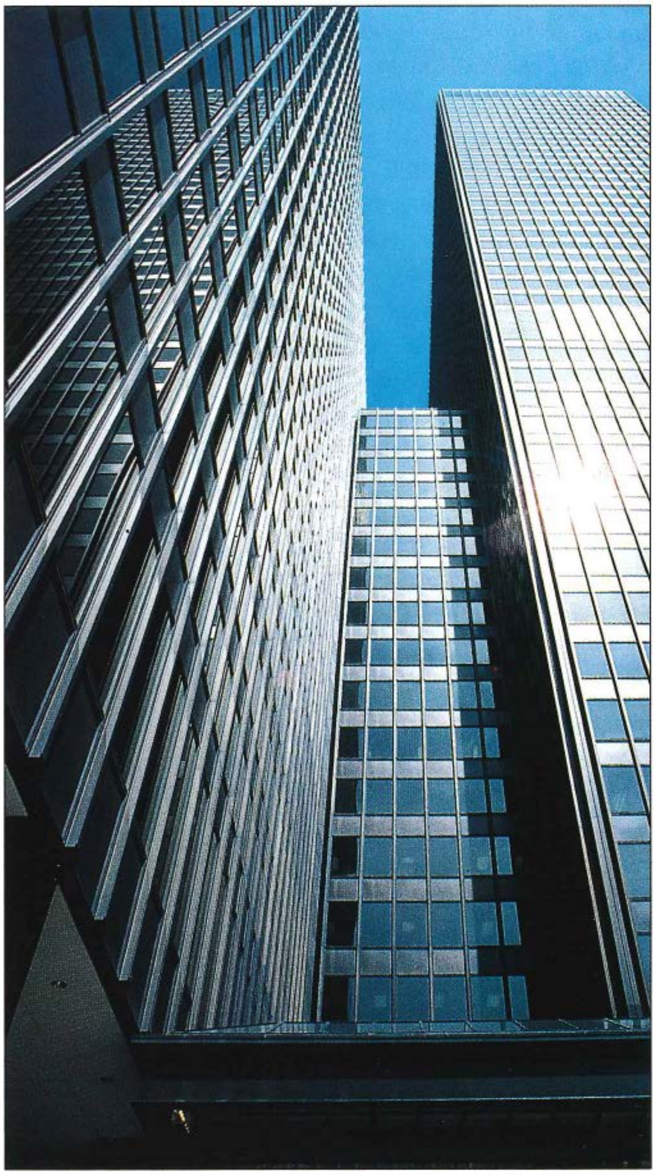
Four utilities are collaborating with EPRI to adapt a distributed, wireless network of remote data loggers for use in monitoring electrical equipment in commercial buildings. The monitoring tool will allow utilities to identify equipment problems and predict the long-term performance of a variety of loads, including heating, ventilating, and air conditioning (HVAC) systems; lighting systems; and miscellaneous motors and appliances. Researchers also expect to demonstrate the value of such a portable, temporary monitoring system for tracking the performance of demand-side management (DSM) technologies and programs.

EPRI's project contractor, Architectural Energy Corporation (AEC), is expanding and customizing for utility use a system for HVAC diagnostics and commissioning that it originally developed under a small-business innovation research contract with the U.S. Army's Construction Engineering Research Laboratory. The system—which includes hardware, software, and user manuals—employs a series of small, battery-powered, microprocessor-controlled, four-channel data loggers that are dispersed throughout a building for data collection and then retrieved 10 to 14 days later for downloading to a computer.

AEC is developing the capability for applying artificial neural networks and fuzzy logic to analyze the collected data automatically. The system software lets users define the characteristics of each component of the equipment to be monitored, thus allowing many combinations of equipment to be analyzed. The software can be expanded to accommodate new types of equipment.

Owing to its modular, expandable structure, the system has the potential to dramatically lower the cost of performance monitoring: it could cost as little as 20% of what current methods for such detailed data collection cost. And its realistic, more-reliable data on the loads and schedules of commercial building equipment will help minimize errors in DSM program planning, implementation, and evaluation.

Possible system applications include measuring lighting use and estimating the potential savings of retrofitting energy-efficient lamps and ballasts; quantifying the effect of installing lighting controls; and designing more-effective programs for HVAC tune-ups and improvements. The system can also be used to screen candidate sites for HVAC retrofit or replacement, commission new HVAC systems, and periodically determine the persistence of cost savings from DSM measures.



Each of the four utilities currently working with EPRI in this effort—the Los Angeles Department of Water & Power, Public Service Company of Colorado, Northeast Utilities, and United Illuminating Company—identified two commercial buildings in its service territory for monitoring. At most of the sites, data loggers were installed this fall after utility personnel were trained in how to program the software and use the AEC system. On the basis of the utilities' experience, AEC will develop a standardized system for use in making long-term performance predictions.

■ *For more information, contact Karl Johnson, (415) 855-2183.*

Infrared Technology for Continuous Emissions Monitoring

New infrared systems that can simultaneously and automatically monitor many of the chemical species in coal-fired power plant emissions are undergoing side-by-side comparison tests at two Baltimore Gas & Electric Company plants. The Fourier transform infrared (FTIR) systems are also capable, in principle, of monitoring some trace species that are currently not regulated under the Clean Air Act.

EPRI is working with BG&E at its Brandon Shores and Crane plants to demonstrate the applicability, reliability, and accuracy of two top-rated FTIR systems for continuous emissions monitoring (CEM). On the basis of a year-long evaluation of FTIR instrumentation that included a survey of all potential vendors, EPRI's project contractor, Entropy Environmentalists, and BG&E selected systems from Bomem, Inc., of Quebec, Canada, and KVB/Analect, Inc., of Irvine, California. The systems are expected to be installed this winter for a three-month trial at the Crane plant, which burns coal with a relatively high (2.3%) sulfur content and uses a conventional dilution-extractive CEM system. This follows a late-summer run of similar length at Brandon Shores, which burns coal with 0.7% sulfur and uses a conventional extractive-only CEM system.

According to Joe Palank, an engineer in BG&E's fossil engineering instruments and controls unit, the FTIR systems are being put through the same daily paces as the conventional CEM systems on which utilities now depend to demonstrate continuing compliance with Clean Air Act emissions limits. The FTIR systems promise substantially greater accuracy and reliability at a cost that is comparable to that of conventional CEM systems, which involve many separate sensors and analyzers.

An FTIR spectrometer uses an optical device called a Michelson interferometer, at the heart of which are a pair of mirrors and a beam splitter, to measure the infrared spectrum of a flue gas sample. The infrared source is split into a pair of beams that recombine in the device to form an interference pattern when one of the mirrors is scanned. A computer converts the pattern into quantitative data on the infrared spectrum of all the gas sample components. Each mirror scan takes only a few seconds; data from several scans are integrated to obtain the necessary sensitivity.

"FTIR systems for CEM applications have several inherent advantages," explains Rick Squires, on loan to EPRI from the United Kingdom's PowerGen (the Institute's first international affiliate). "An FTIR measurement of about one minute yields sufficient resolution for CEM application. The instrument's detection limit for most species is near 1 part per million, and it can simultaneously measure parts per million and percentage levels. Since an FTIR spectrometer has only one moving part, in principle it is quite rugged and does not require the frequent calibration necessary with other measurement technologies. Also, the measurement data can be saved and reevaluated later for pollutant species that were not included in the automated analysis."

The Environmental Protection Agency, which regulates utility compliance with the Clean Air Act, was consulted before the BG&E field tests about the acceptability of FTIR

data and has encouraged the project. As long as the rules governing CEM certification and relative accuracy testing are followed, the FTIR data are fully acceptable for regulatory compliance, the EPA advised project participants. The agency reportedly is interested in FTIR systems for use as backup and mobile CEM units that it could bring to a site for its own monitoring purposes.

Meanwhile, Palank says, BG&E will probably keep the KVB/Analect unit it purchased directly for the field project for later use as a mobile CEM system. Squires says that an EPRI report on the field testing should be available by April of next year.

■ *For more information, contact Rick Squires, (415) 855-2948.*

Demand-Side Management

Utility DSM Activities: 1992 Survey

by Paul Meagher, Customer Systems Division

ABSTRACT *EPRI's 1992 survey of utility demand-side management (DSM) programs produced the most comprehensive set of information on DSM activities ever assembled. Through the responses of 666 electric utilities throughout North America, the survey gathered data on 2321 programs involving more than 19 million utility customers. The findings, which are organized in 10 technology-based categories, offer a wealth of information about utility experiences with DSM. Utility planners can find information about technologies employed, incentives provided, participation levels, energy and demand impacts, and other program parameters that can help them design and implement better DSM programs. The survey findings, which are available in both printed and electronic form, show the increasingly important roles of DSM as a utility resource and as a vehicle for providing increased value to customers.*

There is little doubt that demand-side management (DSM) has become a significant part of the electric utility business. Utilities spend more than $2 billion a year on a wide range of DSM programs offered to electricity consumers across the nation. Projections suggest that utility involvement in this area will continue to grow, with DSM playing an expanding role in utilities' long-term resource plans. In addition, utilities are looking more and more to DSM as a vehicle for providing increased value to their customers.

To help utilities improve the effectiveness of their DSM efforts, EPRI has, since 1977, sponsored the collection and dissemination of information about industrywide DSM activities. EPRI's DSM surveys help utility planners and analysts answer such questions as "What DSM programs are other utilities providing for particular customer classes?" and "What have other utilities learned about a particular DSM approach?"

A two-volume EPRI report, *1992 Survey of Utility Demand-Side Management Programs* (TR-102193), documents the results of the thirteenth DSM survey, conducted in 1992 with the cooperation of the Northeast Region Demand-Side Management Data Exchange. This report provides the most comprehensive collection of information about DSM programs yet assembled—covering 2321 DSM programs offered by 666 utilities.

DSM goals and targeted technologies

The findings of the 1992 survey underscore the variety of DSM technologies that are being used to alter customer electricity consumption patterns. The 2321 programs covered in the survey have been sorted into 10 technology-based categories (Table 1).

The reported utility DSM efforts are largely motivated by the goals of peak clipping and energy efficiency. In fact, one or both of these objectives are cited for over 50% of the programs in each survey category. Load-shifting, valley-filling, and load growth objectives are also associated with many reported activities.

As Table 1 shows, the DSM category receiving the most attention from utilities is heating, ventilating, and air conditioning (HVAC) equipment—in particular, efficient heat pumps and air conditioners, which offer utilities many load modification alternatives. Summer-peaking utilities seeking peak-clipping and energy efficiency benefits promote efficient air conditioners, chillers, and heat pumps to replace less-efficient cooling units. Heat pumps offer the added advantage of load building and valley filling when displacing fossil fuel alternatives. Winter-peaking utilities seeking peak-clipping and energy efficiency benefits promote heat pumps to displace less-efficient electric space-heating equipment. By encouraging customers to operate their heat pumps in conjunction with fossil fuel furnaces, which operate during peak hours, some utilities reap valley-filling benefits without attendant increases in winter peak demand.

Audit and building envelope programs, which stress improved structural and equipment efficiency, are second in popularity. These programs comprise a broad range of utility services (from general walk-through audits to detailed industrial facility process evaluations) and DSM measures (from low-cost weatherization measures to comprehensive building standards for new construction).

Programs on efficient equipment and appliances cover a variety of end uses, including water heating, refrigeration, cook-

Table 1: Reported DSM Programs and Participants

Program Category	Number of Programs*	Number of Participants by Customer Class†			
		Residential	Commercial	Industrial	Agricultural and Other
HVAC	643	2,657,198	120,645	3,094	38
Audit and building envelope	581	5,251,539	113,092	14,147	2,848
Efficient equipment and appliances	484	1,866,998	56,787	12,408	4,422
Load control	467	6,276,949	71,545	3,273	36,172
Lighting and lighting controls	358	1,764,760	240,255	25,210	786
Special rates	216	200,649	83,970	64,688	6,563
Thermal storage	169	31,170	1,429	243	179
Efficient motors and motor drives	156	0	9,650	14,516	717
Standby generation	34	0	279	219	73
Miscellaneous and informational	29	1,881,317	55,849	11,349	12,587

*Because many programs fall into more than one category, the total number of programs here exceeds the total number of reported programs cited in the text.
†Because some participants install more than one type of equipment and hence are allocated to more than one program category, the total number of participants in each customer class here exceeds the number of participants cited in the text.

ing, and industrial processes. By far the most-often-targeted end use in this program category is water heating, which offers utilities the most versatility in shaping load. Utilities promote efficient water heaters both to meet load-building goals, in cases where alternative fuels are displaced, and to meet energy efficiency goals, in cases where less-efficient electrical equipment is replaced.

Load control is one of the oldest and most predictable forms of DSM. The most popular form of load control is direct control, which uses a communications system to remotely control the operation of certain customer equipment—usually residential air conditioners or water heaters—to reduce peak demand.

Lighting and lighting control programs typically target the commercial sector and stress increased efficiency for interior lighting. Although interior residential lighting has received attention in recent years because of the mass market promotion of compact fluorescent lamps, the nonresidential sectors still offer the most lucrative peak-clipping and energy efficiency benefits.

Special rate programs take advantage of the effectiveness and flexibility of rate structures for altering customer electricity use patterns and for addressing the diverse consumption patterns of commercial and industrial customers. Through interruptible-rate programs, which make up the largest group of reported programs in this category, utilities seek to achieve significant per-participant peak-clipping benefits by targeting large industrial customers. Economic development programs, which often involve reduced demand and/or energy charges, attempt to attract nonresidential customers that have significant load-building potential. Residential customer involvement in special rate programs, although significant, is largely restricted to time-of-use rate structures.

Thermal storage programs, which offer utilities summer or winter load-shifting potential, are dominated by residential space-heating and commercial air conditioning applications. Through motor and motor drive programs, utilities attempt to encourage the use of energy-efficient motors and adjustable-speed drives in commercial and industrial facilities. Like interruptible-rate programs, standby generation programs allow utilities to obtain large per-customer peak demand reductions. Miscellaneous and informational programs ordinarily promote energy efficiency but do not endorse the use of specific equipment and hence defy technology-based classification.

Table 2 presents information on the percentage of programs targeting specific end uses. As it shows, the most-often-targeted end uses in residential programs (here covering programs that include, but are not necessarily restricted to, the residential sector) are water heating, air conditioning, and space heating. This is due in part to the large number of load control programs that target these end uses. In nonresidential programs, the most-often-targeted end uses are lighting and air conditioning, followed by motor drives and space heating. The large percentage of nonresidential programs targeting all end uses reflects the influence of special rate, audit, multiple-technology, and standby generation programs. In fact, many of the multiple-technology programs give customers the option of suggesting their own DSM alternatives, taking into account site-specific conditions and energy use characteristics.

DSM sponsors and participants

The 666 utilities providing information in the 1992 survey include 124 investor-owned utilities (conducting 1030 programs), 295 public power utilities (705 programs), 218 distribution cooperatives (501 programs), and 29 generation and transmission cooperatives (85 programs). Program sponsorship is dominated by investor-owned utilities in all categories except load control, where public power and distribution cooperative utilities show the highest involvement.

The 666 reporting utilities do not truly represent the total number of utilities captured in the 1992 survey. Twenty-three program sponsors conduct broad-based umbrella programs that involve an additional 294 cooperative and municipal distribution utilities; hence the actual number of utilities represented is 960.

Of the 2321 reported programs, 1495 specifically target or include residential customers, 1150 include commercial customers, 706 include industrial customers, and 312 include agricultural customers. (Many programs cover more than one customer class.)

Table 2: Targeted End Uses in DSM Programs
(Base of 2301 Programs)

	Percentage of Programs Targeting End Use		
End Use	All Programs	Residential Programs*	Nonresidential Programs
Air conditioning	42	50	28
Space heating	37	47	19
Water heating	36	51	9
Lighting	19	13	30
Building envelope	18	22	9
Motor drives	8	0	20
Refrigeration	7	6	9
Industrial processes	3	0	9
Ventilation	3	1	6
Cooking	2	2	3
Irrigation	2	0	3
Other	6	7	5
All end uses	17	5	37

*Programs including, but not necessarily restricted to, the residential sector.

The 19.6 million participants attracted to these programs comprise an estimated 18.6 million residential customers and over 900,000 nonresidential customers. The latter group consists of over 734,000 commercial, nearly 145,000 industrial, and nearly 64,000 agricultural customers. And because participation figures were not cited for 409 programs, the actual number of participants is undoubtedly much higher.

Table 1 shows the numbers of reported participants by customer class and program category. As can be seen, residential customer participation dominates in all the program categories except standby generation and efficient motors and motor drives. In the residential sector, load control programs and audit and building envelope programs together account for more than 60% of the participants. In the commercial sector, lighting programs have attracted the most participants, largely because of the effectiveness of high-efficiency lighting rebates. In the industrial sector, rate programs are the most popular.

Accessing the survey results

In addition to report TR-102193, the 1992 survey findings can be accessed through two electronic sources. The first, SURIS 4.0 (DSM Survey Information System), is a standalone database that can be installed on the hard disk of an IBM-compatible personal computer. The second, DSIS (Demand-Side Information Service), is an on-line communications link to a variety of databases covering demand-side issues, programs, and technologies. These three products allow DSM practitioners to access information at various levels of specificity and in various formats.

Exploratory Research

Ultramax Methodology for Continuous Process Improvement

by Stan Yunker, Generation & Storage Division

Parametric testing of newly installed power plant systems is typically conducted by vendors to identify the process control settings that ensure optimal performance in terms of cost, efficiency, quality, yield, environmental impact, safety, or other measurable quantities. The basic procedure for such testing—and for other so-called parallel design of experiments (DOE) techniques—involves devising a test matrix that varies control settings in a purposeful manner. After all the tests have been completed, the data are used to create models reflecting the influence of set-point variations on performance. Through response surface analysis techniques, a combination of set points is identified that is likely to optimize performance. Confirmation experiments are then conducted to determine if the optimum has been reached or if additional parallel DOE procedures are necessary.

Once a system is up and running, its control settings are regularly tuned by operators to maintain efficient, cost-effective performance in response to variations in operating conditions. Such tuning is typically based on operating experience, standard operating procedures developed during parametric testing, and/or engineering models that capture process knowledge.

Applying parametric testing and other parallel DOE techniques in production environments can be wasteful, expensive, and time-consuming, however, because systems must sometimes be run at extreme settings to generate data for accurate modeling. And while depending on operating experience to tune control settings can lead to improvements, it is unlikely to allow optimal performance to be identified or maintained—particularly if external variables, such as fuel quality, change.

Ultramax, an optimization methodology based on a sequential DOE approach, avoids these disadvantages. In sequential optimization, data are analyzed following each run, instead of after a series of tests, to identify new control settings that are likely to improve system performance during the next run. Because its models are continuously validated and refined on the basis of the most recent data available, Ultramax sequential optimization converges to near-optimal regions faster than traditional DOE techniques while minimizing the risk of poor performance. In addition, it can be applied on-line to monitor process behavior, compensate for changes in operating conditions or external variables, and chart a course toward continuous improvement.

In recent years, the Ultramax methodology has been applied by major U.S. industries to optimize a variety of operations, including chemical production, engine tuning, and waste reduction and treatment. Two EPRI groups, the Office of Exploratory & Applied Research and the Generation & Storage Division, are collaborating to facilitate utility industry utilization of Ultramax. Exploratory work has produced a user-friendly software interface that makes Ultramax accessible to personnel who do not have a strong statistical or technical background. Divisional research has demonstrated the ability of the methodology to analyze and optimize emissions control and coal-cleaning processes.

ABSTRACT *Sequential optimization is a rapid, relatively inexpensive approach for adjusting control settings to continuously improve system performance. To make this technique more accessible to the utility industry, a user-friendly software interface has been developed for a state-of-the-art sequential optimization methodology known as Ultramax. The software, which allows users to mesh existing process knowledge with powerful analytical capabilities, has been applied to optimize emissions control and coal-cleaning processes. Several other utility demonstrations are under way, and commercialization agreements are being negotiated. These efforts illustrate the synergy between EPRI's exploratory research efforts to introduce novel technologies to the utility industry and the demonstration and commercialization activities conducted by EPRI's technical divisions.*

The methodology

The Ultramax methodology, developed by Ultramax Corporation of Cincinnati, Ohio, has been commercially available since 1982. Typically, applying it involves three steps: problem formulation, sequential optimization, and engineering analysis.

The first step—problem formulation—involves capturing the existing knowledge of operators, engineers, supervisors, and others familiar with process fundamentals, impacts, and economics. Output parameters that serve as indicators of system performance are identified and evaluated to establish optimization goals. Also defined are controlled and uncontrolled variables, constraints, base points, and a set of operating conditions called the prior region.

Controlled inputs are parameters, such as feed rate or temperature setting, that can be adjusted by operators to influence performance. (These inputs are the typical set points for first-level process controllers.) Uncontrolled inputs are variables, such as fuel quality, that affect performance but are outside the control of operators. All inputs are ranked in terms of their potential to yield performance improvements.

Constraints are factors, such as equipment tolerances or minimum performance requirements, that limit input and output values. Base points represent the input values at which the process is usually run. The prior region is a user-defined range around the base points in which the Ultramax engine can begin operating the system and searching for improvement without disrupting performance.

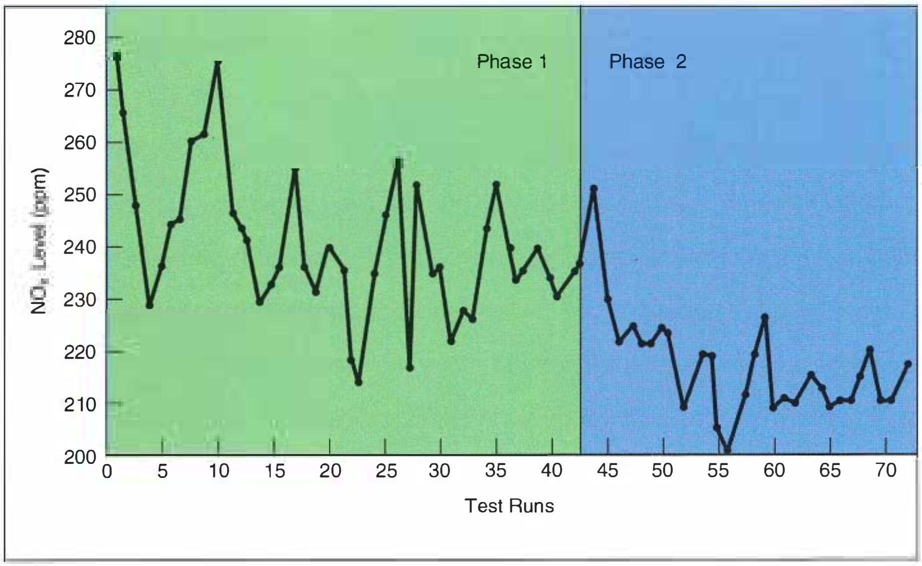
Ultramax Corporation ordinarily supports users during the problem formulation step to ensure that the formulation contains sufficient information for the Ultramax engine to develop a mathematical model reflecting the influence of input values on performance.

In the second step—sequential optimization—the problem formulation is used for model development. (Any existing system data can also be entered.) The Ultramax engine then offers advice for the next system run, identifying combinations of controlled input values within the prior region likely to improve performance. After the run using the new inputs is completed, output data are entered, a new model is generated, and advice is provided for the next run.

As the advice cycle continues within the prior region, the model becomes increasingly accurate. Eventually, the Ultramax engine learns enough about system behavior to intelligently search outside the prior region for input values that will provide further performance improvement. This cycle is repeated until optimal performance for the initial problem formulation is achieved. If external conditions—such as uncontrolled input values—change, the Ultramax methodology can compensate by adjusting the model and providing advice to maintain the relative optimum.

During the third step—engineering analysis—the problem formulation, the sequen-

Figure 1 In a demonstration project to minimize NO_x emissions from a wall-fired boiler by optimizing an overfire air system, the use of the Ultramax methodology resulted in a 22.5% decrease in the NO_x level. This improvement required only four days of testing, two engineers, and no capital expenditures for hardware.



tial optimization data, and the system's performance are studied to learn more about process behavior and to identify avenues for achieving additional improvements. For example, data analyses may identify inputs not included in the formulation that significantly influence system behavior, previously disregarded outputs that prove to be important, or constraints that need to be tightened or relaxed. The formulation can be adjusted to reflect this new knowledge and provide a better representation of the system.

The analyses may also indicate that the process model developed through the Ultramax methodology does not sufficiently explain the influence of input variables on performance. If that is the case, new measurement procedures, statistical approaches, and other techniques can be used to enhance the model's accuracy.

In addition, the analyses may suggest that the capacity, operating conditions, or other characteristics of a particular component or process are limiting the potential for improvement. Such bottlenecks can be eliminated by equipment replacement or system reconfiguration.

Software features

The graphic user interface for the Ultramax engine was developed by Decision Focus, Inc., through EPRI-funded research. The interface operates in a PC-based Windows environment that provides streamlined methods for problem formulation and data manipulation, representation, and interpretation.

An on-line tutorial/help function operates on two levels to define the Ultramax features and to describe how each is used in sequential optimization. Data can be reported in various tabular formats to simplify analysis. And the graphics package provides methods for visualizing the advice-cycle results, such as multicolored contour plots that depict standard operating conditions, recommended operating conditions, and relative optima within these areas.

In addition, an artificial-intelligence-based smart assistant serves as a contextual report interpreter. This interpreter translates statistical data into text that provides users with an update on optimization progress and guides them toward more-profitable areas of operation. When the software is integrated with the process control system, the smart assistant can automatically monitor inputs and outputs over time, serving as an increasingly intelligent advisor that can be slaved to the controller or accessed on an as-needed basis for optimization purposes. This capability offers a significant advantage over parametric-testing-based optimization, which is a discrete rather than a continuous process.

Demonstration results

The Ultramax sequential optimization methodology (with the new software interface) has been successfully applied for rapid performance improvement in several utility demonstrations. The results from three EPRI-funded projects are described below.

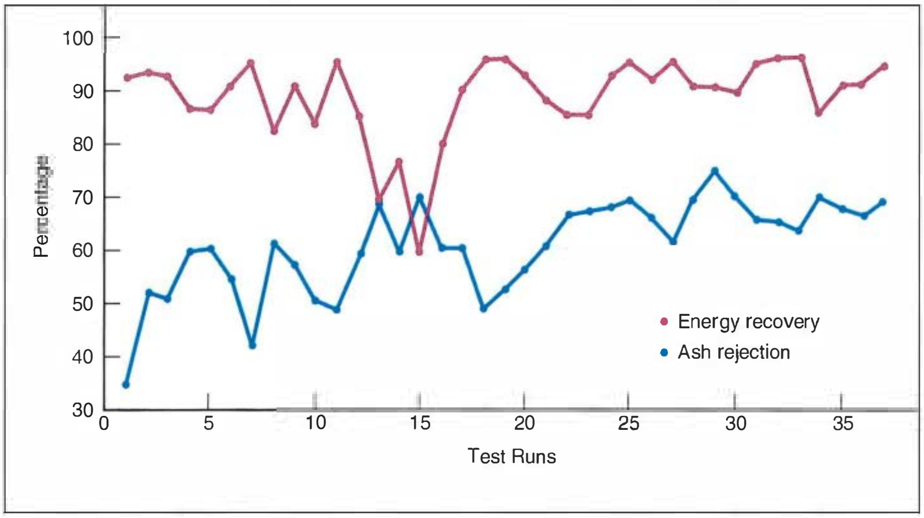
The first application involved the evaluation of an overfire air (OFA) system for reducing emissions of nitrogen oxides (NO_x) from a wall-fired boiler. An on-line optimization routine for the OFA control system was required to adjust the position of multiple air dampers to minimize NO_x emissions while meeting predetermined limits on opacity and on carbon monoxide emissions.

The Ultramax methodology was applied in two phases. The first problem formulation included five controlled inputs (total airflow and OFA flow at each of four dampers), one uncontrolled input (coal flow), and one output variable (NO_x emissions). Historical data were analyzed to develop process models, and 43 runs were carried out under Ultramax advice. As shown in Figure 1, in this phase the average NO_x level was reduced by 16% from a baseline of about 280 ppm.

Then, on the basis of an engineering analysis of the statistical data produced by Ultramax, a second, more accurate formulation was developed. Two more air damper parameters were included as inputs, and 5-minute averaging of all outputs was employed. An additional 29 runs were conducted under this formulation, leading to an average NO_x level of 217 ppm—a total decrease of 22.5%. Four days of testing, two engineers, and no capital expenditures for hardware were required to achieve this performance improvement.

In the second demonstration, Ultramax sequential optimization was applied to the froth flotation unit of a coal-cleaning circuit to maximize ash rejection while maintaining an energy recovery of at least 85%. Figure 2 illustrates the 37 runs made under Ultramax advice as the software learned how to meet optimization objectives while satisfying the energy recovery constraint. Control

Figure 2 In a demonstration project to maximize ash rejection in a froth flotation coal-cleaning unit while satisfying energy recovery requirements, Ultramax was able to achieve 70% ash rejection and 95% energy recovery—results that represent increases of 35% and 6%, respectively, over typical unit performance.



settings were identified that resulted in ash rejection values as high as 70% and energy recovery values as high as 95%. Compared with performance under standard operating conditions, these results represent a 35% increase in ash rejection and a 6% increase in energy recovery.

The third application involved the evaluation of a high-shear mixer and froth flotation cell in EPRI's selective agglomeration coal-cleaning process. Typical parametric-testing techniques had been used to optimize the cleaning performance of a pilot-scale cell for two coals, but limited time and resources were available for testing with a third coal. Ultramax sequential optimization was suggested as a technique for rapidly identifying operating conditions to maximize pyritic sulfur rejection and meet energy recovery constraints.

Historical data from the parametric tests were input to allow the creation of process models. After a series of advice cycles, Ultramax identified control settings that offered a 7% increase in pyritic sulfur rejection and a 13% increase in energy recovery over performance with the testing-based set points. These results would translate into annual savings of $2 million for a full-scale selective agglomeration unit.

Other, ongoing demonstrations are applying the Ultramax methodology to reduce NO_x formation during combustion, conserve energy in end-use applications, and increase generation efficiency during startup and steady-state power plant operation. In addition, Ultramax Corporation has established—with EPRI involvement—a division called PowerMax to facilitate widespread utility application of the methodology and to accelerate the realization of its potentially huge benefits.

The efforts to introduce Ultramax sequential optimization to the utility industry provide an ideal illustration of how EPRI's technical divisions and its Office of Exploratory & Applied Research collaborate in researching, developing, and delivering technologies to meet the requirements of utilities and their customers. These efforts have resulted in a widely applicable, user-friendly optimization technique for rapidly realizing performance improvements that might otherwise be impractical to achieve.

Advanced Fossil Power Systems

Power Plant Cycles Featuring Air Humidification

by Arthur Cohn, Generation & Storage Division

EPRI has been supporting extensive research on new power plant cycles that use air humidification and on the turbomachinery required for those cycles. The cycles are based on combustion turbines and do not include a steam cycle. They feature an air humidifier, or saturator, after the compressor—which greatly lowers the required compressor energy input.

Analyses have shown that in baseload operation a HAT (humid-air turbine) cycle fired with natural gas could have a heat rate 300–400 Btu/kWh lower than that of combined cycles with a similar turbine firing temperature. When integrated with coal gasification, the HAT cycle could offer 10–15% savings in overall plant cost.

For intermediate-load operation, the CASH (compressed-air storage with humidification) cycle is being developed for integration with coal gasification. It has been estimated that an integrated gasification-CASH (IGCASH) plant would save about 15–20% in capital cost per peak kilowatt of capacity, compared with a standard cycling pulverized-coal plant with flue gas scrubbing. The IGCASH plant would be designed to dispatch power to the grid about 60% of the time; compression charging would take place the remaining 40% of the time—usually late at night, early in the morning, or on the weekend. The combination of coal gasification and natural gas firing in a cycle called CASHING (compressed-air storage with humidification, integrated with natural gas) would lower the capital cost even fur-

ABSTRACT *According to EPRI studies, new combustion-turbine-based power plant cycles that do not include a steam cycle but that use humidified air could offer utilities significant cost savings and lead to plants with very flexible dispatch capabilities. Innovative cycles combining air humidification, coal gasification, and compressed-air energy storage are being explored. Current research is focusing on turbomachinery for these cycles and on optimal cycle configurations. The results will point the way for EPRI's future development efforts on humidified cycles.*

ther and would lead to plant types with very flexible dispatch capabilities.

HAT cycle

Figure 1 shows the HAT cycle (described in EPRI report IE-7300). The cycle's key component is the saturator, in which hot water is vaporized into the compressor exit air. This feature greatly increases the total mass flow going through the turbine for a given mass flow of air that is compressed. That, in turn, lowers the fraction of turbine energy that goes to power the compressor. The result is an increase in the net power output per unit airflow.

Another important factor in the cycle's increased efficiency is the recuperator. This equipment transfers a portion of the turbine exhaust gas enthalpy to the wet air at the combustor inlet, thus raising the air's temperature. That reduces the amount of fuel necessary to reach the desired turbine firing temperature. Compressor intercooling and aftercooling increase the temperature range over which the recuperator is effective, contributing to the cycle's efficiency improvement. Intercooling also reduces the power required by the compressor, further increasing the specific power.

Water for the saturator is heated in the intercooler and the aftercooler, as well as in the economizer, which recovers much of the remaining exhaust gas enthalpy downstream of the recuperator. These features further contribute to the efficiency improvement offered by the HAT cycle. And when the cycle is combined with coal gasification, hot water from the gasification system's coolers can also be effectively used in the saturator.

An engineering analysis (to be published in TR-102156) predicts that when designed for and operating on natural gas, the HAT cycle will offer about a 5% heat rate improvement over combined cycles at the same turbine firing temperature. When integrated with coal gasification, the HAT cycle will also offer a significantly lower power plant cost (by about 10–15%) while maintaining a competitive heat rate. This lower cost is achieved by eliminating the steam cycle and by using a quench-cooled gasifier rather than a full heat recovery system featuring radiant and convective syngas coolers. With combined cycles, the use of quench gasification cooling instead of the more-expensive full heat recovery system normally results in a significant drop in efficiency.

The HAT cycle is also expected to have lower operating and maintenance costs because it dispenses with syngas coolers, high-pressure and/or superheated steam, the steam turbine, and the condenser and requires only 25% as much cooling tower capacity. In the coal gasification application, the HAT cycle can, like other gasification systems, offer very low emissions of sulfur oxides and trace elements—and possibly even lower emissions of nitrogen oxides because of the high humidity of the combustion air.

Thus the HAT cycle should lead to power plants with very high efficiency, high specific power, and low environmental impact. Since it does not use steam for generation, the cycle also eliminates any siting, staffing, and certification problems associated with steam. Its main drawback is the projected high cost to develop the special turbomachinery needed for cycle optimization.

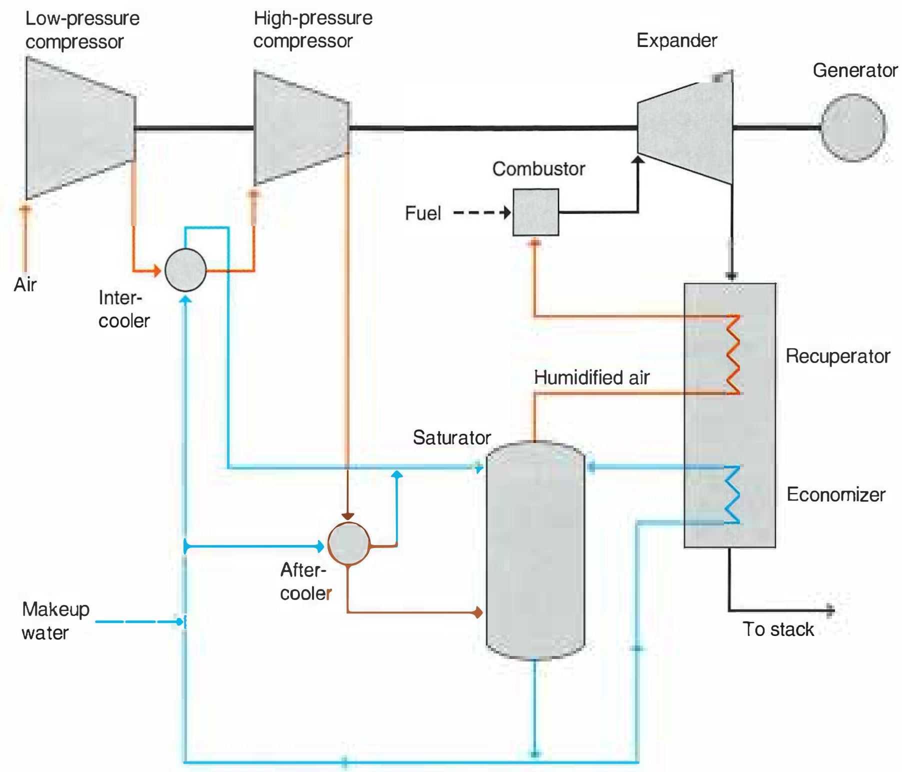
The optimal HAT cycle would have an overall pressure ratio of about 35±5 to 1, with the intercooling taking place at a pressure ratio of about 6±1 to 1. The turbine exhaust mass flow would be 20–30% greater than the compressor inlet flow. Since the overall compression ratio of available aeroderivative gas turbines can match this requirement, EPRI participated in a joint project with United Technologies Corporation (UTC), Fluor, and Texaco to evaluate the modification of an aeroderivative turbine for a HAT power plant (TR-102156). UTC has completed the conceptual design for such a humid-air turbine—a modification of the company's FT4000 simple-cycle aeroderivative turbine, currently under detailed design. That machine, in turn, is a modification of the PW4000 turbofan used in commercial airline service.

Since the FT4000 turbine has a multispool compressor, the addition of an intercooler is feasible but would require the development of a new low-pressure-compressor design. Also, the HAT cycle's very high ratio of turbine gas flow to compressor airflow would require developing a new turbine expansion section.

The study concluded that modifying the 40-MW FT4000 simple-cycle turbine for the HAT cycle application would result in a power increase to 199 MW with a heat rate of 6190 Btu/kWh (lower heating value) when designed for natural gas. The modification would result in a net power output of 205 MW with a heat rate of 8040 Btu/kWh (higher heating value) when designed for and integrated with a Texaco quench-cooled gasifier.

The project's analysis of the capital cost of a HAT power plant using the modified FT4000 turbine is also encouraging. For natural gas firing, the capital cost was estimated to be about the same as that of a combined-cycle plant. For an integrated gasification-HAT plant, the overall cost was estimated to be lower by about $150/kW to

Figure 1 The HAT (humid-air turbine) cycle promises to lead to power plants offering cost savings and dispatch flexibility. Several features contribute to the cycle's high efficiency: its reduced compressor energy requirement (the result of using a saturator to humidify the compressor exit air), its high combustor inlet temperature, and its efficient transfer of flue gas energy back to the cycle.



$200/kW than the cost of an integrated gasification-combined-cycle power plant with the same heat rate. That significant cost decrease is mainly due to the HAT plant's use of the quench-cooled gasifier.

The development cost of the FT4000 HAT modification, however, was estimated at more than $200 million—judged to be too high for the project participants to continue. Nevertheless, the development of the FT4000 HAT is receiving attention in other projects. It is one of the plant types being studied by UTC in the Collaborative Advanced Gas Turbine (CAGT) Project—a major international effort with several sponsors, now led by EPRI. Other CAGT contractors will also study aeroderivative turbines applicable to the HAT cycle. (For more information on CAGT, see the feature article on page 24 of this issue.)

In addition to the FT4000 HAT study and the other aeroderivative HAT studies, EPRI has a project with Westinghouse to investigate the modification of heavy-frame components for HAT applications. The project will study the adaptation of current heavy-frame components to an intercooled HAT cycle in a configuration as close to the optimum as feasible. It will also study the adaptation of a current heavy-frame gas turbine to a nonintercooled HAT cycle. The latter is expected to be simpler in terms of development but would not have the heat rate advantage of the intercooled HAT plant.

CASH, IGCASH, and CASHING cycles

Figure 2 shows another new approach to power generation—the CASH cycle (TR-101584). This cycle combines innovations from the HAT cycle and from compressed-air energy storage (CAES) technology to promise a lower plant capital cost and greater operating flexibility.

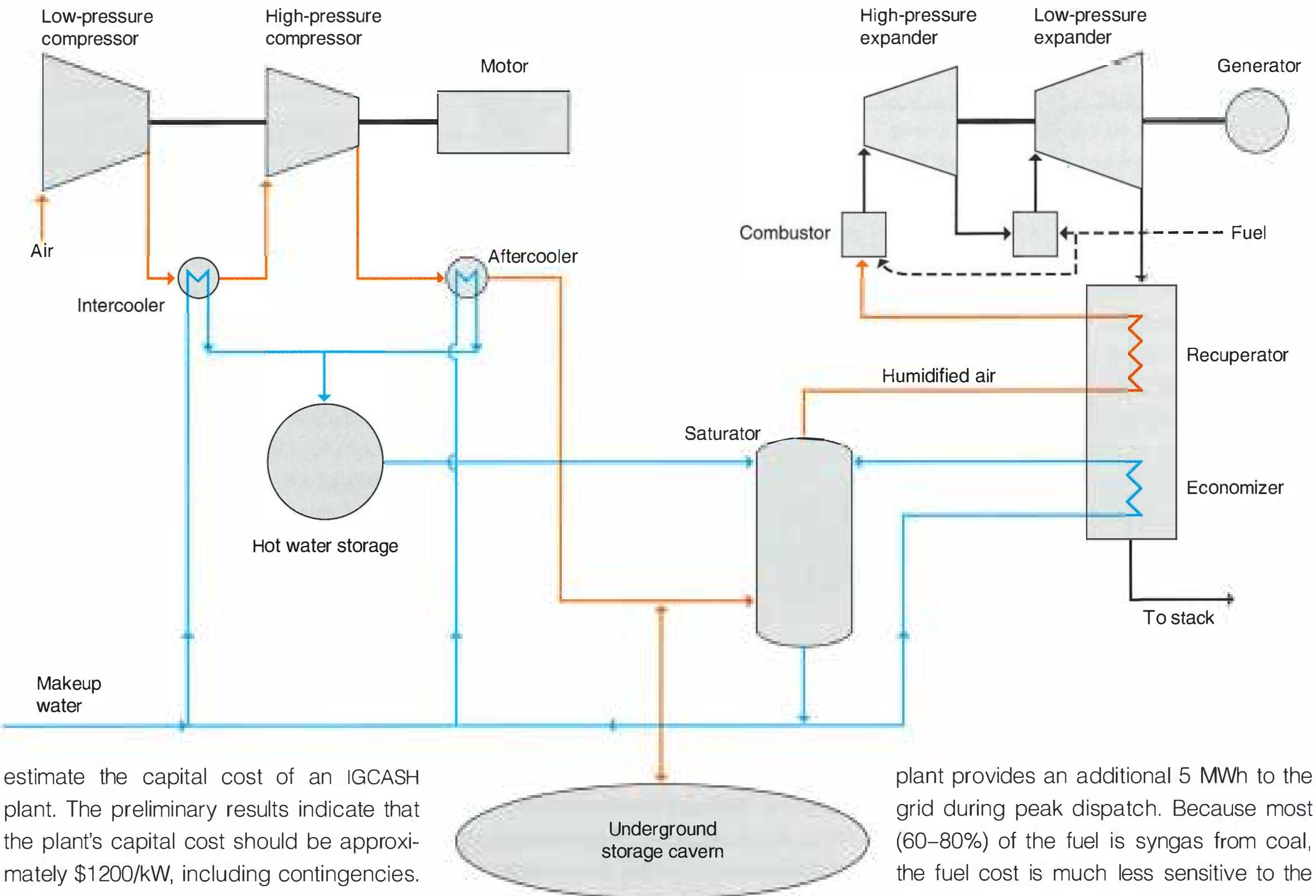
As in the HAT cycle, the compressed air is humidified in a saturator and heated by recuperation before entering the combustor. However, the CASH compressor operates only during off-peak hours, sending most of the compressed air into a storage cavern for later use. The CASH turbine operates constantly and independently of the compressor, using the stored compressed air when the compressor is off. Thus, during high-demand hours, none of the turbine's power is used for air compression; all of it is available for dispatch to the grid. The result is a lower-specific-cost power plant. Another benefit of the CASH cycle is that heat removed from the compressed air, which must be below about 100°F for cavern storage, is returned to the cycle.

Compared with a dry CAES plant, the CASH system has a much smaller ratio (about 40%) of charging energy to dispatched energy because the mass flow is greatly increased as a result of humidification. The turbine generator provides the power for the electric-motor-driven air compressor. For a compressor that is large enough to take all the turbine generator power, charging occurs approximately 40% of the time—during the night and/or weekend hours, when demand is very low. When the compressor is shut off—about 60% of the time, during the higher-demand hours in the daytime and early evening—the turbine generator dispatches all its power to the grid. (Alternatively, a lower-flow compressor system taking only some of the turbine generator power can run more of the time, with the remaining power delivered to the grid even during compressor operation.) A CASH system firing natural gas thus allows for steady consumption of fuel while providing variable power output to the grid. Benefits would be a lower gas line capacity and a lower fuel capacity charge.

Integrating the CASH cycle with coal gasification has advantages over other integrated gasification cycles for intermediate-load duty. The greatest advantage of an IGCASH system is that, for a given power output to the grid, it can use a much smaller, less expensive gasifier than other gasification power plants. Because the compressor is turned off during dispatch, all the turbine power goes to the grid. In standard combined-cycle plants, in contrast, only about 60% of the power output goes for dispatch, with the other 40% being used to run the compressor.

EPRI currently has a project with Bechtel, with the assistance of Energy Storage & Power Consultants (RP2834-3 and -4), to

Figure 2 The CASH (compressed-air storage with humidification) cycle. In this cycle, the compressor system operates only during off-peak hours and sends most of the compressed air into a storage cavern, thus enabling the turbine to provide all of its power to the grid during high-demand hours. Air humidification reduces the time the compressor must operate and also lowers the system heat rate. Like the HAT cycle, the CASH cycle can operate on natural gas or can be integrated with a coal gasification system.



estimate the capital cost of an IGCASH plant. The preliminary results indicate that the plant's capital cost should be approximately $1200/kW, including contingencies. That estimate, which is based mainly on actual bids, is about $200/kW lower than the estimated cost of a cycling pulverized-coal steam plant with scrubbers. The overall heat rate of an IGCASH plant is calculated to be about 10,000 Btu/kWh, which is about 1000 Btu/kWh better than that of the cycling coal steam plant. The use of turbines especially modified to fit the CASH application would lower the IGCASH plant's heat rate to about 9200 Btu/kWh.

The CASHING power plant is an IGCASH plant with an additional natural-gas-fired CASH turbine generation system. The natural-gas-fired system would include only a turbine generator, a saturator, a recuperator, and a hot water heater; it would not have an additional compressor system or an additional storage cavern, with their large costs. The required additional equipment has been estimated to cost about $250/kW. For a plant with natural-gas-fired and syngas-fired turbines of equal capacity, the overall specific capital cost would be only about $725/kW (on a peak kilowatt basis). Adding even more natural gas CASH capacity with no increase in compressor equipment or volume storage would lower the specific capital cost per peak kilowatt even further.

The natural-gas-fired turbine operates mainly during peaking hours, with the result that approximately twice the basic IGCASH power capacity is provided to the grid during this period. In the late evening and night hours, no power from the continuously operating IGCASH system is dispatched; it is all used for air compression. For each 2 MWh lost from dispatch during the late evening hours (to provide the additional compressed air required for the natural-gas-fired turbine), the CASHING plant provides an additional 5 MWh to the grid during peak dispatch. Because most (60–80%) of the fuel is syngas from coal, the fuel cost is much less sensitive to the price of natural gas than in natural-gas-fired combined cycles. The CASHING plant should be appropriate for peaking and intermediate operations (3000–5000 hours a year).

In support of both the HAT and CASH cycles, an important project is under way with Textron-Lycoming to test the combustion of humid air with natural gas and with syngas. Another important supporting project, sponsored by EPRI's Energy Storage Program with Glitsch, Inc., is studying saturators for CASH and HAT applications. Saturators are common at refineries, but using them with high-pressure air is an extension of current practice. Tests for such an application are being planned as part of this project.

In a key project being conducted in coordination with the Energy Storage Program, Westinghouse is investigating the conversion of its combustion turbine (and steam turbine) equipment to CAES and CASH applications. Because the use of storage separates in time the flow of air out of the compressor and the flow into the turbine, the matching problems encountered in the HAT cycle are eliminated. That greatly lowers the development cost of the turbomachinery, which can be simply modified from current equipment, or, in the case of the compressor, purchased separately.

EPRI is also starting evaluation projects with three utilities—Public Service Electric & Gas Company, Florida Power Corporation, and the Tennessee Valley Authority—to identify the optimal configurations for CASH, IGCASH, and CASHING plants on their systems. These projects will include dispatch studies and system expansion analyses of various configurations of these plants versus alternative power plant types. Emphasis will be placed on the CASHING cycle because of its very low capital cost, its low fuel cost, and its relative insensitivity to the price of natural gas. The results of these projects will determine the direction of EPRI's future development efforts on humidified cycles.

Ecological Assessment

GLOCO: Modeling the Global Carbon Cycle

by Robert Goldstein, Environment Division

ABSTRACT *Most suggestions for mitigating potential global climate change focus on regulating atmospheric concentrations of greenhouse gases—in particular, carbon dioxide and methane. Analysis of the efficacy of such strategies requires a predictive, quantitative understanding of the global carbon cycle. That cycle consists of numerous interacting biogeochemical and hydrodynamic processes that affect the movement of carbon within and between the atmospheric, terrestrial, and oceanic systems of the earth. To help clarify the dynamics of the global carbon cycle, plan experimental research, and analyze policy options, a desktop computer model called GLOCO has been developed. Using an annual time step, this model dynamically simulates the processes that govern the global carbon cycle.*

The reservoir sizes and the annual fluxes of the global carbon cycle, as quantified by the Intergovernmental Panel on Climate Change (IPCC), are illustrated in Figure 1. Fluxes of about 200 billion metric tons, or gigatons (Gt), of carbon are exchanged annually between the atmosphere and the oceans and between the atmosphere and the land.

The IPCC estimates that fossil fuel combustion annually transfers approximately 5 Gt of carbon to the atmosphere. The atmospheric carbon content is currently 750 Gt and is increasing by 3 Gt/yr. It is important to note that the 5- and 3-Gt/yr rates are factors of approximately 40 and 70 less than the estimated annual flux from the earth's surface (oceans and continents combined) to the atmosphere (about 200 Gt) and the flux back (also about 200 Gt). Because the annual fluxes of carbon to and from the atmosphere by natural processes are so large compared with the transfer of carbon from fossil fuel combustion, a framework for predicting future changes in atmospheric carbon must include calculations of natural sources and sinks, which may change with time.

The GLOCO model

GLOCO is a desktop computer model for analyzing the global carbon cycle. The physical compartments, chemical components, and major processes simulated by GLOCO are summarized in Table 1. The model divides the globe into one atmosphere, six natural terrestrial biomes, and two oceans. In addition, it simulates three human activities: fossil fuel combustion, forestry, and agriculture. Gaseous carbon is simulated as carbon dioxide (CO_2) and methane (CH_4).

The locations of the terrestrial ecosystems on the globe are not specified; only their areas are. The oceans are given locations relative to each other to simulate global ocean circulation. Climate (temperature) for each biome and ocean surface can be specified as a function of atmospheric CO_2 and a lag time. Alternatively, users may define specific temperature scenarios. Process rates in the model are temperature dependent.

GLOCO has been calibrated by using CO_2 concentrations from ice cores and measurements of atmospheric CO_2 at Mauna Loa. The historical data indicate that atmospheric CO_2 was about 280 ppmv (parts per million by volume) in 1750 and has risen (especially rapidly in the latter part of this century) to about 350 ppmv today.

GLOCO's atmosphere is limited to one compartment, since the interhemispheric mixing time is about the same as the model's time step (one year). The atmosphere contains CO_2 and CH_4, and the model simulates the oxidation of CH_4 to CO_2.

The six natural terrestrial ecosystems in GLOCO are tropical forest, temperate forest, boreal forest, grassland, tundra, and desert. They have the same parameters but are differentiated by the values of those parameters.

The ecosystems fix carbon from the atmosphere and convert it into plant biomass, which is divided into foliage, structural material, and fine roots. Carbon in the forms of CO_2 and CH_4 is released to the atmosphere as a result of biomass respiration and organic matter decomposition. There are three pools of organic matter in the soil—litter, intermediate soil organic matter, and humus. Dead biomass cycles through these pools, decomposing further in each.

The soil also contains a pool of available nitrogen. GLOCO simulates the cycling of nitrogen within the soil, within plants, and between the two. The rate of photosynthesis is a function of both atmospheric CO_2 and plant nitrogen. A deficiency of nitrogen can limit the potential of plants to increase their uptake of atmospheric carbon in response to increased CO_2 levels. (Such increased uptake is known as the carbon fertilization effect.) Nitrogen is added to a terrestrial system by atmospheric deposition and fixation and is removed by leaching and denitrification.

There are two oceans in GLOCO: high latitude and low latitude. The former is divided into a surface layer and a deep layer, the latter into a surface layer and 68 lower layers. In addition to vertical mixing within and horizontal mixing between oceans, there is a large-scale circulation pattern that includes sinking at high latitudes and upwelling at low latitudes.

The exchange of CO_2 between the atmosphere and the oceans is bidirectional. Acid-base reactions—including those of borate, dissolved organic carbon (DOC), and phosphate—affect the speciation of dissolved inorganic carbon (DIC) and hence the partial pressure of dissolved CO_2, which in turn affects gas exchange. In the oceans' surface layers, biota convert DIC to particulate organic carbon, DOC, and calcium carbonate ($CaCO_3$). Inorganic carbon and organic carbon are redistributed within and between the oceans by advection/dispersion and settling. A fraction of the particulate carbon in the oceans is buried in sediments. Throughout the oceans, mineralization converts organic to inorganic carbon. In addition to simulating this cycling of carbon, GLOCO simulates the physical and biological cycling of phosphorus, which also influences the rate of organic carbon production.

One of the three human activities simulated by GLOCO is the release of CO_2 and CH_4 into the atmosphere from fossil fuel combustion. The model includes estimates of fossil fuel inputs from 1850 to the present, as well as four IPCC scenarios for fossil fuel combustion from 1990 to 2100. Users can select any of the four scenarios in combination with the historical estimates or can substitute scenarios of their own.

A module for forestry, the second human activity, allows users to impose harvesting

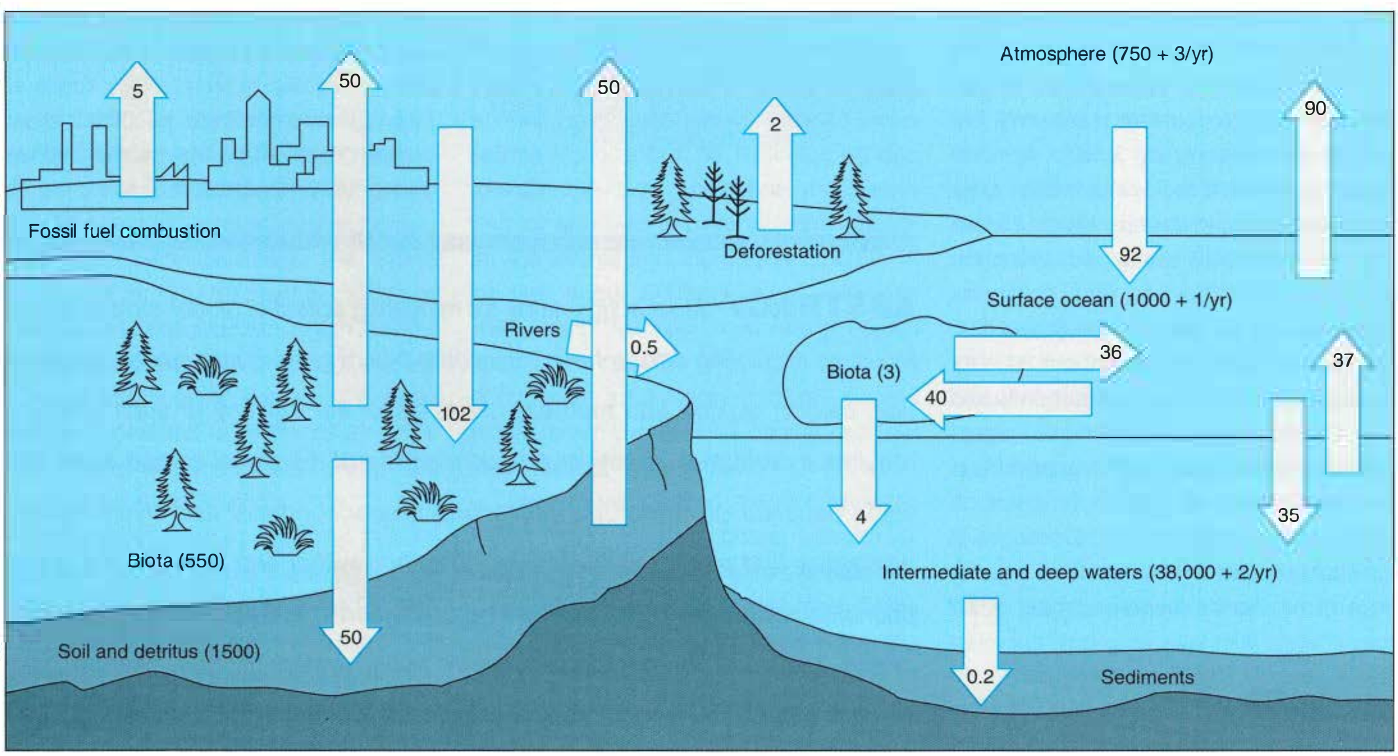


Figure 1 Global carbon cycle, based on 1990 estimates from the Intergovernmental Panel on Climate Change. The numbers in parentheses indicate the size of carbon reservoirs and the annual rate of change (in Gt); the numbers in the arrows indicate fluxes between reservoirs (in Gt/yr). Although fossil fuel combustion annually transfers about 5 Gt of carbon to the atmosphere, that figure is a factor of 40 less than the annual fluxes of carbon to and from the atmosphere as a result of natural processes.

System	Compartments	Components	Major Processes
Table 1: Elements of GLOCO			
Atmosphere	Well-mixed atmosphere	Carbon dioxide (CO_2) Methane (CH_4)	CH_4 oxidation CO_2 exchange with oceans/biomes
Terrestrial ecosystems	Tropical forest Temperate forest Boreal forest Grassland Tundra Desert	Foliage carbon Wood carbon Root carbon Litter carbon Intermediate soil organic matter Humus carbon Available nitrogen	Photosynthesis Respiration Litterfall Humification of litter Humus mineralization Production of CH_4
	River	Dissolved inorganic carbon Dissolved organic carbon (DOC) Alkalinity Phosphorus	Weathering and transport to oceans
Oceans	Low-latitude ocean Surface layer 68 lower layers High-latitude ocean Surface layer Deep layer	Total inorganic carbon DOC Alkalinity Phosphorus Particulate organic carbon (POC) Biogenic calcium carbonate ($CaCO_3$)	Acid-base equilibria CO_2 exchange with atmosphere Advection/dispersion New production of POC and DOC POC settling and mineralization POC burial DOC mineralization Biological $CaCO_3$ formation $CaCO_3$ dissolution and burial
Human activities	Agriculture Forestry Fossil fuel combustion	Humus carbon 10-year wood 100-year wood	Agricultural production Litter humification Humus mineralization Production of CH_4 Land use changes Forest harvesting Decay of wood products CO_2 and CH_4 emission

and reforestation scenarios for the three forest ecosystems. When an area is harvested, its carbon is divided among soil organic matter, biomass fuel, and wood products with 10- and 100-year average lifetimes. The biomass fuel is immediately converted to atmospheric carbon.

The last human activity modeled is agriculture. Considered a seventh terrestrial biome, agricultural land is divided into cultivated land, paddy fields, and rangeland. GLOCO users can impose scenarios for converting land in the natural terrestrial ecosystems to agriculture and for abandoning agricultural land to the natural ecosystems. When land is converted, its carbon is divided into compartments similar to those used during forest harvesting.

GLOCO has a single river, which simulates the total river runoff from the terrestrial ecosystems. This runoff is mixed into the surface layer of the low-latitude ocean. The river flow contains phosphorus, DIC, DOC, and alkalinity. The model accounts for the fraction of DIC produced by the weathering of primary minerals (e.g., aluminum silicates) and that produced by the weathering of carbonate rock.

Using GLOCO

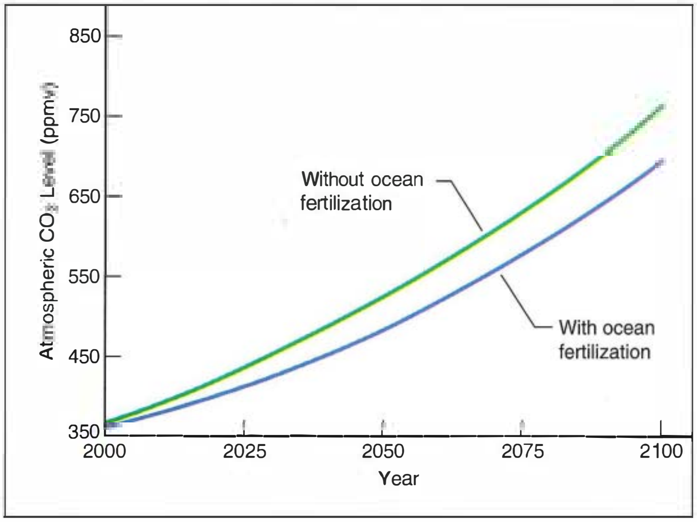
The GLOCO model can be used to test scientific hypotheses and to evaluate management scenarios concerning the global cycling of carbon. Through sensitivity analyses, the model can be used to help identify parameters that require measurement and processes that require additional research.

In one case, GLOCO was used to examine the fertilization of high-latitude oceans. Biological carbon fixation in some ocean areas, including the Antarctic, appears to be limited by the supply of iron, a trace nutrient. Fertilization of these areas with iron has been proposed as a means of reducing future increases in atmospheric CO_2.

To simulate the effects of this fertilization, researchers used the IPCC's business-as-usual fossil fuel emissions scenario and increased the phosphorus uptake coefficient for the high-latitude surface ocean to bring ambient phosphorus concentrations down to those found in the low-latitude ocean surface waters. (This approach is based on the assumption that in the high-latitude ocean the photosynthesizing biota's ability to use available phosphorus had been limited by the supply of iron.) Figure 2 presents atmospheric CO_2 levels for the business-as-usual emissions scenario with and without ocean fertilization. As can be seen, the projected CO_2 concentration for the year 2100 is about 10% lower with ocean fertilization.

As this application illustrates, the GLOCO model is a useful tool for analyzing the global carbon cycle. Its graphic interface and speed of execution enhance its potential for analysis, teaching, and communication. Although GLOCO might be considered a relatively simple model compared with highly spatially disaggregated models, its response surface is multidimensional and complex. This is due to the comprehensive and detailed mechanistic representations included to simulate carbon transport and conversion processes.

Figure 2 GLOCO was used to simulate the fertilization of high-latitude oceans with iron—a potential strategy for reducing atmospheric carbon. Two cases using the IPCC's business-as-usual fossil fuel emissions scenario were run, one with ocean fertilization and one without. The fertilization case showed about a 10% decrease in the level of atmospheric CO_2 projected for the year 2100 relative to the case without fertilization.



GLOCO is currently being beta-tested by oceanographic, terrestrial, and atmospheric scientists. Meanwhile, several extensions of the model are being considered: the simulation of precipitation and soil moisture; the differentiation of carbon by isotopes to provide an independent means of calibration; the inclusion of autosensitivity testing and error propagation analysis routines; and the construction of a variable-time-step hemispheric version that would simulate intra-annual, latitude-dependent fluctuations in the concentration of atmospheric carbon.

New Contracts

Project	Funding/ Duration	Contractor/EPRI Project Manager
Customer Systems		
Distribution Automation/Demand-Side Management Demonstration (RP2568-33)	$238,000 30 months	Union Electric Co./ *L. Carmichael*
Demonstration of Synthetica Detoxifier Applied to Medical Waste Disposal (RP2662-47)	$300,000 17 months	Synthetica Technologies/ *M. Jones*
Uncouplers of Oxidative Phosphorylation Applied to Control of Excess Biological Sludge (RP2662-54)	$75,900 21 months	University of Washington/ *M. Jones*
Demand-Side-Management-Related Software Integration Study (RP2863-14)	$116,400 7 months	Mykytyn Consulting Group/*P. Meagher*
Dual-Fuel and High-Efficiency Unitary Heat Pump Market Research (RP2891-21)	$51,700 6 months	Decision Analyst/*W. Krill*
Demonstration of End-Use Data Transferability, Phase 1 (RP2980-42)	$87,800 5 months	Aspen Systems/*R. Gillman*
Generic and Site-Specific Studies of Energy Storage on Rail Systems (RP3025-8)	$134,400 13 months	Carnegie Mellon Research Institute/*P. Symons*
Reliability of Uninterruptible Power to Nuclear Plant Instrument/Control Cabinets (RP3088-11)	$237,900 13 months	Westinghouse Electric Corp./*B. Banerjee*
Electrical Systems		
Power System Analysis Package: Dynamic Data Conversion (RP1208-11)	$72,700 8 months	Ontario Hydro/*P. Hirsch*
ETMSP Enhancements (RP1208-12)	$234,500 9 months	Ontario Hydro/*P. Hirsch*
Power System Analysis Package Enhancements (RP1208-13)	$80,800 8 months	Ontario Hydro/*P. Hirsch*
Field Trials of TOMCAT 2000 (RP2472-12)	$79,000 6 months	Houston Lighting & Power Co./*H. Mehta*
RISKMIN Enhancements (RP2537-3)	$79,400 10 months	Stone & Webster Management Consultants/ *R. Adapa*
Advanced Metering Project (RP2592-6)	$2,799,500 18 months	Southern California Edison Co./*V. Tahiliani*
Static Condenser (RP3023-3)	$2,400,000 49 months	Tennessee Valley Authority/*A. Edris*
Engineering Calculators (RP3066-2)	$82,600 10 months	Power Computing Co./ *T. Kendrew*
Energy-Based Dynamic Security Assessment Tools for Maintaining Voltage Stability (RP3103-4)	$82,700 13 months	University of Wisconsin, Madison/*G. Cauley*
Portable Electric Utility Software for Parallel Computers (RP3103-6)	$224,400 10 months	University of Maryland/ *P. Hirsch*
Development of Production-Grade TRELSS (Transmission Reliability Evaluation for Large-Scale Systems) Program (RP3159-4)	$400,000 28 months	Southern Company Services/*A. Vojdani*
State-Estimation Issues: Demonstration of Inter-Control-Center Communications Protocol (RP3355-3)	$168,700 14 months	ECC/*A. Vojdani*
Development of Advanced Multilevel Converter Circuit (RP3389-7)	$485,900 31 months	University of Wisconsin, Madison/*A. Sundaram*
Development of High-Efficiency, Multi-function Converters (Custom Power Technology) (RP3389-9)	$305,000 31 months	University of Florida/ *A. Sundaram*
Conceptual Study for Novel Power Quality Compensator (Custom Power Technology) (RP3389-13)	$224,800 36 months	McGill University/ *H. Mehta*
Life Evaluation of Direct-Buried In-Service Cables (RP3392-3)	$338,900 13 months	Powertech Labs/ *B. Bernstein*
Battery Monitoring System, Phase 3 (RP3493-1)	$453,200 20 months	MCM Enterprise/ *B. Damsky*

Project	Funding/ Duration	Contractor/EPRI Project Manager
Environment		
Generic NO_x Control Intelligent System: Feasibility Study (RP1402-65)	$55,000 3 months	ARD Corp./*R. Squires*
Causes of Failure of FGD System Materials (RP2248-7)	$59,300 19 months	Cortest Columbus/ *P. Radcliffe*
Assessment of Technologies to Reduce Toxic Metals in Residual Fuel Oils (RP2869-21)	$58,400 7 months	Carnot/*W. Rovesti*
Occurrence of Childhood Brain Tumors in Relation to Wire Code Configurations and Electric Appliances (RP2964-20)	$205,500 20 months	Fred Hutchinson Cancer Research Foundation/ *L. Kheifets*
Methods for the Operational Evaluation of an Air Quality Model (RP3189-7)	$257,000 25 months	University of Washington/ *D. Hansen*
Risk Evaluation of Chronic Exposure to Hydro Arsenicism in the Lagunera Region of Mexico (RP3370-11)	$78,000 12 months	Instituto de Investigaciones Biomédicas/*J. Yager*
Occupational Exposure Assessment and Bioavailability of Arsenic (RP3370-12)	$61,300 16 months	Specialized Institute of Hygiene/Epidemiology/ *J. Yager*
Investigation of the Relationship Between Arsenical-Induced Genotoxicity and Choline Deficiency (RP3370-15)	$147,200 10 months	Integrated Laboratory Systems/*J. Yager*
Impacts of Coal Pile Runoff on Soil and Water Quality (RP3507-1)	$362,200 20 months	Tetra Tech/*I. Murarka*
Kauai Seabird Study, Task 2: Ecological Study (RP3521-2)	$197,000 62 months	Point Reyes Bird Observatory/*J. Huckabee*
Plume Rise and Downwash Modeling: Model Development and Beta Testing (RP3527-1)	$367,500 24 months	Sigma Research Corp./ *C. Hakkarinen*
Plume Rise and Downwash Modeling: Field Measurements (RP3527-2)	$463,800 23 months	ENSR Consulting and Engineering/*C. Hakkarinen*
Risk Management Framework for Visibility Improvement at the Golden Circle (RP3592-4)	$171,800 8 months	Applied Decision Analysis/ *R. Goldstein*
Exploratory & Applied Research		
Dynamic Compaction in Material Fabrication (RP8012-17)	$100,000 12 months	IAP Research/ *T. Schneider*
Dynamics of Neural Learning (RP8015-2)	$159,600 22 months	Oregon Graduate Institute of Science & Technology/ *J. Maulbetsch*
Integration of Artificial Neural Networks in a Fault Diagnostic System (RP8015-3)	$234,900 59 months	Arizona State University/ *A. Wildberger*
Genetic Optimization of Neural Network Architecture for Electric Utility Applications (RP8016-4)	$78,000 6 months	Honeywell/*A. Wildberger*
Ceramic-Supported Polymer Membranes (RP8019-3)	$75,000 24 months	University of California, Los Angeles/*B. Bernstein*
Remediation of Arsenic Contamination in Groundwater (RP8020-2)	$80,000 5 months	Argonne National Laboratory/*M. McLearn*
Isolation of Syngas-Utilizing Bacteria for Production of Oxygenates (RP8021-1)	$120,100 12 months	Engineering Resources/ *S. Yunker*
Seawater-Irrigated Halophytes for Sequestration of Carbon in Coastal Desert Soils (RP8021-2)	$298,300 25 months	University of Arizona/ *L. Pitelka*
Evaluation of Halophytes for Utilization of Power Plant Cooling Water and Storm Drainage (RP8021-3)	$192,800 31 months	University of Arizona/ *L. Pitelka*
Coal Desulfurization Process (RP8022-3)	$200,000 6 months	University of Akron/ *C. Kulik*
Removal of Trace Elements From Coal (RP8022-4)	$123,800 8 months	Alberta Research Council/ *C. Kulik*

Project	Funding/ Duration	Contractor/EPRI Project Manager
Generation & Storage		
Field Testing of a Hydraulic-Turbine-Driven Boiler Recirculation Pump at Lenenergo in St. Petersburg, Russia (RP1403-25)	$73,100 10 months	Joseph Technology Corp./ *W. Piulle*
Preventive Diagnostic Monitoring Development (RP1648-15)	$99,800 24 months	Controlled Vibrations/ *T. McCloskey*
On-line Performance Monitor Development (RP1689-29)	$97,200 15 months	Marine Biocontrol Corp./ *J. Tsou*
Battery, Superconducting Magnetic Energy Storage, and Compressed-Air Energy Storage Stability Models (RP2123-27)	$99,000 7 months	Power Technologies/ *S. Eckroad*
Commercialization of GEMS (Generator Expert Monitoring System) (RP2591-17)	$2,372,700 28 months	General Electric Co./ *J. Stein*
Ceramics for Gas Turbines (RP2608-3)	$1,250,000 30 months	General Electric Co./ *W. Bakker*
Design Manual for Aerating Weirs (RP2694-17)	$298,700 33 months	Tennessee Valley Authority/ *D. Morris*
Predictive Maintenance Workstation: Prototype Development and Implementation (RP2817-34)	$192,200 12 months	Automation Technology/ *R. Colsher*
Field Testing of 180-MW District Heating Turbine at Lithuenergo's Vilnius Power Plant No. 3 (RP2819-30)	$75,500 9 months	Joseph Technology Corp./ *W. Piulle*
Compressed-Air Energy Storage Cavern and Well Monitoring (RP2894-15)	$126,400 8 months	PB-KBB/*B. Mehta*
Wind Power Development and Implementation (RP3404-7)	$253,600 22 months	Hansen, McOuat, Hamrin & Rohde/*E. Davis*
Advanced Wood-Fired Combustors/ Gasifiers (RP3407-7)	$50,000 34 months	University of Wisconsin, Madison/*E. Hughes*
Development of a High-Accuracy Resistance Temperature Detector for High-Temperature Applications (RP3499-4)	$618,000 30 months	Martin Marietta Energy Systems/*J. Weiss*
Carbonate Fuel Cell Module Design and Evaluation (RP3515-1)	$1,226,100 30 months	Energy Research Corp./ *E. Gillis*
Gas Turbine Capacity Enhancement (RP3534-2)	$273,800 20 months	Lincoln Electric System/ *H. Schreiber*
Adjustable-Speed Hydro: Issues and Benefits (RP3577-1)	$165,600 21 months	Harza Kaldveer/*J. Stein*
Development of Methods to Predict Agglomeration and Deposition in Fluidized-Bed Combustors (RP3579-1)	$200,000 36 months	University of North Dakota/ *A. Mehta*
Controls and Automation Technical Support (RP3644-3)	$213,800 11 months	Automation Technology/ *M. Blanco*
Integrated Energy Systems		
Review of Environmental Externality Studies (RP3231-6)	$60,300 14 months	Decision Focus/ *V. Niemeyer*
Characterization of Air Toxics Trace Elements in Utility Fuels (RP3440-3)	$55,000 9 months	Energy Ventures Analysis/ *J. Platt*
Estimates of Damages From Climate Change (RP3441-15)	$312,200 21 months	Industrial Economics/ *T. Wilson*
Climate Change Valuation Research: Design Support and Synthesis (RP3441-16)	$140,000 8 months	RCG/Hagler, Bailly/ *T. Wilson*
Enhancement of Contract Mix for Uranium Users (RP3604-3)	$90,100 14 months	Decision Focus/*C. Clark*
Strategic Asset Management Framework Case Study (RP7026-1)	$200,000 10 months	Strategic Decisions Group/ *L. Rubin*
Nuclear Power		
Optical Fibers and Components in Nuclear Plant Environments (RP2409-25)	$212,000 19 months	Ohio State University Research Fund/*R. James*
Electromagnetic Emissions Testing in Support of Digital Safety-Related Systems at Nuclear Plants (RP2409-26)	$224,700 9 months	National Technical Systems/*R. James*
On-line Probe for Metallic Corrosion Particulates (RP3173-4)	$208,100 35 months	General Electric Co./ *P. Millett*

Project	Funding/ Duration	Contractor/EPRI Project Manager
IPROM (Integrated Piping Reliability Optimization and Management) Software: Phase 2, Structural Mechanics (RP3175-9)	$59,800 10 months	Structural Mechanics Analysis/*S. Gosselin*
Evaluation of Zinc Additions to the Primary Coolant of PWRs (RP3223-4)	$1,794,500 36 months	Westinghouse Electric Corp./*R. Pathania*
Digital Safety Systems—SPIN and CO_3—in Nuclear Power Plants in France (RP3352-4)	$120,100 7 months	CEA/*S. Bhatt*
Verification and Validation of Knowledge-Based Systems Using Computer Aided Software Engineering Tools (RP3352-5)	$474,700 25 months	Science Applications International Corp./ *S. Bhatt*
Instrumentation and Control Reliability Experience Review (RP3373-7)	$99,800 10 months	Science Applications International Corp./ *C. Lin*
Instrumentation and Control Life-Cycle Management Methodology (RP3373-9)	$122,200 7 months	Queue Systems/ *C. Wilkinson*
Full-System Chemical Decontamination Application Assistance (RP3396-2)	$171,000 32 months	J. A. Jones Applied Research Co./*C. Wood*
Application of Risk-Based Technology: Licensing Requirements Reduction (RP3477-1)	$561,400 36 months	Science Applications International Corp./*F. Rahn*
Application of Risk-Based Technology: On-line Versus Off-line Maintenance (RP3477-3)	$134,400 18 months	Quadrex Energy Services Corp./*F. Rahn*
Application of Neural Network Methodology to Fuel Failure Analysis (RP3500-15)	$63,200 4 months	Halliburton NUS Corp./ *O. Ozer*
Exploratory Research on Enhanced Decay Heat Removal (RP3500-18)	$281,300 23 months	Massachusetts Institute of Technology/*E. Rodwell*
Chemistry of Failed LWR Fuel Rods (RP3564-2)	$365,000 36 months	University of California, Berkeley/*S. Yagnik*
Modeling of Failed Fuel Degradation (RP3564-3)	$485,300 24 months	Anatech Research Corp./ *O. Ozer*
BWR Stability Methods (RP3574-1)	$240,000 24 months	Computer Simulation and Analysis/*L. Agee*
CORETRAN Development (RP3574-2)	$275,000 11 months	S. Levy, Inc./*L. Agee*
BWR User Interface for VIPRE-2 (RP3574-3)	$148,800 11 months	Scientech/*L. Agee*
Stability Methodology (RP3574-4)	$50,000 9 months	Yankee Atomic Electric Co./*L. Agee*
Arkansas Nuclear One Instrumentation and Control Upgrade, Unit 1 (RP3586-1)	$147,100 10 months	ABB Combustion Engineering/*C. Wilkinson*
BWROG Reference Leg De-gas Test (RP3665-1)	$638,700 7 months	Continuum Dynamics/ *J. Munchausen*
Integrity of Reactor Pressure Vessels (RP3757-3)	$78,600 10 months	Sartrex Corp./*R. Carter*
SQURTS Seismic Qualification Testing (RP4414-1)	$124,500 12 months	Farwell and Hendricks/ *K. Huffman*
Enhancement of GOTHIC Containment Analysis Code (RP4444-1)	$578,700 35 months	Numerical Applications/ *A. Singh*
In-reactor Monitoring of Stress Corrosion Cracking at Quad Cities 2 (RPC101-27)	$1,499,700 31 months	General Electric Co./ *K. Ramp*
Arresting Intergranular Attack in Steam Generators (RPS511-3)	$491,500 36 months	Rockwell International Corp./*P. Paine*
Qualification of On-line Use of Morpholine for Once-Through Steam Generators (RPS520-5)	$191,500 24 months	Babcock & Wilcox Co./ *P. Millett*
PWR Steam Cycle Water Chemistry Model (RPS521-3)	$84,200 15 months	San Diego State University/ *P. Millett*
Steam Generator Deposit Characterization Guidelines (RPS523-1)	$73,800 9 months	Dominion Engineering/ *P. Millett*
Experimental Modeling of Eddy-Current Response (RPS530-1)	$284,200 24 months	Westinghouse Electric Corp./*M. Behravesh*
Steam Generator Database and User Interface Development (RPS541-1)	$214,800 11 months	CFD Research Corp./ *G. Srikantiah*
Validation of ATHOS, PORTHOS, and ZOOM Codes With Clotaire Data (RPS543-2)	$124,500 7 months	CFD Research Corp./ *G. Srikantiah*

EPRI Events

DECEMBER

7
Air Toxics R&D Results
Atlanta, Georgia
Contact: Denise O'Toole, (415) 855-2259

7–8
Distribution Cable Aging
Boca Raton, Florida
Contact: Kathleen Lyons, (415) 855-2656

7–9
Utility Motor and Generator Predictive Maintenance Workshop
San Francisco, California
Contact: Susan Bisetti, (415) 855-7919

8
Air Toxics R&D Results
Denver, Colorado
Contact: Denise O'Toole, (415) 855-2259

8–9
6th Annual Conference on Utility Strategic Asset Management
St. Petersburg, Florida
Contact: Lori Adams, (415) 855-8763

8–10
Efficient Lighting Symposium
Scottsdale, Arizona
Contact: David Ross, (703) 742-8402

8–10
Expert Systems Applications for the Electric Power Industry
Phoenix, Arizona
Contact: Jouni Keronen, (415) 855-2020

JANUARY 1994

18–20
Fossil Plant Inspections
San Antonio, Texas
Contact: Lori Adams, (415) 855-8763

25
Electric Arc Furnace Dust Treatment Symposium
Pittsburgh, Pennsylvania
Contact: John Kollar, (412) 268-3243

25
EPRI Partnership for Industrial Competitiveness
Pittsburgh, Pennsylvania
Contact: Jamil Nehme, (916) 497-1452

31–February 4
Fireside Performance of Coal-Fired Boilers
Irving, Texas
Contact: Ursla Rosenblum, (215) 758-4090

FEBRUARY

7–8
Workshop on Rate Design in the 1990s
Tampa, Florida
Contact: Pam Turner, (415) 855-2010

9–11
Innovative Electricity Pricing Conference
Tampa, Florida
Contact: Pam Turner, (415) 855-2010

9–11
Outage Risk Assessment and Management (ORAM) Workshop
Orlando, Florida
Contact: Jeff Mitman, (415) 855-2564

15–16
Customer Value Deployment
Dallas, Texas
Contact: Lynn Stone, (214) 556-6529

MARCH

1–2
Needs-Driven Program Design
Dallas, Texas
Contact: Lynn Stone, (214) 556-6529

3–4
Clean Air Response: Achieving Compliance in an Evolving Market
Baltimore, Maryland
Contact: Jeremy Platt, (415) 855-2628

3–4
Continuous Emissions Monitoring Quality Assurance
Dallas, Texas
Contact: Lynn Stone, (214) 556-6529

14–16
EMF Science and Communication Seminar
Santa Clara, California
Contact: Amelia Birney, (612) 623-4600

15–16
Distributed Utility Workshop
Baltimore, Maryland
Contact: Susan Marsland, (415) 855-2946

16–17
Asbestos Control and Replacement
San Diego, California
Contact: Linda Nelson, (415) 855-2127

22–23
4th Annual NMAC Conference and Technical Workshop
Charlotte, North Carolina
Contact: Jayne Adkisson, (704) 547-6141

23–25
Fossil Plant Cycling
New Orleans, Louisiana
Contact: Lori Adams, (415) 855-8763

23–25
Weld and Repair Technology for Fossil Power Plants
Williamsburg, Virginia
Contact: Susan Bisetti, (415) 855-7919

29–31
Nondestructive Evaluation of Fossil Plants
Dallas, Texas
Contact: Lynn Stone, (214) 556-6529

APRIL

5–6
Global Warming: A Call for International Coordination
San Francisco, California
Contact: Colleen Hyams, (415) 855-2143

5–7
Direct Demand-Side Management Marketing
Dallas, Texas
Contact: Lynn Stone, (214) 556-6529

26–29
Transformer Performance Monitoring and Diagnostics
Eddystone, Pennsylvania
Contact: John Niemkiewicz, (215) 595-8871

MAY

3–5
Heat Rate Improvement
Baltimore, Maryland
Contact: Susan Bisetti, (415) 855-7919

10–13
Decision Quality/Decision Analysis Seminar and Workshop
Newport, Rhode Island
Contact: Susan Marsland, (415) 855-2946

11–13
NO_x Controls for Utility Boilers
Scottsdale, Arizona
Contact: Pam Turner, (415) 855-2010

16–20
Applications of Static Compensators and Other FACTS Power Flow Controllers
Madison, Wisconsin
Contact: Bill Long, (608) 262-2061

17–19
Fluidized-Bed Combustion for Power Generation
Atlanta, Georgia
Contact: Linda Nelson, (415) 855-2127

17–19
6th Predictive Maintenance Conference
Philadelphia, Pennsylvania
Contact: Lori Adams, (415) 855-8763

19–20
Improving Building Systems in Hot and Humid Climates
Arlington, Texas
Contact: Susan Swanson, (409) 862-2291

JUNE

1–2
Customer Value Deployment
Dallas, Texas
Contact: Lynn Stone, (214) 556-6529

6–8
ISA POWID/EPRI Controls and Instrumentation
Orlando, Florida
Contact: Lori Adams, (415) 855-8763

29–July 1
Service Water Systems Reliability Improvement
St. Louis, Missouri
Contact: Susan Otto, (704) 547-6072

EPRI JOURNAL

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